The effect of fatigue during deep metro evacuations and its implications on evacuation modelling tools

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Disclaimer

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Abstract

The thesis purpose is to determine how people's evacuation performance is affected by carrying weight while performing a stair-climbing motion. The fire safety engineering and physiology fields are merged to increase the knowledge regarding ascending evacuation. A laboratory experiment was conducted, in which participants performed three different sessions; during the first session, participants performed a sub-maximal test that would support the calculations for the prediction of the ideal step-rate estimating their VO_{2max} by measuring their heart rate during a cardiovascular activity maintained approximately for 6 minutes; during sessions 2 and 3, participants performed a 5-minutes stair-climbing exercise, they did so under two modalities: 1) by not carrying an 8 kg backpack during one session, and 2) by carrying the 8 kg backpack during the remaining session. Measurements for oxygen uptake (VO_2), heart rate (HR), and perceived exertion using the RPE Borg's scale, where obtained during the stair-climbing experiment, and calculations for the energy expenditure (M) were then compared. A simple evacuation modelling case using the Mass-Motion software (MM) was conducted to obtain evacuation times; the model was configured in different manners, using 1) default parameters 2) walking speed distributions from available field experiments and 3) data from the current laboratory results. Using the findings during the laboratory experiment and considering people's physiological aspects that can limit a stair-ascent motion during an evacuation, an additional scenario is described; this scenario includes a stair divided in 4 sections and separated by 3 resting planes, according with the average reduction-time requests by the participants during the "backpack" session.

Key words: stair-ascent evacuation, stair evacuation modelling, stairs, physiology, fire safety engineering

Resumen

El objetivo de esta tesis radica en determinar como el desempeño de una persona, se puede ver afectado por cargar peso adicional al de su propio cuerpo, mientras suben gradas. El campo de ingeniería en seguridad contra incendios y fisiología, se han unido para aumentar el conocimiento sobre evacuaciones ascendentes. Se realizo un experimento en laboratorio, para el cual los participantes atendieron tres diferentes veces; durante la primera sesión, los participantes fueron sujetos a un examen sub-máximo para respaldar los cálculos que determinar la velocidad de la máquina de escalera, esto fue hecho calculando el consumo máximo de oxígeno a partir de las mediciones de su ritmo cardiaco al realizar una actividad cardiovascular por aproximadamente 6 minutos; durante la segunda y tercera sesión, los participantes subieron gradas en la máquina de escalera, esto fue realizado en dos modalidades diferentes: 1) no cargando peso adicional de 8 kg, y 2) cargando 8 kg como peso adicional en una mochila. Las mediciones tomadas durante el experimento para medir el nivel de fatigue incluyeron: Consumo de oxigeno (VO_2), ritmo cardiaco (HR), y la percepción del esfuerzo usando la escala RPE de Borg, adicional, el gasto de energía (M) fue calculado a partir de los resultados. Los resultados obtenidos, en términos de la distribución de velocidad al caminar, fueron aplicados a un simple caso de prueba usando el programa de simulación mass motion (MM). Con esta aplicación, se obtuvieron tiempos de evacuación que luego fueron comparados con los parámetros predeterminados del programa, y con los resultados obtenidos a través de un experimento de campo. Finalmente, una propuesta de escenario es planteada, incluyendo hallazgos durante el experimento de laboratorio, y que pretende incluir limitantes fisiológicas que puede limitar la capacidad de los usuarios de metros para sostener un movimiento ascendente en gradas durante una evacuación; este escenario está basado en el experimento con la mochila de 8 kg, y considera los tiempos promedio en los cuales los participantes solicitaron una reducción en la velocidad de ascenso.

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1. Introduction

After the inauguration of the world's first underground railway system at London in 1863, other cities started to build this type of transport facilities. Nowadays, 157 cities around the world have a metro system in operation with nearly two thirds of these networks located in Asia and Europe (UITP, 2014). As part of the planning and construction of metro stations several factors must be considered, such as the number of expected users, the increasing population of a city, and the availability of space in the surroundings. The latter is especially important when planning expansions of the metro systems, as the limitation of space represents a challenge to the designers' usual strategies of evacuation and fire safety.

