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Estimation of vertical displacement during ascending evacuation

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Abstract: This paper describes an ascending evacuation model based on physical work capacity, when exhaustion may play a key role during evacuation. The experiment was carried out on a stair machine (Stair Master, SM5, USA) which involved 13 male and 12 female subjects. Individual climbing speeds at 50% and 70% of their maximal aerobic capacity (% VO_{2max}) level (L1 and L2) were selected for 3 minutes, and 90%, the last level (L3) was up to 5 minutes or until exhaustion for the model development on the first 19 subjects. The model was then validated on the last 6 subjects with intended exercise levels at their 60%, 75% and 90% of their maximal aerobic capacity corresponding up to 120, 15 and 5 minutes of continuous work, respectively. The maximum vertical displacement (h_{vert} in m/min) can be calculated according to: $h_{vert} = -21.7727 + 0.4024 * VO_{2max} + 0.2658 * \% VO_{2max}$.

Keywords: Physical work capacity; Oxygen consumption; Heart rate; Fatigue; Evacuation speed; Stairs

1 Introduction

The physiological fatigue may considerably affect the evacuation performance and outcome during ascending long stairs [1]. Ascending velocity and the reduction of speeds are related to the distance to be covered [2, 3]. Stair climbing and step tests have been used as a method for physical assessments and evaluations of cardiovascular ability in sports and medical fields for long time [4-8]. However, the studies on ascending evacuation in relation to physical work ability are not readily available [3]. Nevertheless, some interesting attempts have been made in the recent years [9]. It has been shown that ascent on stairs requires about twice the effort than descending the same stairs [7].

Oxygen consumption capacity is not the only limiting physiological factor. Repetitive movements and continuous force production are required for both central and peripheral muscles in the demanding task during ascending many stairs, especially in an emergency situation [10]. Previous research has shown that people manage to keep up an activity for up to 5 minutes if it is carried out at about 90% of their maximal oxygen consumption (VO_{2max}) level (90% for a trained person lays in average around 600 W/m². Moreover, a work at about 475 W/m² ($\approx 70\%$ of VO_{2max}) can be contained for about 15-20 min [11]. These findings had an agreement to an earlier summary by Louhevaara et al. (1986) [12]. At the onset of the exercise, anaerobic energy yielding processes

dominate until oxygen transport to the working muscle tissues develops [13]. Anaerobic processes cause build-up of lactic acid in working muscles that needs to be taken care of oxygenation processes. The critical time of lactic acid development for performance is 2 minutes after the onset of an exercise [8]. Thus, evacuation that takes 2-3 minutes or more may be affected by either cardiorespiratory capacity or lactate tolerance or both. Reaching any of these limits does reduce ascending speed, and thus, evacuation flow. Also, a highly repetitive activity may cause local fatigue in the muscles due to development of lactate as the blood flow, and thus, oxygen supply to the working muscles at that pace is not sufficient [14-15] in spite of that one may have reached optimum oxygen consumption from whole body perspective.

The objective of the laboratory tests was to examine if the physical work of real stair climbing could be simulated on a stair machine, and thus, be utilized in the future for data collection on variety of populations at lower costs, but also on specific populations, e.g. people with disabilities, elderly etc., in a controlled and safer environment than real tall buildings. The method was then expected to function for testing buildings "higher" than available. Also, it was expected that by observing the relationship "evacuation of the group-evacuation of an individual-laboratory simulation of individual evacuation" it might be possible to estimate group evacuation from the laboratory tests. Based on field tests, the labo-

ratory exercise was designed for developing a mathematical model of ascending evacuation based on human physical capacity.

2 Methods

2.1 Study design

Three levels of physical load were selected in order to develop the model of work capacity associate with ascending velocity. These exertion levels were to represent the time limited activity levels as defined by Holmér and Gavhed [11] and redrawn by Bohgard et al. [16], and cover most of the possible emergency evacuation scenarios;

- 50 % of individual VO_{2max} -heavy work that can be continuously maintained up to 2 hours;
- 70 % of individual VO_{2max} -very heavy work that can be continuously maintained up to 15 minutes;
- 90 % of individual VO_{2max} - near maximal work that can be continuously maintained up to 5 minutes.

