Physiological Capacity During Simulated Stair Climbing Evacuation at Maximum Speed Until Exhaustion

Amitava Halder ^{*}, Division of Ergonomics and Aerosol Technology,
Department of Design Sciences, Faculty of Engineering, Lund University,
Box 118, 221 00 Lund, Sweden

Kalev Kuklane , Division of Ergonomics and Aerosol Technology,
Department of Design Sciences, Faculty of Engineering, Lund University,
Box 118, 221 00 Lund, Sweden and Institute for Safety (IFV), P.O. Box
7112, 2701 AC Zoetermeer, The Netherlands

Michael Miller , Department of Health Sciences, Faculty of Medicine, Lund
University, Box 117, 221 00 Lund, Sweden

Axel Nordin , Division of Product Development, Department of Design
Sciences, Faculty of Engineering, Lund University, Box 118, 221 00
Lund, Sweden

Jeannette Unge, Department of Health Sciences, Faculty of Medicine, Lund
University, Box 117, 221 00 Lund, Sweden

Chuansi Gao , Division of Ergonomics and Aerosol Technology,
Department of Design Sciences, Faculty of Engineering, Lund University,
Box 118, 221 00 Lund, Sweden

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Abstract. Stair-ascending at maximum ability is required during emergency evacuations to reach a safe refuge from deep underground structures. We hypothesized that an ascent can last maximum 5 min at the individual's maximum step rate (SR), and oxygen uptake ($\dot{V}O_2$) would not reach a stable state. This study explored stair-ascending endurance and some physiological constraints of performance. Eighteen healthy volunteers with mean (standard deviation, SD) age 26.7 (4.0) years, height 172.2 (10.7) cm, weight 68.0 (11.3) kg, BSA 1.8 (0.2) m², $\dot{V}O_{2\max}$ 48.5 (5.4) mL min⁻¹ kg⁻¹, and HR_{max} 192 (9) b min⁻¹ ascended on a stair machine at a SR equivalent to their 100% $\dot{V}O_{2\max}$. The mean (SD) ascending duration was 3.47 (1.18) min, supporting the hypothesis. The calculated vertical height covered was 85.5 (32.1) m. The $\dot{V}O_{2\text{highest}}$ reached 44.8 (7.3) mL min⁻¹ kg⁻¹, which was 92.3 (9.7)% of $\dot{V}O_{2\max}$ when the HR_{highest} peaked at 174 (11) b min⁻¹. However, the mean ($\dot{V}O_2$) reached a relatively steady state after the sharp rise. The post-ascent blood lactate, respiratory exchange ratio, and perceived exertion values recorded were high, 14.4 (4.0) mmol l⁻¹, 1.20

* Correspondence should be addressed to: Amitava Halder, E-mail: Amitava.Halder@design.lth.se

(0.09), and 18.2 (0.7), respectively, indicated that exhaustion was reached. The ascending SR rate was above the lactate threshold; therefore, the attainment of $\dot{V}O_2$ steady state was slowly reached. EMG amplitudes of four major leg muscles increased and the median frequencies of two muscles decreased significantly ($p < .01$) indicating local muscle fatigue (LMF). Leg LMF and hyperventilation resulted in speedy exhaustion leading to termination. These results infer that stair ascending at maximum ability ($122 \text{ steps min}^{-1}$) is possible to sustain 2–6 min. These overall results offer useful and vital information to consider when designing underground emergency evacuation facilities.

Keywords: Stairclimbing capacity, Oxygen uptake, Maximum-intensity work, Physical fitness, Muscle fatigue, Electromyography, Blood lactate, Stairclimbing duration

Abbreviations

AD	Ascending duration (s)
AMP	Electromyographic (EMG) amplitude (μV)
AS	Ascending speed (m s^{-1})
BLa ⁻	Blood lactate (mmol l^{-1})
BMI	Body mass index (kg m^{-2})
BSA	Body surface area (m^{-2})
CPET	Cardiopulmonary exercise testing
HR _{max}	Maximum heart rate reached during maximal aerobic capacity test (b min^{-1})
HR _{highest}	Maximum heart rate reached during stair-ascending test (b min^{-1})
LMF	Local muscle fatigue
MAIS	Muscle activity interpretation square
MARC	Muscle activity rate change
MDF	Medium frequency of motor unit action potentials (Hz)
MVC	Maximum voluntary contractions
RER	Respiratory exchange ratio, CO_2/O_2
RPE	Rating of perceived exertion
SR	Step rate calculated corresponding to 100% $\dot{V}O_{2\text{max}}$ (steps min^{-1})
$\dot{V}E$	Minute ventilation (L min^{-1})
V_{height}	Vertical height reached (m)
$\dot{V}O_{2\text{max}}$	Maximum oxygen uptake reached during maximal aerobic capacity test ($\text{mL min}^{-1} \text{ kg}^{-1}$)
$\dot{V}O_{2\text{highest}}$	Maximum oxygen uptake reached during stair-ascending test ($\text{mL min}^{-1} \text{ kg}^{-1}$)

1. Introduction

Stair-ascending is a frequently encountered demanding task in our daily life [35, 45, 46]. It requires high physical capacity particularly for the larger thigh muscles to bear the whole body weight against the gravity [2, 16]. Non-stop ascending at maximum speed can be required when people respond to the demands that arise in emergency evacuations for example, terror attacks or fire incidents. In most cases, people would choose their maximal possible step rate (SR) to reach a safe refuge when they need to ascend from deep underground structures, such as subways, or exits at the higher levels or rooftop in high-rise buildings. The ability for humans to meet the high energy requirements for longer periods of such quick ascent depends on several physiological factors including fitness, oxygen uptake ($\dot{V}O_2$) capacity, lactate tolerance, and economy of activity [4, 38]. A few studies

have explored stair-ascending endurance in critical life-saving situations, such as natural calamities, fires and terror attacks, where people need to climb stairs using their full physiological capacities.