To achieve a holistic design, including factors as comfort and functionality for the metro users as well as safety, it is highly significant to discuss emergency evacuations. Even when the main goal remains the same disregarding the type of facility, it is important to discuss that conditions inside a metro station will vary significantly from the ones usually mentioned in literature, mostly related to descending stair evacuation in buildings; for instance, studies have been conducted intended to collect data for a better understanding of people movements during buildings evacuation, and therefore use this data to improve the predictive capability of the evacuation models (Fahy and Proulx, 1997; Kuligowski et al., 2014; Peacock et al., 2012). When discussing evacuation of a metro station, long ascending distances while using stairs or escalators must be addressed as they can affect the performance of the users while they move towards an exit.

Disregarding the high usage of metro stations around the world, few studies can be found concerning the implications of fatigue during ascending evacuation, even when it is known that an ascending motion represents a challenge for people (Lin et al., 2005). A study led by Lund University has shown that a continuous ascent can only last in between 2 to 6 minutes at 90% of the maximum capacity of the subjects (Halder, 2017) pointing out the need of continuing the research in this field to analyze if other factors (e.g. exertion and load-carrying.) need to be included into the evacuation modelling tools scope specifically for deep-metro evacuations; These engineering tools support the design process of fire safety systems, by including human behavior aspects that brings the simulations to a more realistic and therefore, more accurate representation of reality.

On a daily basis, it is usual to observe metro-user with luggage as the metro serves to connect airports and train stations; It is not uncommon to observe parents carrying their children on their arms or inside the so-called ”piggyback riders” position; there is also an increase of the metro station accessibility for impaired persons, which in some cases means that metro users can also need wheelchairs to mobilize underground. These three scenarios show that the effects of carrying weight while performing a stair-ascent evacuation, must not be disregarded as metro users are usually exposed to such kind of situations. By including the impact of carrying weight as an additional variable, the fire safety design process can widely benefit the tool's results by improving the reproduction of a real-life decision-making process.

Based on the statements above, this thesis focuses on challenges in deep metro stations evacuations, while reviewing existing literature involving complementary fields to fire safety such as physiology. In parallel, a laboratory experiment is conducted to estimate up to which extent people's performance is affected by carrying weight during a stair-ascent motion. As an example of evacuation modelling tool, mass motion software (Oasys, 2017) is used to develop a simple hypothetical case, showing the differences in results while applying different parameters, aiming to highlight the importance of keep improving this kind of software to enhance the capabilities to model stair-ascent evacuations.

1.1 Aims and objectives

The main objective of the thesis is to determine how the performance of people during a stair-ascent evacuation is affected by carrying additional weight. To achieve this, gathering relevant data during the experimental phase is of high importance. With the laboratory results, is intended to prove the negative impact that carrying additional load has over the subject's performance during a stair-ascent motion. Therefore, exertion is analyzed by studying heart rate and oxygen consumption by following the cardiovascular/anaerobic model, which links the performance of muscles to the available oxygen transported by the blood current (Noakes, 2000). The perceived exertion is also analyzed by using the Borg's RPE scale, serving as a link between physical effort and the subject's subjective perception of exertion (Borg, 1998).

Additionally, the thesis focuses on a theoretical baseline to remark the importance of considering fatigue-related behavioral and performance aspects when using evacuation modelling tools, aiming to support fire safety designers in real projects, by considering people's limitations due to exertion when carrying weight and the negative consequences that this implies in terms of evacuation. The research questions answered through the development of this thesis are:

A. Literature background
   - What challenges can be expected while performing an underground metro system evacuation?
   - How does fatigue affect the ability of people carrying weight to perform ascending stair evacuation?
   - Which variables can be used to physically measure fatigue and the perception of fatigue?

B. Laboratory experiment
   - To which extent people's performance during ascending evacuation can be affected by carrying weight? (e.g. backpacks)
   - How does carrying weight affects the time threshold before reaching physical exhaustion?
   - Which is the maximum vertical distance that people can handle before reaching physical exhaustion?
   - Which is the maximum vertical distance that people should walk and find a rest area to avoid reaching physical exhaustion while carrying weight?
   - How does the perceived exertion and acceptable exertion correlates to have acceptable levels when designing evacuations routes in deep metro stations?