In order to define the individual work load at defined

VO_{2max} level, all the recruited subjects had to take part the maximal capacity (VO_{2max}) test. The VO_{2max} test was performed by running with progressive resistance with increasing speed up to a manageable level and followed by increasing inclination on treadmill until exhaustion [17-18]. Before the maximal aerobic capacity test, thorough information on the study was given and written consent was acquired.

2.2 Subjects

Table 1 summarizes the subjects' age, height, weight, maximal oxygen consumption (VO_{2max}) and maximal heart rate (HR_{max}) for females and males separately, for development and validation groups, and altogether. The first 19 subjects were used for model development and the rest (6) for validation. The female and male data was pooled for analysis and model development. The age and VO_{2max} of the development and validation groups did differ significantly (t-test, $p < 0.01$), but not the other parameters.

Table 1 Subject characteristics: mean (SD). VO_{2max} :-maximal oxygen consumption; HR_{max} :-maximal heart rate

	No	Age(years)	Height (m)	Weight (kg)	VO_{2max} (ml/kg/min)	HR_{max} (b/min)
Female	12	33.8(13.4)	1.69 (0.06)	65.8(6.9)	47.2(9.7)	186 (13)
Male	13	36.6 (11.6)	1.75 (0.07)	82.3 (20.8)	47.0(8.6)	195 (12)
Development	19	33.1 (10.7)	1.73 (0.07)	74.7 (19.4)	48.8(8.7)	191 (13)
Validation	6	42.2 (15.5)	1.70 (0.07)	73.6 (11.2)	41.7(8.1)	192 (15)
All	25	35.3 (12.3)	1.72 (0.07)	74.4 (17.6)	47.1(9.0)	191 (13)

The study involved the following moments: arrival of the subject, instrumenting the subject and climbing on the stair machine. The tasks on stair machine were to climb the stairs at selected pace in three levels (L1, L2 and L3) (Fig. 1). Any changes of the velocity were not possible during the exercise on each level. Nevertheless, since all subjects of this study did not climb the stairs with the same step rate (SR), then their relative effort was set individually at approximately the same and known level.



Fig. 1 A fully instrumented subject who performed the tests on the StairMaster.

The last task estimated at 90 % VO_{2max} SR level (L3) which was carried out up to 5 minutes or until exhaustion. Such setup allowed studying the effect of pace on oxygen consumption but also the effect of body size and fitness. Step rates for each climbing level were calculated from VO_{2max} and the intended percentage of maximal effort individually.

2.3 Equipment

The stair machine (SM5, StairMaster, USA) allows adjusting the physical load to 20 levels with SRs ranging from 24 to 162 steps per minute (step height 20.5 cm and depth 25.0 cm). Each level differed from the previous and the next by 7-8 steps/min. For model development the closest estimated SR to the individual VO_{2max} percentage was chosen. However, as during the development phase some subjects did not manage to complete the expected time (5 minutes) with the individual highest load then during the validation phase the lowest closest SR corresponding to the estimation was selected.

After arrival the subjects began preparation by wearing a heart rate belt and monitor (RS400, Polar Electro, Finland). The subjects were also equipped with an EMG equipment (ME6000, Megawin, Finland) and maximum voluntary contraction exercise was carried out before proceeding to the stair machine. Oxygen consumption was measured with the same equipment as in the field (Metamax II, Cortex Medical GmbH, Germany). EMG results are reported elsewhere [19].

2.4 Model development

During the development phase, the percentage work capacity data at first two lower workloads at 50 and 70 % of each individual's VO_{2max} related calculated speed levels (L1 and L2) reached around 60 and 75 %, respectively. Therefore, SR levels work capacity data for both the development and validation phases were averaged together, and all three (L1, L2 and L3) levels were defined as 60, 75 and 90 % of VO_{2max} , respectively (Table 2).