Physical exhaustion and muscle fatigue play a limiting role on evacuation performance, which needs to be investigated [47, 48]. The evacuation capacity in emergency conditions including travel time and walking facilities of subway stations were estimated using different models [14, 57]. The necessity to include fatigue and exhaustion measures in evacuation modelling has been addressed by the fire research community [40]. A conceptual model of the impact of fatigue on pedestrian movement during stair-ascending evacuations has been presented [49]. However, the essential, physiological exhaustion-related ascending parameters have not been integrated into the models. The improved models that include physiological parameters can potentially help in planning and designing the evacuation facilities in modern buildings.

Maximum capacities in the severe intensity domain have been explored by performing various exercises until exhaustion: in cycling, ramp or all-out effort [5, 53]; in running [12]. One study elucidated the relationships between ascending speed (AS), $\dot{V}O_2$ and efficiency for different patterns of stair-ascending movement [58]. A previous field evacuation study reported physiological capacities including $\dot{V}O_2$, heart rate (HR), and leg muscle electromyography (EMG) when ascending stairways in three different buildings [24]. Based on those field tests and three different sub-maximal SRs in the laboratory [23], an evacuation model has been presented that contains a formula for vertical height and step rate calculations [33]. An evacuation study simulated on a stair machine showed that the ascending duration (AD) is limited to 4.3 min at a SR corresponding to 90% of $\dot{V}O_{2max}$ due to leg local muscle fatigue (LMF) [23]. $\dot{V}O_2$ usually rises linearly and reaches a steady state within 2–3 min during a constant rate of moderate exercise [32]. When the work rate is too high above the critical power [10, 19] no steady state is reached, and the exercise leads to exhaustion and early termination [6, 31, 55]. A stable $\dot{V}O_2$ kinetics is important when considering the possible AD and covered vertical height (V_{height}). It means that the ascent in such a situation is maintained at a tolerable rate, when both the uptake and utilization of $\dot{V}O_2$ are in balance. This allows the continuation of the ascent at that intensity, which is presumed to be at a sub-maximum level ($\approx 75\%$ of $\dot{V}O_{2max}$) [23, 24].

Maintaining the maximal ascending SR as long as possible is the key for maximizing the evacuation performance. Few studies have addressed the constraints and limiting factors during stair-ascending evacuation at maximum intensity. Therefore, it is important to investigate the physiological capacities required during evacuation at maximal SR. The aim of this laboratory study was to investigate the effects of maximal ascending evacuation speed on ascending capacity including AD, vertical height (V_{height}) reached, $\dot{V}O_2$, HR, minute ventilation ($\dot{V}E$), muscular performance (EMG data), the production and tolerance of blood lactate (BLa^-). In this study, we hypothesized:

- A stair-ascent could only be sustained up to 5 min at SR corresponding to 100% $\dot{V}O_{2\max}$ on a stair machine in this simulated evacuation situation, partly due to exhaustion, and leg fatigue as evidenced by EMG amplitude (AMP) and median frequency (MDF);
- Oxygen uptake during ascending ($\dot{V}O_{2\text{highest}}$) evacuation simulation at maximal SR could not reach a stable state in the end, and the ascent is terminated with a lower $\dot{V}O_{2\text{highest}}$ than $\dot{V}O_{2\max}$.

2. Materials and Methods

2.1. Subjects

Eighteen healthy university students evenly divided by gender without any musculoskeletal problems, history of any major illness or disabilities were selected (Table 1). To determine eligibility, the test subjects completed a questionnaire that revealed the basic information about their health including history of diseases and medications. Written informed consent was obtained from all participants. A health declaration form was also delivered in advance and filled in by the subjects.

2.2. Study Protocol and Ethics

The subjects received verbal and written information about the test procedures twice: once during the recruiting period and once before the tests. The experiments were conducted on two different days: on day 1, the $\dot{V}O_{2\max}$ was measured on a treadmill; on day 2, the main experiment involving stair-ascending movement to simulate evacuation was conducted. The protocol is described in the schematic flowchart in Fig. 1. The subjects were asked to refrain from drinking alcohol and exercising at least 24 h before the tests. They were also requested to avoid heavy meals, or drinking coffee or tea for at least 2 h before the test. They were asked to do a trial walk on the treadmill and a trial ascent on the stair machine before the actual tests, if they were not familiar with the instruments. The subjects were instructed that they might terminate the test at any time without providing any reason. The methods and procedures used in this study comply with the [56]. The Regional Ethical Review Authority in Lund, Sweden also approved the protocol (Dnr. 2016/1061).

2.2.1. Maximal Aerobic Capacity ($\dot{V}O_{2\max}$) Test In order to determine the subject's maximal aerobic capacity on day 1, $\dot{V}O_{2\max}$ tests were carried out on a treadmill (Exercise™, x-track elite, Sweden) using the ramp testing protocol. The test started with a 5-min sitting rest followed by walking at 4 km h⁻¹ for 3 min and then jogging at 8 km h⁻¹ for 2 min. The speed was further increased every 2 min until the subject reached a comfortable pace and then the treadmill was inclined while continued running. The inclination was increased by 3% every 2 min until exhaustion [1]. The maximum $\dot{V}O_2$ in mL min⁻¹ kg⁻¹ and HR values in end 10-s average were designated as the individual's $\dot{V}O_{2\max}$ and HR_{max}, respectively.