C. Implications for evacuation modelling tools (mass motion example)
   - How can the effects of fatigue (including carrying weight) be included in the modelling tool when applied to a simple case study?
   - How is evacuation time affected when changing escape route configurations?

1.2 Limitations

Although the research was thoroughly prepared, there are still limitations to be considered. These limitations are different for the three main parts of the document: 1) Literature review, experimental phase, and evacuation modelling. Besides the individual limitation for the aforementioned parts, the research undergoes the influence of general limitations. To have more realistic results, a full-scale experiment in a metro station is ideal, however due to time constraints, a laboratory set-up was designed for this purpose; Time constraint affects the data-gathering process and the number of subjects recruited for the study, as it requires special attention to schedule the experimental session with each test participant, and to set a short-time period where experiments can be conducted.

For the literature review, the main limitation is the availability of studies with a stair-ascent focus. After the terrorist attack to the World Trade Center in 2001, there was an increase of the literature involving data concerning stair-descent evacuation, mainly from high rise buildings evacuations. Information can be found regarding the physiological aspects of stair-ascending motion; however a lower quantity of material is found involving the effects of carrying load while performing such activity in terms of evacuations.

Regarding the laboratory experiments, even though the attempt is to recreate real life conditions as much as possible, the results carry limitations in terms of ecological validity; these limitations rely on the sample's features, the laboratory set-up, and the characteristics of the stairs. It must be considered that the sample was taken from a healthy and young student population in their 20's, whom were asked to modify certain habits before the test (e.g. drinking coffee and doing extenuating exercises), it was also recommended to wear comfortable clothing and sport shoes during the sessions; this is not an accurate representation of the real conditions people may experience while evacuating a metro station during an emergency. The difference between the laboratory set-up and a metro station is also a limitation for the accuracy of the obtained results (Underwood, 2009); the dimensions of the Västra Skogen metro station in Stockholm, which is used as a guide for some of the evacuation simulations, differ from the ones found in the stair machine used in the laboratory experiments, this results in differences on people's performance while ascending the stairs. The experimental conditions, which include individual performances, also limited the applicability of the results, as no group-behaviour is considered. Limitations also appear due to the utilization of a stair machine; even when this machine offers several step-rates, the ascending-speed is controlled by it and not by the participant, consequently, the subjects are not free to reduce or increase their speed to match their preferred speed, making impossible to match this movement with a more natural and realistic one.

In terms of fire-safety designs with evacuation modelling tools, the limitations involve the availability of data regarding human behavior during evacuation of metro stations. Most of the available studies have collected data about movement of people under non-emergency scenarios while using stairs, mainly for stair-descent motions or horizontal displacements (Fahy and Proulx, 1997; Peacock et al., 2012; Pelechano and Malkawi, 2008; Proulx and Fahy, 1997; Ronchi and Nilsson, 2014) however, it is of high importance to have engineering tools that can estimate the behavior of people during emergency evacuation; for this reason, mass motion (MM) is used as an example of an evacuation modelling tool in this document, applying a hypothetical case which is limited the laboratory experiment criteria (e.g. individual results, stair configuration, sample features).

1.3 Literature review

As humans gain access to new technologies, they also increase their dependence on them. This tendency represents a change in their daily habits. Before, humans were required to have a good physical condition to survive, they were either hunting or working in fields which demanded certain level of fitness to perform the tasks. Nowadays, considering the introduction of machines and several advances in technology, humans are not obliged to depend on physical activity to survive; spears and arrows have been replaced by computers, which prompts sedentarism and reduces fitness condition. This situation can affect their performance in daily-life situations that requires any demand to their muscles.

1.3.1 Fatigue, perceived exertion and exhaustion

Over the years, the concept of fatigue has been discussed without a complete understanding of its meaning or physical implications; many authors have proposed a definition of it, but it's usual to find criticism around the literature. For instance, fatigue can be referred as a high level of tiredness that affects the performance of people while they are engaged in a physical activity (Borg, 1998) however, this is mostly related to muscle fatigue, which is associated with the inability to maintain certain required or expected force (Porter, 1981). Considering this, two terms are introduced: muscle fatigue and exhaustion.