Table 2 The study conditions and related performance mean (SD) during exercise in all three levels on stair machine for all subjects (N = 25)

Parameters	L1 (60% VO_{2max})	L2 (75 % VO_{2max})	L3 (90 % VO_{2max})
Corresponding SM5 level	7 (2)	10 (2)	13 (2)
Climbing duration (s)	180	180	Maximally 300
Climbing managed (s)	180.0 (0.0)	180.0 (0.0)	259.2 (68.7)
Step rate (SR) steps/min	66.1 (16.3)	88.3 (17.0)	109.4 (17.9)
Averagespeed _{max} (m/s)	0.36 (0.09)	0.48 (0.09)	0.59 (0.10)
h_{vert} (m/min)	13.2 (3.3)	17.7 (3.4)	21.9 (3.6)
Height _{reached} (m)	39.7 (9.8)	53.0 (10.2)	95.0 (30.8)

N.B.: Stair climbing performance were evaluated by average climbing duration managed in seconds (s); step rate (SR) per min (steps/min); average maximum speed (Speed_{max}) in (m/s); vertical displacement (h_{vert}) in meter per min (m/min); calculated vertical height reached (Height_{reached}) in meter (m) for each levels in Table 2 and 4.

For the model development and validation, a multi-variable linear regression was utilised in XLSTAT (Version 2014.1.01, Addinsoft). As the work load does not only depend on the SR but also on step height, then the data analysis was run for vertical displacement, as well. The prediction was expected to be usable together with population fitness data [20-22]. All details on model development together with limitations of the model, and suggested the literature and databases that allow for practical use are published in a paper by Kuklane and Halder (2016) [23].

3 Results and discussion

3.1 Maximum aerobic capacity tests (VO_{2max})

Subjects maximum aerobic capacity were determined by the maximum values for heart rate (HR_{max}) in beats per minute (b/min), maximum oxygen consumption (VO_{2max}) in millilitre/kg/minute (ml/kg/min) recorded during the test. The relative average maximum VO_2 values during the maximum test were not varied so much between male and female. However, the HR_{max} was higher for the male than female during the VO_{2max} test (Table 3).

Table 3 Shows the maximum capacity test results mean (SD) for all (N = 25) subjects and comparison between male and female before the test on stair machine

VO_{2max} (l/min)	VO_{2max} (ml/kg/min)	HR _{max} (b/min)
3.43 (0.72)	47.1 (9.0)	190.9 (13.2)
Parameters	Male (N = 13)	Female (N = 12)
VO_{2max} (l/min)	3.77 (0.69)	3.08 (0.60)
VO_{2max} (ml/kg/min)	47.0 (8.6)	47.2 (9.7)
HR _{max} (b/min)	195.4 (12.4)	186.1 (12.9)

3.2 Stair climbing tests

The physical work load values including maximum HR, average relative maximum VO_2 obtained at L3 reached about 90-95% of the VO_{2max} test (Table 4). This study results also showed that the average ascending duration was about 4.32 min. The participants have managed to climb an average 95 m vertically in these calculated close to individual maximum ascending speeds. The two third of the participants (N = 17) out of 25 who have managed to sustain ascending for this stipulated 5-min duration and they termed it was extremely hard task. On the contrary, the rest 8 participants did quit before stipulated 5-min because of exhaustion, and their quitting times started from the 2nd min. The joint analysis of EMG and VO_2 results does discuss if discontinuation was

related to oxygen consumption capacity or local muscle fatigue. An excessive workload for the leg muscles might force the subjects to quit and did not allow the VO_2 to reach the equal values which were obtained during the

VO_{2max} test [19]. Preliminarily, it can be speculated that most discontinuations might have been related to insufficient energy supply through blood flow to local muscles for lifting the legs under highly repetitive activity.