Table 1
Demographics and Maximum Oxygen Uptake ($\dot{V}O_{2\max}$) Test Results of All Subjects (N = 18) with Mean (Standard Deviation, SD)

Parameters (units)	Age (years)	Height (m)	Weight (kg)	BSA (A_{Du} , m^{-2})	BMI ($kg\ m^{-2}$)	$\dot{V}O_{2\max}$ ($mL\ min^{-1}\ kg^{-1}$)	$HR_{\max}$ (b min^{-1})	BLa^{-} ($mmol\ l^{-1}$)	RER	$\dot{V}E$ ($L\ min^{-1}$)	BF (min^{-1})	RPE
Mean (SD)	26.7 (4.0)	1.73 (0.11)	68.0 (11.3)	1.8 (0.2)	22.6 (2.0)	48.5 (5.4)	192 (9)	14.2 (2.5)	1.17 (0.06)	130.0 (26.8)	57.0 (10.5)	17.9 (0.9)

Figure 1. Schematic flowchart and protocol of the stair-ascending movement test for evacuation on a stair machine in the laboratory.

Figure 2. One of the test subjects was ascending on the stair machine in the laboratory. Data were collected by using a synchronized motion capture system and electromyography.

2.2.2. *Stair-Ascending Movement Test for Evacuation* Fatigue may interfere when sustaining the ascending speed (AS) at the desire level. However, an “all-out” effort [53] is always to be expected in real life emergencies during which the AS may not be constant. In this laboratory study, however, the subjects ascended on a stair machine with a step height of 20.5 cm and depth of 25.0 cm (StairMaster, SM5, Vancouver, WA, USA) (Fig. 2). A constant speed had to be used on the stair machine due to its design and function. The SR was determined for each subject and was equivalent to the relative $\dot{V}O_2$ values of each individual’s 100% $\dot{V}O_{2max}$. SR was calculated based on the following equation,

$$SR = 24.0267 + 2.0121 (\dot{V}O_{2max})$$

This equation was modified from the previous field and laboratory studies on stair-ascending movement test for evacuation [23, 24, 33].

The simulated evacuation was designed to ascertain ascending duration (AD), vertical distance, $\dot{V}O_{2\text{highest}}$, HR_{highest} , and minute ventilation ($\dot{V}E$) at the maximal ascending speed (AS). Moreover, the blood lactate (BLa^-), respiratory exchange ratio (RER), and rating of perceived exertion (RPE) were collected in order to confirm the fatigue and exhaustion, and to assess correlations with the leg muscles' EMG data. The subjects were encouraged to keep on climbing at the maximal speed as long as they could in order to simulate an evacuation. However, in accordance with our ethics protocol; they were assured in advance that they could stop at any time, if they requested. Finally, they were asked to rate between 6 and 20 on the Borg scale (from no exertion at all to maximal exertion) to get the RPE values and the BLa^- was measured in the fingertip using a hand-held analyzer Lactate Scout + (EKF diagnostics, Penarth, Cardiff, UK). These results were recorded at the end of both $\dot{V}O_{2\text{max}}$ and stair-ascending tests.

2.3. Instrumentation and Subject Preparation

2.3.1. Cardiopulmonary Exercise Testing (CPET) System Each subject was instrumented with the physiological measurement systems on both visits. The instruments included a chest belt, which was buttoned to a HR transmitter (Polar H7, Polar Electronics, Finland) and a cardiopulmonary exercise testing (CPET) system (Metamax 3B-R2, Cortex Biophysik GmbH, Germany) consisting of a facemask fastened with a comfortable snip-snap head harness and straps. The CPET-system with HR transmitter were used to measure the respiratory oxygen uptake ($\dot{V}O_2$), minute ventilation ($\dot{V}E$), heart rate (HR) and O_2 , CO_2 concentrations in breath-by-breath mode. All these cardiopulmonary data were averaged over 10 s periods.

The Metamax 3B-R2 CPET system was reported to be reliable (both percentage errors, and percentage technical error of measurements < 2%) for measuring expired $\dot{V}E$, $\dot{V}O_2$, and $\dot{V}CO_2$ productions [36].

The Polar H7 sensor is HR measurement system for sports and fitness. A comparable study with other available devices in the market showed that the chest strap monitor (Polar H7) had the best agreement with ECG ($rc = 0.996$) [21]. It transmits data in coded form (Polar Own Code 5 kHz transmission). This is an important feature as it avoids interference.

2.3.2. Electromyography (EMG) and Measured Leg Muscles Activity The EMG biomonitor, Megawin (ME6000-T16 Mega Electronics, Kuopio, Finland), was synchronized with an eight-camera Pro-Reflex motion capture (MoCap) system (Qualisys, Gothenburg, Sweden). The technology of EMG biomonitor, ME6000 is recognized for its high precision and accuracy to detect sensitive signals of human muscular performance both in a noisy laboratory environment and in varying field conditions. A retrospective EMG study showed a moderate diagnostic accuracy for radiculopathy and confirmed no bias while they assessed the intra-rater and inter-rater reliability [39].

