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Limitations of oxygen uptake and leg muscle activity during ascending evacuation in stairways

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A B S T R A C T

Stair ascending performance is critical during evacuation from buildings and underground infrastructures. Healthy subjects performed self-paced ascent in three settings: 13 floor building, 31 floor building, 33 m stationary subway escalator. To investigate leg muscle and cardiorespiratory capacities and how they constrain performance, oxygen uptake (VO_2), heart rate (HR) and ascending speed were measured in all three; electromyography (EMG) in the first two. The VO_2 and HR ranged from 89 to 96% of the maximum capacity reported in the literature. The average highest VO_2 and HR ranged from 39 to 41 $mL \cdot kg^{-1} \cdot min^{-1}$ and 162 to 174 $b \cdot min^{-1}$, respectively. The subjects were able to sustain their initial preferred maximum pace for a short duration, while the average step rate was 92–95 $steps \cdot min^{-1}$. In average, VO_2 reached relatively stable values at ≈ 37 $mL \cdot kg^{-1} \cdot min^{-1}$. EMG amplitudes decreased significantly and frequencies were unchanged. Speed reductions indicate that climbing capacity declined in the process of fatigue development. In the two buildings, the reduction of muscle power allowed the subjects to extend their tolerance and complete ascents in the 48 m and 109 m high stairways in 2.9 and 7.8 min, respectively. Muscle activity interpretation squares were developed and proved advantageous to observe fatigue and recovery over time.

1. Introduction

There is a current trend to build modern, high-rise buildings and deeper underground infrastructures in order to utilise urban space maximally and to develop transportation networks to meet increasing demands. Stairs are the most important emergency access and means of evacuation from these structures during power failures, fires, subway attacks and other accidents (Lam et al., 2014). Generally, descending stairs is the main form of evacuation (Peacock et al., 2010). Ascending long, vertical stairways in cases of evacuation from lower levels, however, can become physically challenging for people during egress from such structures. Physical exertion and ascending strategies influence the prospects of a successful evacuation upwards in long staircases as the physical effort increases. This leads to exhaustion and can constrain performance during emergency situations (Delin et al., 2016). A continuous ascent may not be possible at the individual's maximum speed for a long duration. Cardiorespiratory capacity (CRC) is commonly believed to be the main indicator of human physical limits. Repetitive muscle activities on stairs can induce local muscle fatigue (LMF) that may interrupt evacuation capacities (Cheng and Rice, 2013) such as climbing speed, and group evacuation flow during ascending (Arias et al., 2016; Burghardt et al., 2013; Delin et al., 2016; Ronchi et al., 2015). CRC and LMF can constrain a person's ascent up to a certain height by affecting the evacuation speed and duration. The biomechanical aspects of this demanding task are reflected in surface electromyographic muscle activity, the measurement of which can be utilised as an important physiological parameter and indicator of neuromuscular fatigue to evaluate the performance (Hanon et al., 1998).

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Abbreviations

AD	Ascending duration
AS	Ascending speed ($m \cdot s^{-1}$)
AMP	Amplitude
ANOVA	Analysis of variance
CPET	Cardiopulmonary exercise testing
CRC	Cardiorespiratory capacity
EMG	Electromyography
GM	Gastrocnemius medialis
GL	Gastrocnemius lateralis
HR	Heart rate ($b \cdot min^{-1}$)
$HR_{mean\ stable}$	Average heart rate that had reached relatively stable state after the initial increase ($b \cdot min^{-1}$)
$HR_{highest}$	Maximum heart rate reached during test ($b \cdot min^{-1}$)
LMF	Local muscle fatigue
LT	Lactate threshold
M	Metabolic rate ($W \cdot m^{-2}$)
MAIS	Muscle activity interpretation squares
MARC	Muscle activity (amplitude and frequency) rate changes
MDF	Median frequency (Hz)
M_{mean}	Average metabolic rate ($W \cdot m^{-2}$)
$M_{mean\ stable}$	Average metabolic rate that had reached relatively stable state after the initial increase ($W \cdot m^{-2}$)
$M_{highest}$	Maximum metabolic rate reached during test ($W \cdot m^{-2}$)
RF	Rectus femoris
SE	Stationary escalator
SR	Step rate per minute ($steps \cdot min^{-1}$)
V_{disp}	Vertical displacement ($m \cdot min^{-1}$)
VL	Vastus lateralis
VM	Vastus medialis
VO_2	Oxygen uptake ($mL \cdot kg^{-1} \cdot min^{-1}$)
VO_{2max}	Maximal oxygen uptake
$VO_{2mean\ stable}$	Average oxygen uptakes that had reached relatively stable state after the initial increase
$VO_{2highest}$	Maximum oxygen uptake reached during test
VT	Ventilatory threshold
13F	Thirteen floors
31F	Thirty-one floors