Table 4 Stair climbing tests performance comparison between male (N = 13) and female (N = 12) and overall all subjects (N = 25) performance at level 3 (L3) or 90 % VO_{2max} related individual step rates (SR) are given below with mean (SD)

	Parameters	Male (N=13)	Female (N=12)
L1 (maximum 3 min at 60 % of VO_{2max})	Climbing managed (s)	180.00 (0.00)	180.00 (0.00)
	Speed _{max} (m/s)	0.36 (0.08)	0.36 (0.10)
	SR (steps/min)	65.9 (15.4)	66.3 (18.0)
	h _{vert} (m/min)	13.2 (3.1)	13.3 (3.6)
	Height _{reached} (m)	39.6 (9.2)	39.8 (10.8)
	% VO_{2max} reached *	62.2 (4.9)	62.8 (5.6)
	% HR _{max} reached #	71.5 (4.9)	77.3 (4.8)
L2 (maximum 3 min at 75 % of VO_{2max})	Climbing managed (s)	180.00 (0.00)	180.00 (0.00)
	Speed _{max} (m/s)	0.47 (0.08)	0.48 (0.1)
	SR (steps/min)	87.2 (15.7)	89.4 (19.0)
	h _{vert} (m/min)	17.5 (3.1)	17.9(3.8)
	Height _{reached} (m)	52.3 (9.4)	53.7 (11.4)
	% VO_{2max} reached *	77.6 (7.5)	79.7 (5.6)
	% HR _{max} reached #	83.9 (6.0)	89.9 (3.0)
L3 (maximum 5 min or until exhaustion at 90 % of VO_{2max})	Climbing managed (s)	235.38 (75.35)	285.00 (51.96)
	Speed _{max} (m/s)	0.59 (0.09)	0.59 (0.11)
	SR (steps/min)	108.9 (16.2)	109.8 (20.2)
	h _{vert} (m/min)	21.8 (3.2)	22.0 (4.0)
	Height _{reached} (m)	85.4 (30.1)	105.4 (29.1)
	% VO_{2max} reached *	92.5 (7.2)	94.8(4.6)
	% HR _{max} reached #	94.8 (4.6)	98.0 (2.0)
L3	Average climbing performance for all subjects (N = 25)		
	Climbing managed (s)	259.2 (68.7)	
	Speed _{max} (m/s)	0.59 (0.10)	
	SR(steps/min) and range	109.4 (17.9) and (68.0-133.0)	
	h _{vert} (m/min)	21.8 (3.6)	
	Height _{reached} (m)	95.0 (30.8)	
	% VO_{2max} reached *	93.6 (6.1)	
% HR _{max} reached #	96.9 (3.0)		

* % VO_{2max} reached :-percentage of VO_{2max} reached during ascending

% HR_{max} reached :-percentage of HR_{max} reached during ascending

As most of the subjects who quitted before 5 min were males, then it can be expected that relatively large mass could affect the performance. However, it seems not to be the case as their body masses were distributed between 65 and 128 kg and their VO_{2max} levels were between 32.8 and 57.3 ml/kg/min, i. e. there was a high variation even in selected SRs. Only their subjective complains at the end of the exercise were related to the difficulty to lift the legs or pain in legs/joints. Also, in many subjects it was observed and visible that they star-

ted to put extra effort into the arms while they were gripping the stair machine handlebars. This strategy does indicate an effort which was made by subjects to reduce the leg muscles load in order to continue climbing, thus reduce the intensity of local fatigue. Simultaneously, as more body parts will be working then the total oxygen uptake capacity, and not only blood supply to local muscles, would at certain stage increase in importance for performance. However, all the participants have managed to ‘survive’ the 3 min exercise duration in the two lower ascending

intensities at L1 and L2 compared to the L3.