Raw EMGs were recorded at a sampling rate of 1024 Hz (the time events to an accuracy of 1 ms) in the Qualisys Track Manager (QTM) Software version 2.17

during the stair-ascent test on the second visit. The EMG biomonitor and cables weighed in total 550 g and were strapped securely to the test subject's lower back. EMG was measured unilaterally on the subject's dominant leg. Four lower limb muscles were measured to observe muscle activity: (1) Vastus Lateralis (VL) is a knee extensor muscle and located in lateral part of thigh. (2) Rectus Femoris (RF) is a hip flexor and knee extensor muscle, which is located in the middle part of thigh. (3) Gastrocnemius Lateralis (GL) is a foot plantar flexor muscle and located in lateral part of the calf. (4) Tibialis Anterior (TA) is located at the anterior part of the lower leg and is responsible for ankle dorsiflexion.

Raw EMG signals were obtained by using pre-gelled bipolar (AgCl) surface electrodes in pairs (Ambu Neuroline-720, Ballerup, Denmark). In order to get good contact and EMG signals, subject's skin was prepared first by shaving the hair of the leg, then scrubbed lightly with fine sandpaper to take away skin debris, finally cleaned with 70% isopropyl alcohol. Electrodes were placed along the direction of the underlying muscle fibers with a center-to-center distance of approximately 15–20 mm. The placement of the electrodes for each muscle and reference ones followed the recommendations of the SENIAM project (Surface Electromyography for the Non-Invasive Assessment of Muscles) (www.seniam.org, Enschede, Netherlands) [25]. The same experienced investigator performed all the placements of electrodes on all subjects [39].

2.4. Data Collection and Processing

Three isometric maximum voluntary contractions (MVCs) of the dominant knee extensors (VL and RF), ankle plantar (GL) and dorsiflexor (TA) were performed and the EMG recorded prior to the stair-ascending test. To obtain the MVCs of the individual subject, one of the investigators applied maximal manual isometric resistance at midrange for the respective muscle. Each MVC duration lasted for 3–5 s with a development of the contraction for about 1–2 s for the RF, GL, and TA muscles when laying supine on a plinth except the VL, which was obtained in sitting.

2.4.1. EMG Signal Processing and Normalization The raw EMG signals were band-pass filtered (20–499 Hz). The low pass filter would essentially eliminate skin movement artifacts during this dynamic task. Each subject's AD was divided into 10 equal-length periods to achieve time normalization of the individual AD. This time normalization method was applied so that the dynamic muscle activities at each 10th percentile period for all subjects could be compared [18, 37]. The filtered raw signal was rectified and averaged using root mean square averaging in order to obtain the muscles' average amplitude (AMP) in μV for each 10% period. A frequency spectrum was obtained by applying the fast Fourier transform and thus the median frequency (MDF) in Hz could be calculated. The averages of the normalized AMP and MDF for each equally divided 10% period [3] were calculated to yield one data point for each subject; in total, 10 data points for each subject and then for all subjects. The average of three individual maximum AMPs

from the MVC tests was used to normalize each AMP data point for each muscle with the aim to reduce EMG variations.

2.4.2. EMG Data Interpretation in the MAIS The muscle activity interpretation square (MAIS) [23, 24] was used to observe over time along with separate interpretation of AMP and MDF to confirm the LMF. The MAIS is based on Cifrek et al.'s four assumptions [15] of EMG muscle activity (MDF and AMP) rate change (MARC). The MARC was derived from the average AMP and MDF values of each 10th percentile of the total ascending period of each subject. These 10 periodical average AMP and MDF data points (10–100%) and the changes between the unit times represent the MARC. Then both the AMP and MDF MARC values were used to plot one final point for each 10th percentile duration as a MARC point and placed in the MAIS. This was used to observe muscle activity and eventually to identify the onset of LMF over time.

2.4.3. Calculation and Statistics The $\dot{V}O_{2\text{highest}}$ and HR_{highest} were calculated as described in the previous publication [23]. Breath-by-breath data from the CPET system were analyzed at 10-s averages. Paired sample t-tests were performed to determine the statistical significance of the physiological variables between the stair-ascending and maximal capacity tests. The normal distribution of EMG data was challenged, which threatened the mixed model and analysis of variance (ANOVA) tests. Therefore, nonparametric-related samples Friedman's test was performed to observe how the related muscle activity changed over time (10–100%) for both AMPs and MDFs. All physiological data including $\dot{V}O_2$, HR, $\dot{V}E$, and end respiratory exchange ratio, CO_2/O_2 (RER) were also time normalized to 0–100% periods following the same procedure of stair-ascending EMG data normalization. The AS was calculated in the slope direction of the stair machine while the height, width of the step, and the SR were taken into consideration. The averages of all the normalized parameter values were calculated within each of the 10% normalized periods for the same subject and then for all subjects at each of the 10% periods. In addition, the MARC representing both average AMP and MDF values were also derived from the equation in the previous study [23].

The calculations and statistical analyses were carried out in *Matlab R2016a* (The MathWorks AB, Kista, Sweden), *Excel 2016* (Microsoft Corporation, USA) and *Statistical Package for the Social Science (SPSS)*, version 24.0 (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 at Maximum Speed

Ascending durations (ADs) were varied depending on the individuals' capacity. Most of the participants reported pain in their legs, breathlessness, and rated the simulated evacuation as "extremely tough". The post-ascent physiological and

Table 2
The Results of Stair-Ascending Movement for Evacuation at 100% $\dot{V}O_{2max}$ Step Rates for All Subjects (N = 18) with Mean (Standard Deviation, SD)

