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A model to estimate vertical speed of ascending evacuation from maximal work capacity data

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ABSTRACT

This paper describes the development of an ascending evacuation model based on physical work capacity of a selected sample. The model is based on the combination of several field experiments, existing databases and pre-tests that were combined to define initial test conditions in the laboratory environment on a step machine. Maximal oxygen consumption (VO_2max) of 13 male and 12 female subjects (data was pooled), was measured, and they climbed at 3 step rates specified according to individual percentage of their maximal aerobic capacity (%VO_2max) levels. The first nineteen subjects were used for model development and the last six for validation. The paper gives an overview on the collected laboratory data and puts it into relation with the field data from both oxygen consumption and heart rate perspective. The maximum vertical displacement (h_{vert} in m/min) can be calculated according to: $h_{vert} = -21.7727 + 0.4024 * VO_2max + 0.2658 * \%VO_2max$. The discussion covers limitations and possibilities of the model and suggests the literature and databases that form the basis for practical use of the prediction model. Paper defines the needs for future work and possible information sources to improve the model.

1. Introduction

The question on the effect of physiological fatigue on the outcome of evacuation on ascending long stairs has been raised by Frantzich (1993) in relation to reduced velocity dependence on covered height (Delin and Norén, 2014; Norén et al., 2014). Although, stairclimbing and step tests have been used for sports and medical evaluations for long time (Bassett et al., 1997; Johnson et al., 1977; Margaria et al., 1966; Spurway, 1992; Teh and Aziz, 2002), the studies on ascending evacuation in relation to physical work ability are not readily available (Norén et al., 2014). Nevertheless, some interesting attempts have been made in the recent years (Lam et al., 2014). It has been shown that ascent on stairs requires about twice the effort than descending the same stairs (Teh and Aziz, 2002).

Also, the development of fatigue and changes in evacuation behaviour as their function during upwards climbing on the stairs has not been described. In comparison with earlier studies, today the population characteristics are strongly affected by physical inactivity, increasing overweight and aging (Commission of the European Communities, 2008). This has a negative impact on physical performance of the population during evacuation (Spearpoint and MacLennan, 2012).

When evacuating upwards in long stairs there is a reason to believe that physical exertion, human behaviour and mental experience can influence the prospects for a satisfactory evacuation. It is also likely that human behaviour in a long stair upwards differs from the behaviour in a short stair as the physical effort is increasing. There is a reason to believe that:

a. physical exertion is a descriptive parameter for the evacuation process (and it affects the walking speed, flow and the human behaviour when evacuating upwards);
b. the design of stairs affects the evacuation processes when evacuating upwards in long stairs.

Previous research has shown that people manage to keep up an activity for up to 5 min 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/m^2; Holmér and Gavhed, 2007). Work at about 475 W/m^2 (≈70% of VO_2max) can be contained for about 15–20 min (Holmér and Gavhed, 2007). Their research matches an earlier summary by Louhevaara et al. (1986). However, oxygen consumption capacity is not the only limiting physiological factor. At the onset of the exercise, anaerobic energy yielding processes dominate until oxygen transport to the working muscle

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tissues develops (Wilmore et al., 2008). 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 after 2 min after onset of exercise (Spurway, 1992). Thus, evacuation that takes 2–3 min 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 (Christensen et al., 1960; Sjøgaard et al., 1988) in spite of that one may have reached optimum oxygen consumption from whole body perspective.

The described work is part of a larger project (Ronchi et al., 2015) on the impact of physical exertion on ascending evacuation. In particular, human physiological capacity is investigated with the main aim to study the influence of oxygen consumption of an individual during ascending evacuation, and the relationship between maximal oxygen consumption and distance covered either in terms of vertical displacement, ascending speed or steps per minute. Muscle fatigue estimation methods based on EMG measurements (Disselhorst-Klug et al., 2009) for dynamic exercise are under development, and the EMG data is reported separately (Halder et al., 2016a,b).