3.3 Predictions for ascending evacuation

Based on available maximal capacity recordings of a few subjects who did participate in the field trials and assuming that the tested population would correspond with their maximal capacity to the measured student population [24] and utilizing multivariable linear regression (XLSTAT) a prediction model was developed. Based on that, the step rate was calculated from VO_{2max} and aimed percentage of VO_{2max} . According to Holmer and Gavhed (2007) and International Organization for Standardization (ISO 8996) [25] a person could manage about 5 minutes at one's 80-90 % of VO_{2max} , about 15 minutes at 70-80 % of VO_{2max} and up to 2 hours at 50-60 % of VO_{2max} . Thus the predictions were aimed towards 50%, 70% and 90% of each individual's VO_{2max} . The intended percentage of VO_{2max} during predictions or development phase (N=19) reached higher than the validation phase (N=6). However, as there was much less comparable information available on lower workloads, then the measured values in the laboratory were quite close at high workload but exceeded the prediction considerably at lower and medium workloads (Fig. 2).

Based on the first 19 laboratory experiment subjects, a new prediction model was developed and it was validated on the 6 last subjects. As the original prediction underestimated the lower workloads, then this time 60%, 75% and 90% of VO_{2max} was aimed in order to match previously collected data. Adopting the new prediction, no subject did quit, and the aimed percentages stayed within the standard deviation of the measured values. Heart rate values were still closer to the maximal than VO_2 values indicating that an additional strain could have been caused by other factors than physical workload only (Fig. 2 and Table 4).

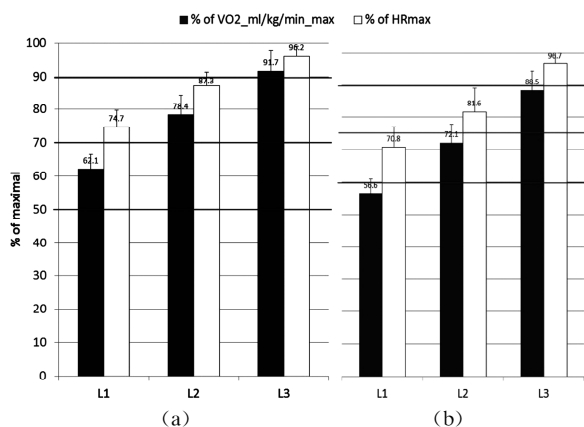


Fig. 2 Measured percentage of maximal values of (a) 19 subjects of the development phase and (b) 6 subjects of validation phase. Prediction was carried out for relative VO_{2max} values in ml/kg/min.

The percent of maximal heart rate (% of HR_{max}) are given for comparison. The thick horizontal lines mark the intended percentages

The prediction equation for the step rate (SR) in steps/min was:

$$\text{Step rate (SR)} = -108.8633 + 2.0121 * VO_{2max} + 1.3289 * \% VO_{2max} \quad (1)$$

The fitness adjusted R^2 was 0.915. Similar prediction based on heart rate led to a correlation with adjusted R^2 of 0.705.

Considering that the SR may not be the most useful for practical use due to the possible effect of step height etc. then also an equation for vertical displacement (h_{vert} , m/min) was suggested:

$$\text{Vertical displacement (} h_{vert} \text{)} = -21.7727 + 0.4024 * VO_{2max} + 0.2658 * \% VO_{2max} \quad (2)$$

4 Conclusions

A wide range of data bases with human physical capacity information and results from field experiments allowed to develop a physiological model of ascending evacuation. The model relates to maximal physical capacity of a healthy individual. The vertical displacement can be calculated as $h_{vert} = -21.7727 + 0.4024 * VO_{2max} + 0.2658 * \% VO_{2max}$ ($R^2 = 0.915$). The equation was validated on 6 subjects in the laboratory conditions. In order to allow a broad utilization of the prediction accurate fitness estimation of the target populations is needed. Also, validation in field with different stairwell configuration, carried load, age groups etc. would allow improvement of the model as a planning tool.

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