Parameters (units)	AD (min)	AS (m s ⁻¹)	SR (steps min ⁻¹)	V _{height} (m)	$\dot{V}O_{2highest}^{\S}$ (mL min ⁻¹ kg ⁻¹)	HR _{highest} [§] (b min ⁻¹)	% $\dot{V}O_{2max}^*$	%HR _{max} [*]	BLa ⁻ (mmol l ⁻¹)	$\dot{V}E$ (L min ⁻¹)	BF ^a (min ⁻¹)	RPE
Mean	3.5	0.66	122.2	85.5	44.8	174	92.3	90.8	14.4	122.2	51.4	18.2
(SD)	(1.2)	(0.05)	(9.7)	(32.1)	(7.3)	(11)	(9.7)	(4.0)	(4.0)	(33.1)	(9.4)	(0.7)

§Significantly lower during stair-ascending movement for evacuation simulation tests $p < .01$ for all than the $\dot{V}O_{2max}$ tests
*The calculated average $\dot{V}O_2$ and HR reached during the stair-ascending test in relation to the $\dot{V}O_{2max}$ and HR_{max} values from the treadmill $\dot{V}O_{2max}$ test

Figure 3. Average ($N = 18$) oxygen uptake ($\dot{V}O_2$) (a), heart rate (HR) (b), minute ventilation ($\dot{V}E$) (c) and respiratory exchange ratio (RER) (d) kinetics during normalized time ascending periods (0–100%) until exhaustion.

related values including $\dot{V}O_{2\text{highest}}$, $t(17) = -3.35$, $p > .01$; HR_{highest} , $t(17) = -9.79$, $p > .01$; breathing frequency (BF), $t(17) = -3.35$, $p > .01$ were significantly lower than the values during $\dot{V}O_{2\text{max}}$ test; but not the minute ventilation ($\dot{V}E$). On the contrary, blood lactate (BLa^-), rating of perceived exertion (RPE), and respiratory exchange ratio (RER) were higher without significant differences than those during the $\dot{V}O_{2\text{max}}$ tests. The main results of the stair-ascending tests are listed in Table 2.

3.1.1. $\dot{V}O_2$, HR, $\dot{V}E$ and RER During the Simulated Stair-Ascending Movement for Evacuation $\dot{V}O_2$, HR and $\dot{V}E$ and RER kinetics are shown in Fig. 3a–d. $\dot{V}O_2$, HR and $\dot{V}E$ kinetics showed an increase; however, $\dot{V}O_2$ reached a relatively stable state just before stopping the ascents by the subjects.

3.2. Leg Muscle Electromyography (EMG)

3.2.1. Changes in EMG AMP and MDF Over Time The EMG AMP of the 10th percentile values of all four measured muscles were significantly ($p \leq .01$) increased during stair-ascending until exhaustion (Tables 3, 4; Fig. 4a). On the contrary, only major thigh (VL) and anterior leg (TA) muscles' MDFs (Tables 3, 4; Fig. 4b)

Table 3
The Mean (Standard Deviation, SD) of EMG AMP % MVC, and MDF Results (N = 18) of Stair-Ascending Movement for Evacuation at 100% $\dot{V}O_{2max}$ Step Rates Over Normalized Time (10-100%)

Periods %	10	20	30	40	50	60	70	80	90	100
<i>Muscles</i>	<i>EMG AMP %MVC, mean (SD)</i>									
VL	36.32 (21.31)	45.44 (24.77)	49.71 (28.61)	53.07 (33.60)	56.89 (40.69)	56.17 (42.01)	57.46 (41.91)	58.64 (41.12)	61.02 (40.52)	64.65 (46.37)
RF	22.91 (17.64)	29.22 (22.96)	31.06 (22.38)	32.82 (24.04)	34.29 (31.32)	34.03 (33.06)	34.65 (34.59)	38.40 (41.47)	43.14 (48.93)	45.78 (54.63)
GL	57.70 (35.48)	65.45 (35.69)	67.40 (35.34)	67.65 (36.28)	74.06 (42.26)	71.03 (42.83)	71.13 (45.07)	77.32 (49.68)	78.94 (52.01)	82.44 (57.59)
TA	29.50 (10.91)	35.14 (14.36)	34.87 (12.57)	35.95 (14.28)	36.22 (14.35)	36.05 (14.29)	35.87 (13.98)	40.38 (14.73)	43.98 (16.82)	43.90 (18.78)
	<i>EMG MDF, mean (SD)</i>									
VL	64.5 (10.9)	60.4 (13.7)	59.8 (12.4)	59.2 (11.1)	59.0 (11.2)	59.2 (11.5)	59.6 (11.2)	59.9 (10.7)	61.1 (11.0)	59.4 (11.3)
RF	68.7 (39.9)	58.7 (9.6)	57.6 (10.2)	58.2 (9.1)	57.6 (9.1)	57.3 (9.7)	58.4 (9.3)	57.6 (9.1)	59.3 (8.6)	58.6 (8.7)
GL	73.5 (22.1)	71.8 (23.1)	73.4 (23.6)	72.9 (20.3)	72.5 (20.2)	71.4 (20.5)	72.2 (20.4)	72.8 (20.0)	79.5 (14.6)	79.4 (14.8)
TA	86.4 (17.2)	78.8 (17.7)	75.1 (18.4)	73.0 (19.5)	70.9 (20.7)	69.8 (23.0)	69.3 (22.9)	67.9 (23.6)	67.9 (23.4)	67.8 (23.0)

Table 4
Non-parametric Friedman’s Test Results with Pearson’s Chi-Square (χ^2) Value (Rounded to Two Decimal Places), and the Significance Level on All Four Muscles’ EMG Amplitude (AMP) and Median Frequency (MDF)

Parameters	VL, AMP	RF, AMP	GL, AMP	TA, AMP	VL, MDF	RF, MDF	GL, MDF	TA, MDF
N	12	12	11	12	13	13	13	13
χ^2	53.04	28.36	39.62	18.11	25.55	6.37	5.14	58.25
Sig.	.00	.00	.00	.00	.00	.70	.82	.00

The degrees of freedom (*df*) was 9 for all muscles’ AMP and MDF

Figure 4. Average changes in normalized EMG AMPs (a) and MDFs (b) for four muscles over the normalized time (10–100%) ascending duration.

showed a significant decrease ($p \leq .01$) while no significant difference was found on the MDFs of RF and GL (calf) muscles. These results suggest the onset of local muscle fatigue (LMF) in the legs.