Muscle fatigue decreases performances in activities requiring muscular force, most people experience an increasing difficulty in maintaining a certain activity level. If the level is higher than what has been define as the 'habitual level', the difficulty grows rapidly (Astrand et al., 1986) causing the individual to reach levels of exhaustion. In most of the studies, fatigue is considered only as a physical consequence of exertion without considering the effects that human psychology can have over the performance of an energy-demanding activity, such as the stair ascent. To cover this knowledge gap, the concept of perceived exertion is also introduced and investigated by Gunnar Borg since the mid '50s. In his work, he states that experiences such as effort, breathlessness, and muscle ache can help to shape the concept. He also mentions that in low intensity efforts, the perceived exertion can cause a positive influence on the individual, however this is not the case for high-intensity or energy-demanding exercises (Borg, 1998), indicating the need of considering perception when studying performances.

Borg defines the perceived exertion as being closely related to exercise intensity but at the same time, linked to motivational, emotional and pathological conditions leading to the following definition: "perceived exertion is the feeling of how heavy and strenuous a task is". To provide a tool that could lead to a better understanding of the link between physical effort and the subjective estimation caused by it, the RPE scale was developed. The scale is shown in Figure 1-1.

The Borg RPE scale uses verbal anchors allowing to determine the level of perceived exertion. This scale also permits an easy comparison with physiological measurements as it was designed with a linear increase with the heart rate (HR), and oxygen consumption (VO_2) while cycling. The number 6 was taken as a starting point as it gives an easy relation between the lowest HR of a resting adult (60 bpm). Number 20 is taken an "absolute maximum" which is hypothetical constructed; most people have only experienced a level of 19 during any exercise. (Borg, 1998).

6	No exertion at all
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (heavy)
16	
17	Very hard
18	
19	Extremely hard
20	Maximum exertion

Figure 1-1: RPE Borg's scale (Borg, 1998)

Several models have been developed to study the physiological and biochemical elements of muscle fatigue during exercise, however not all of them are widely used nor include all the metabolic or biomechanical attributes considered for this thesis. The most common models are summarized in Table 1-1, which presents a summary of the models as described by Noakes, 2000.

Table 1-1: Muscle-fatigue determination models (From Noakes, 2000)

Model	Summary
The cardiovascular/anaerobic model	fatigue is a direct consequence of a failure of oxygen delivery to the exercising muscles
The energy supply/energy depletion model	Fatigue is due to the inability to provide enough (ATP) at rates sufficiently fast to sustain exercise.
The muscle recruitment (central fatigue)/muscle power model	The brain concentration of serotonin alters the density of the neural impulses reaching the exercising muscles, influencing the fatigue-developing rate
The biomechanical model	Elasticity of muscles reduces torque, increasing efficiency by delaying the achievement of "core temperature" of the muscle.
The psychological/motivational model	the ability to sustain exercise performance results from a conscious effort

For this thesis, a focus on the cardiovascular/anaerobic model is made. This model holds that endurance performance is determined by the heart's capacity to pump blood and oxygen to the muscles. If more blood is pumped, the muscles achieve a higher work rate before they exceed the available oxygen supply (Noakes, 2000). This model predicts that training increases ''cardiovascular fitness'' especially by increasing the body's maximum capacity to consume oxygen, measured as the maximum oxygen consumption (VO_{2Max}).

1.3.2 Physical implication of stair and escalator ascending

With an increasing number of metro stations around the world, more people have access to them on a daily basis, exposing them to means of egress that rely on stairs, escalators, and in some cases on elevators. NFPA 130 indicates that escalators running in the direction of egress shall be permitted to remain operating meanwhile the escalators running in the opposite direction, should be capable of being stopped remotely or manually (National Fire Protection Association, 2006), meaning that during emergency circumstances, these escalators could be completely stopped, forcing metro user to perform an ascending stair evacuation. This regulation effectiveness can be exemplified by the King's Cross underground fire (Crossland, 1992) where escalators were not stopped on time and flames were able to spread upwards, reducing the available safe time for egress and leading to 31 fatalities.