2. Aims and objectives

2.1. The project

The primary objective of the project (Ronchi et al., 2015) was to increase the understanding on ascending emergency evacuation by a multidisciplinary approach through including and mapping the variables of physical work, exhaustion and behavioural changes in relation to the height of the stairs. The aim was to develop a new method to design the stairs for evacuation from underground facilities and buildings where people are expected to take long stair upwards for escape purposes, and:

- increase the understanding on emergency evacuation by studying and describing physical work and exhaustion effect on walking velocity and behaviour while ascending the stairs;
- develop a mathematical model that includes effects of physical work, that does consider the behavioural changes in relation to the height of stairs, thus, acting as a design tool for evacuation planning;
- develop a method that can be utilized in a laboratory environment to study physical load while ascending high-rise buildings.

2.2. Research questions

1. How will exhaustion and fatigue affect walking velocity?
2. How can the height of the stairs and physical work be described in the mathematical evacuation models?
3. Where do the physiological limits lay for the safe evacuation upwards in relation to the height of the building/construction?

2.3. The laboratory experiment

An objective of the laboratory tests was to examine if the physical work of real stair climbing could be simulated on a step 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 laboratory exercise was designed for developing a mathematical model of ascending evacuation based on human physical capacity.

3. Methods

The whole project, including the laboratory experiments was reviewed and approved by the Regional Ethical Review Board at the Lund University, Sweden (Dnr. 2014/54).

3.1. Background

In order to answer the objectives a laboratory experiment on a step machine (SM5, StairMaster, USA) simulating the evacuations at 3 physical exertion levels was designed. The basis of the experiment was grounded on the field studies within the project "Ascending evacuation in long stairways: Physical exhaustion, walking speed and behaviour" (Ronchi et al., 2015). In the project three (3) field series were carried out:

1. Evacuation exercise of 13 floors (Ideon Gateway, Lund, Sweden);
2. Evacuation exercise of 31 floors (Kista Science Tower, Stockholm, Sweden);
3. Evacuation exercise on 33 m deep subway escalator (Västra Skogen, Stockholm, Sweden);

where heart rates, walking speeds, oxygen consumption, etc. were recorded during ascending evacuation tasks (Arias et al., 2016; Delin et al., 2015; Halder et al., 2016a,b; Norén et al., 2015).

Oxygen consumption (VO_2) represents the oxygen amount that is used to burn energy to carry out a defined task, i.e. move a mass at a specific speed to a defined distance. In any case, either knowing the maximal heart rate (HRmax) or maximal oxygen consumption (VO_2max) would allow better prediction/correlation when instead of absolute values one would use percentage of individual maximum (relative heart rate or relative oxygen consumption).

Heart rate (HR) is relatively easy to measure and there are several available methods for maximal heart rate estimation (Robergs and Landwehr, 2002). However, the errors in maximal heart rate estimation are still high (Robergs and Landwehr, 2002), and estimated maximal heart rate used in work capacity estimations would lead even to higher errors due to individual variation. Maximal pulse may differ in a larger range than from 180 to 210 b/min, e.g. 1 standard deviation corresponds to about 15 b/min, and thus, at least as high variation in a recorded pulse under a specific exercise can be expected. Fitness parameters include beat volume, lung capacity, anaerobic capacity, etc., i.e. during near maximal exercise heart rate alone cannot be expected to explain all. The heart rate may also be affected by psychological or thermal impact (ISO 8996:2004; Kuklane et al., 2015).

Based on field tests and literature, e.g. Loe et al. (2013) the maximal heart rate is not correlated to fitness of a person. It was further confirmed by a relatively poor correlation of heart rates with performance under the field trials (Halder et al., 2016a). Thus, the model was decided to be based on the relative oxygen consumption in ml/kg/min as there the effect of body weight is considered, too. Anyway, the heart rates, as they do reflect the general stress levels, were reported in the results. Also, in the laboratory