3.2.2. Muscle Activity Rate Change (MARC) in Muscle Activity Interpretation Square (MAIS) The appearances of 10th percentile MARC points in the MAIS show the status of muscle activity changes from the beginning to the end. The AMP and MDF rate changes of all four muscles show a similar pattern in the MAIS. Most of the MARC values aggregate between the *muscle force increase* and *muscle fatigue* squares of each muscle diagram (towards the right half in all the diagrams in Fig. 5). It is important to note that the end period (90–100%) MARC values were concentrated in and close to the *muscle fatigue* square (Fig. 5).

Figure 5. Muscle activity rate change (MARC) during ascending at the SR corresponding to 100% $\dot{V}O_{2max}$ for four muscles in normalized time (10–100%) in the muscle activity interpretation square (MAIS).

4. Discussion

4.1. The Capacity of Simulated Stair-Ascending Movement for Evacuation at Maximal Step Rate (SR)

The main findings of the study showed that the subject could manage an ascending for an average of 3.5 (1.2) min, at the constant SR corresponding to 100% of individual $\dot{V}O_{2max}$ in a simulated evacuation. This result supports the first hypothesis of the ascending duration (AD). In present study, the mean (standard deviation, SD) SR was 122.2 (9.7) steps min^{-1} . An average vertical distance (V_{height}) reached was 85.5 (32.1) m at a vertical displacement of 24.4 (1.9) m min^{-1} , when

the calculated ascending speed (AS) was $0.66 (0.05) \text{ m s}^{-1}$. This calculated V_{height} is approximately 29 floors. These are in agreement with the previous results of average AD 4.3 min when the subjects reached a calculated V_{height} 95.0 m at an AS of 0.59 m s^{-1} at the 90% of $\dot{V}\text{O}_{2\text{max}}$ level with reasonably a lower SR $109.4 \text{ steps min}^{-1}$ [23]. The novel datasets presented in these current and referenced papers [23, 24] provide worthwhile information for both fire safety researchers and engineers to conduct fire safety design as well as the calibration of evacuation modelling tools. The results of this study also validate the previously developed evacuation model, that is being used to calculate the SR and V_{height} [33].

In this controlled study, the speed of the stair machine was fixed due to the stair machine's technical limitations. The subjects might have been able to prolong their effort in a real life emergency by slowing down according to the individual physiological capacities, situations, conditions and knowledge of the evacuation path. These results could help to estimate the appropriate V_{height} for arranging safety measures, such as where to place resting planes or egress facilities in long staircases of deep underground constructions to ensure a safe evacuation. However, these results should be applied carefully to real life situations when considering the step height and depth. In the recent field stair-ascending study on 13 and 31 floor building stairways, the average SRs were 92 and 95 steps min^{-1} , respectively, in the self-preferred pace. The continuous reduction of ASs through SR were observed about or after 1 min of the onset [24]. Therefore, the suggested tolerance limit of ascending could be about 2–6 min at maximum intensity and constant rate. $\dot{V}\text{O}_{2\text{highest}}$ can be achieved very shortly too (within $\sim 1 \text{ min}$) during this study's constant and very-fast exercise [42, 53]. Vanhatalo et al.'s study recommended that a constant and high intensity work or an all-out effort duration should be 3 min to reach exhaustion. In addition, Holmér and Gavhed [27] reported that people could manage to maintain an activity level for about 5 min at their maximum intensity [27]. Moreover, the results of this specific study are limited to healthy and young adult participants. It is therefore, expected that the observed performance might be different on a more diverse population, but the previous study at 90% $\dot{V}\text{O}_{2\text{max}}$ SR with multiple demographic characteristics supported this and was in-line with these present results.

4.2. Stair-Ascending $\dot{V}\text{O}_2$ Kinetics and Workload Until Exhaustion

The mean $\dot{V}\text{O}_2$ kinetics showed that it reached a relative stable state following the exponential increase during the 60-70% normalized time (Fig. 3a); however, the termination of the ascents was obvious and happened immediately. Thus, this result rejects the second hypothesis of this simulated evacuation study. The obtained $\dot{V}\text{O}_2$ pattern demonstrated that a relative stable state could be reached, even at the end of this constant and intense step rate (SR) while reaching exhaustion. This $\dot{V}\text{O}_2$ kinetics evidenced that most of these ADs were sufficiently long $\geq 1\frac{1}{2}$ –2 min to achieve the relative stable states [26, 41]. This $\dot{V}\text{O}_2$ kinetics after the exponential increase showed several fluctuations suggesting that the sustainment

of the SR or work tolerance [17] within this heavy work intensity domain [9, 10, 29, 44], extended thus the AD from about 70 to 100% periods. The relative $\dot{V}O_2$ stabilization at the end was related to the fact that the subjects could tolerate this constant load of stair-ascents for a short period as the fatigue process had already started [13, 30, 53, 59]. Thus, the ascending SR influences the $\dot{V}O_2$ kinetics and the V_{height} . The estimated SR was based on the ramp responses ($\dot{V}O_{2\text{max}}$ tests). These obtained results suggest that $\dot{V}O_2$ component of any heavy-intensity activity, which was based on the ramp responses, should be further studied.