Previous research suggests that the important role of physical exhaustion during longer evacuation performance should be further investigated (Pelechano and Malkawi, 2008; Ronchi and Nilsson, 2013). Human physiological challenges and capacities for both ascending and descending have been explained to some extent using various designs and protocols (Aziz and Teh, 2005; Halsey et al., 2012; Lam et al., 2014; Teh and Aziz, 2002). The first two of these studies measured the ascending energy expenditure on a regular stairway by measuring oxygen uptake (VO_2) and/or heart rate (HR) to describe the physical work capacity. Teh and Aziz (2002) estimated that the oxygen uptake in the last 30 sec (s) was 33.5 $mL \cdot kg^{-1} \cdot min^{-1}$, while the gross energy expenditure of ascending stairs in an 11 story building (180 steps) on average was 10.2 $kcaL \cdot min^{-1}$ (711 W). Lam et al. (2014) studied a few physiological parameters such as HR and blood pressure during a long stair ascent (40 floors). The majority of the previous studies have measured VO_2 on regular stairways involving relatively short climbing periods of approximately one or two min2 min. These durations may be insufficient to reach the cardiorespiratory steady state and anaerobic threshold that is necessary to interpret muscle fatigue.

Duffield et al. define Critical Power as the “maximum exercise intensity sustainable for an extended duration” (Duffield et al., 2007). VO_2 kinetics is proposed to be an important determinant of severe intensity exercise performed above the Critical Power (Burnley et al., 2011; Cannon et al., 2011). One study showed that changing the work rate in the severe-intensity domain increases the amount of work and exercise tolerance (Dekerle et al., 2015), which is closely related to the VO_2 slow component (Rossiter et al., 2001). Moreover, prior heavy-intensity exercise provokes the VO_2 kinetics (Burnley et al., 2011); in particular, high-intensity leg muscle work is associated with the VO_2 slow component (Poole et al., 1991; Zoladz et al., 1995). A study showed that the EMG mean power frequency increased significantly while the integrated EMG/VO_2 ratio remained constant over the duration of the VO_2 slow component (Sabapathy et al., 2005). Another study reported that low-intensity cycling showed no VO_2 slow component and MDF increase, but that intensive leg muscle exercise contributes to a rise in the VO_2 slow component and MDF (Saunders et al., 2000). During moderate-intensity work below the lactate threshold (LT), VO_2 continues to rise slowly (slow component) after 2–3 min and it stabilises. If the exercise is performed at a higher level or critical power above the LT, the task leads to $VO_{2highest}$ and termination (Barstow, 1994; Whipp and Wasserman, 1972). The VO_2 slow component shows the progressive loss of skeletal muscle work efficiency and the occurrence of fatigue (Cannon et al., 2011; Jones et al., 2007, 2011; Vanhatalo et al., 2011; Zoladz et al., 2008).

A simulated stair climbing EMG study showed that metabolic cost and muscular activity were higher during a double-step than a single-step strategy on an inclined treadmill (Gottschall et al., 2010). Another study reported that ascending activity was significantly higher than descending activity, whereas calf (GL and GM) muscle activities were higher than tibialis anterior muscle activity (Eteraf Oskouei et al., 2014). However, both of these studies may not reflect real-life stair climbing due to the set pace. Scheuermann et al. (2002) used both EMG and VO_2 measurements to observe physiological responses during cycling. A progressive decrease in the EMG median frequency (MDF) was found during fast ramp (64 $W \cdot min^{-1}$) cycling, while it remained relatively constant during slow ramp (8 $W \cdot min^{-1}$) cycling at the same pedaling cadence of 70 rotations per minute. The amplitude (AMP) increases were related to the work rate increase during exercise below the LT (Scheuermann et al., 2002). Moreover, the fatigue index (FI) was used to define the level of muscle fatigue at the beginning and end of the work (Oksa et al., 2002). The FI uses a ratio of muscle force (maximum voluntary contractions, MVC) over AMP.

The study presented in this paper observed both AMP and MDF changes over time. It did so in order to evaluate the development of leg muscle fatigue during ascending evacuation on stairways based on muscle activity rate changes (MARC) in muscle activity interpretations squares (MAIS). Although muscle fatigue has been investigated during cycling exercises (Saunders et al., 2000; Scheuermann et al., 2002), we have not found studies that directly focus on muscle fatigue during stair ascending. Therefore, the primary research question of this study is: What are the CRC (VO_2 and HR) and the leg LMF levels that limit stair ascent capacity at the subjects' self-preferred pace? The hypothesis was that LMF rather than CRC constrains the ascending capacity. In order to test