In this study, neither the $\dot{V}O_{2\text{highest}}$ nor the HR_{highest} reached 100% of $\dot{V}O_{2\text{max}}$, supporting the hypothesis. These post-ascents lower cardiorespiratory capacities than the $\dot{V}O_{2\text{max}}$ test evidenced that the ascent was ended before reaching the subjects maximal level (Table 2). Only the $\dot{V}O_{2\text{highest}}$ of the six subjects' were $\geq \dot{V}O_{2\text{max}}$. However, the achieved average $\dot{V}O_{2\text{highest}}$, $44.8 \text{ mL min}^{-1} \text{ kg}^{-1}$ was reasonably higher than the value of $43.9 \text{ mL min}^{-1} \text{ kg}^{-1}$ from the previous evacuation experiment at 90% of $\dot{V}O_{2\text{max}}$ SR [23]. In the evacuation study in different buildings at self-selected ascending pace, the average $\dot{V}O_{2\text{highest}}$ and HR_{highest} ranged from 39 to $41 \text{ mL min}^{-1} \text{ kg}^{-1}$, and 163 to 174 b min^{-1} , respectively. Moreover, the mean stable $\dot{V}O_2$ was found to be between 37.2 and $38.5 \text{ mL min}^{-1} \text{ kg}^{-1}$, and while the mean stable HR was between 163 and 168 b min^{-1} , when the subjects managed ascending both 13 floor (3 landings/floor) and 31 floor (2 landings/floor) buildings at $92\text{--}95 \text{ steps min}^{-1}$ upon completion [24]. These stable $\dot{V}O_2$ and HR values for ascending on those two buildings were found $\approx 75\text{--}80\%$ of $\dot{V}O_{2\text{max}}$ corresponding SR tests those were used in the previous lab study [23], and $\geq 85\%$ of average maximal capacities reported in the databases [34]. The intensity of those field study's SRs ($\geq$ ventilatory threshold) seemed tolerable enough to be able to continue ascending for a long duration without being exhausted, contrary to the SR used in this study.

The reasons for the achieved lower levels of physiological values in the stair-ascent evacuation than those in the $\dot{V}O_{2\text{max}}$ tests were because of the two different types of activities with different durations: incremental ramp test to the simulated stair-ascending movement test for evacuation maintained at a constant work rate. However, stair-ascending movement required working against gravity and local muscle fatigue (LMF) might precede the whole body exhaustion due to very highly repetitive activity of the leg muscles. The static posture of the upper extremities might have reduced oxygen demand and contributed to a lower $\dot{V}O_{2\text{highest}}$ values during the ascents than the $\dot{V}O_{2\text{max}}$ tests [32, 42]. These healthy subjects were allowed to hold the handles for support and the engaged muscles were somewhat different in stair-ascending compared to running on a treadmill.

4.3. Muscular Endurance and Activity Analysis, and Interpretation Using MAIS

EMG activations of all four muscles represented how the leg muscle activity influenced the stair-ascending performance at maximum and constant intensity. High

velocity muscular efforts were required to maintain the intense step rate (SR) that were also reflected by the initial high and progressive AMP values. The development of $\dot{V}O_2$ appears to be associated with the gradual recruitment and rate coding of motor units of fast-twitch type II. However, type IIX motor units, although have the largest number of fibers, which are also metabolically fatigable, and thus less efficient for prolonged exertion. The significant increase in EMG AMP 10th percentile values (Tables 3, 4) were found for all four major leg muscles including two thigh (VL and RF); calf (GL) and TA of the anterior leg measured in this study, while the MDFs were significant decreased mainly the antagonists muscles, vastus lateralis (VL) and tibialis anterior (TA). The different fatigue patterns were observed between the mono- (VL) and bi-articular, rectus femoris (RF) muscles in EMG recording, which was similar to the study by Ebenbichler et al. [20] (Fig. 4). The initial AMP increase within 1 min indicated the recruitment of fast-twitch fibers characterized by high force production but low endurance, and that the fatigued motor units had been replaced spontaneously to maintain the high intensity ascending [8]. The subjects tried to minimize the use of the calf, gastrocnemius lateralis (GL) and other thigh muscles in this experiment during exhaustion by off-loading their body weight through their forearms while holding on to the handles of the stair machine. The decreased MDF results of this study were similar to the progressive decrease of MDF results that were found during a fast ramp cycling exercise [52].

The MARC points at the 90–100% periods of all four measured muscles appeared in or at least close to the *muscle fatigue* squares in the MAIS. This supports the muscle activity assumptions [15]. The MARC points were distributed between the *muscle force increase* and *muscle fatigue* squares. Some MARC points of the VL, RF and GL muscles during the 60–80% period were not found in the *muscle fatigue* square but appeared in the *muscle force increase* square, showing the evidence of decreasing MDFs (Fig. 5). This suggests that the subjects were maintaining the highest possible force productions to comply with the machine-controlled high SR before reaching fatigue. This interpretation advocates that the MARC points in the MAIS may be used for observing muscle activity changes over time.

4.4. Other Stair-Ascending Performance Constraints

The achieved physiological results of ascents showed the extreme nature of the tasks. The subjects' blood lactate (BLa^-), respiratory exchange ratio (RER), breathing frequency (BF), and rating of perceived exertion (RPE) values suggest that they were super-exhausted. The average post stair-ascending BLa^- level increase was similar to the post- $\dot{V}O_{2max}$ test, both were 14 mmol l^{-1} . The BLa^- range obtained in this study is also comparable to Goodwin et al.'s reported value ($15\text{--}25 \text{ mmol l}^{-1}$) during 3-8 min long "all-out" maximal exercise intensity [22]. The high repetitive SR increased the energy demand and provoked the high BLa^- productions, leading to the progressive increase of $\dot{V}O_2$, eventually termination of the ascents just immediately after reaching the relative stable state [50, 51, 55]. The subjects' mean RER calculated 1.2 at the end and their mean RPE calculated

on average 18.2 out of 20 in Borg's scale, which is maximal exertion. These high values were higher for the post-ascending test (Tables 1, 2) provide the evidence of hyperventilation [54], when BF reached 51 min^{-1} . These above results suggest that this constant SR was above the lactate threshold at which the subjects reached their limits [38]. As the SR rate was above the lactate threshold, the attainment of a steady state was reached slowly before quitting the ascents. Thus, those high BLa^- , RER and RPE values also met the required level of the secondary but disputable [42, 43] $\dot{V}\text{O}_{2\text{max}}$ criteria, which also indicates the subjects reached the fatigue threshold [7, 28].

Most of the subjects also reported “*burning and painful legs*”, in the thighs and/or calves. The very-fast SR induced local muscle fatigue (LMF) of the legs in advance of the anticipated maximum capacity leading to the discontinuation of the ascents and restricted the $\dot{V}\text{O}_{2\text{highest}}$ to reach $\dot{V}\text{O}_{2\text{max}}$ [11]. Additionally, the recorded mean minute ventilation ($\dot{V}E$) value at the end of ascents was also lower than the $\dot{V}\text{O}_{2\text{max}}$ tests mean value indicating an intensive ascending activity. These results suggest that the developed anaerobiosis in the leg muscles constrained the subjects' ascending performance as well as the $\dot{V}\text{O}_2$ capacity. The unprecedented stop of the ascents by the subjects was due to lack of energy supply to the working muscles because of the impaired oxygen supply or metabolism in response to the excessive demand to maintain the high SRs. The results revealed that physical exhaustion takes place very quickly, thus impaired evacuation performance, if the speed is at the maximum level and constant speed. This should be considered when deciding the SR in case of long ascending evacuation on the stairs. In order to simulate a more relevant and practical evacuation situation for determining the stair ascending endurance, a laboratory study is recommended allowing subjects to control their own speeds after starting the ascents at their maximum levels. Further experiments are required too to ascertain the recovery periods after the unprecedented stops due to exhaustion at different strategies or speeds in order to prolong the onset of fatigue or continue ascending at different heights for evacuation.

5. Conclusions

The average ascending duration was 3.5 min and the vertical height reached was 85.5 m with an ascending speed 0.66 m s^{-1} , when the subjects performed a simulated stair ascent evacuation at the constant step rate (SR) of $122.2 \text{ steps min}^{-1}$. These indicate the maximal ascending endurance and threshold in terms of duration and vertical height, when the subjects need to stop after ascending at their maximum speed. The recorded average highest oxygen uptake ($\dot{V}\text{O}_{2\text{highest}}$) during ascending was $44.8 \text{ mL min}^{-1} \text{ kg}^{-1}$ while the highest HR peaked at 174 b min^{-1} , which were lower than the subjects' $\dot{V}\text{O}_{2\text{max}}$ and HR_{max} . However, the $\dot{V}\text{O}_2$ reached a relative stable state just before termination of the ascents in this high workload when it reached only 92.3% of the subjects' $\dot{V}\text{O}_{2\text{max}}$ and 90.8% HR_{max} . The high repetitive and intensive activity resulted in a high lactate production

14.4 mmol l⁻¹ at the end of stair ascents, which was supported by the *maximal exertion* on the Borg' scale rated by the subjects at termination.

Moreover, electromyography results evidenced the local muscle fatigue (LMF) of the major leg muscles, especially thigh and anterior lower leg at the end of the ascents. In addition, the muscle activity interpretation square (MAIS) was found useful for observing the status of muscle activity rate changes (MARC) per unit time through the MARC points for the total ascending period. This result recommends using the MAIS to perform analyses of EMG data from dynamic tasks. These cumulative results infer that the subjects $\dot{V}O_{2\max}$ level was unattainable when the onset leg LMF contributed to advancing the exhaustion due to a very high SR against gravity. These results imply that in real evacuation situations, the cardiorespiratory and musculoskeletal systems are exposed to a very high physical workload. This high SR allows a little opportunity to take micropauses for recovery when ascending performs at maximal speed resulting an unexpected stop. These results of mean ascending duration, speed or step rate, vertical height and displacement results at individual maximum speed are recommended to be considered and incorporated into a new or existed evacuation models for engineering calculations. These data integrated into new models may reduce the uncertainty of calculations and estimations when planning and designing of buildings and deep underground infrastructures in terms of deciding number of entries or exit levels, resting planes, distance, capacities and characteristics of stairways. Thus, this might improve the assessment of life safety performance, estimate the adequacy of safety measures, success of evacuations and rescue operations of such buildings and subways in case of an emergency.

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Authors' contribution

AH, KK, CG jointly conceived, designed the research, led the research team and conducted experiments. AH, KK, MM, AN, CG analyzed the data. AH and AN contributed analytical tools. AH mainly wrote the manuscript while CG, MM, and KK helped. All authors read and contributed to improving and drafting the manuscript. They all reviewed and approved the final version.

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Compliance with Ethical Standards

Conflict of interest The authors declare that there is no conflict of interest.

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