Stair-ascending evacuations, challenges the human body as it requires using different leg muscles if compared to their usage in different conditions; for instance, the force made at the hip and knee joints is larger during stair-ascent than during stair-descent at a late stance phase (Lin et al., 2005). A pull-up movement is introduced to the stair ascending motion, this implies a remarkable difference with stair descending as it demands more energy to be used by the knee extensors to complete the ascending task (McFadyen and Winter, 1988). Considering this, people's evacuation techniques also differs between the two kinds of motions; qualitative observations during a laboratory and field experiments performed in Sweden, showed that people tend to use the handrail to help themselves up when walking up in stairs (Ronchi et al., 2015), this could be interpreted as the subject's need to reduce the discomfort in the lower limbs due to the tiredness produce by the exercise.

When discussing stair ascent and its physical implications, the stance phase must be specifically mentioned, as it differs from the one found in level-walking and in stair descent motions. A stance phase is considered within a normal gait cycle, starting with the strike of the heel on the ground and ending with the lift of the toe before moving to the swing phase. For stair ascending, the stance phase can be sub-divided in 3 sub-phases: weight acceptance (WA), pull-up (PU) and, forward continuance (FCN); on the other hand, the swing phase is sub-divided into two sub-phases: foot clearance (FCL) and, foot placement (FP). For a stair-descending motion, the stance phase is divided into three specific sub phases: Weight acceptance (WA); 2) forward continuance (FC), and controlled lowering (CL). The swing phase of descent is subdivided into two specific sub-phases: Leg pull through (LP), and preparation for foot placement (FP) (McFadyen and Winter, 1988)

As stated before, a pull-up movement is considered when conferring stair ascent. Within the pull-up motion, people can make more advance towards finishing the stair-climbing exercise (McFadyen and Winter, 1988) making this sub-phase a challenging one, as it is correlated to each person's Body Mass Index (BMI); if the BMI is higher, the loading at the joint is larger than from a person with low BMI (Amirudin et al., 2014). The pull-up motion forces the joint to endure most of the movement while being supported by only one leg, which creates more stress on the joint.

The performance of an individual can also be affected by the additional weight they are carrying. A study performed with children carrying backpacks while ascending stairs (Hong and Li, 2005), showed that gait pattern changes if an external load is applied; when applying an external load, the subject's center of gravity relocates to a higher position, this causes a prolongation of the stance phase as the subjects adapts until getting stability. During another study involving the repetition of ascending motion with and without an external load (22 kg) it was found that load-carrying increases the electromyography (EMG) activity of the extensor muscles during the WA sub-phase for the knee and ankle extensors (Moffet et al., 1993); the increase of the EMG activity can indicate a higher functional demand of the extensor muscles in order to complete the stair ascending movement (Moffet et al., 1993).

The first part of a study conducted by Kent Pandolf in 1977, involved several individuals using backpacks (32, 40, and 50 kg) while walking at different velocities on a same-level surface for 15 minutes; this experiment showed that energy expenditure increases when the walking velocity increases as well. The second part of the same study involved other participants using the same backpacks but standing still in the same position for 20 minutes; this showed that increasing the load of the backpack will also increase the energy expenditure even when there is no change in the position of the subject (Pandolf et al., 1977)

Even when the experiments briefly described in this section include variables considered for this thesis, the experimental conditions do not match with the criteria stablished for the research questions in section 1.2. For instance, in all the experiments, backpacks are used as an external load, however during the experiment conducted in 2005 (Hong and Li, 2005), even when it includes a stair-ascent motion, the main aim was to understand the changes in gait pattern when a load is included. For the experiment done in 1993 (Moffet et al., 1993), the focus of the experiment was to identify the functional demand of the muscles with an EMG test. For the experiments conducted by Pandolf in 1977, the main objective was to come up with a new prediction formula for the energy expenditure base on experimental results. The first two experiments focus on human kinetics, and even when this thesis requires knowledge in the field, it is not the main scope. During the experiments conducted by Pandolf, characteristics of the subjects indicates a higher level of fitness state than the average metro user considered in this study; also, his study was performed on a same-level surface, which again, is not part of the present scope.

Since the previously mentioned experimental set-ups do not include all the variables involved in the scope of this thesis, two other researches were considered as starting point. The first one, is a 2-years long project that aimed to investigate the effects of fatigue on walking speeds, physiological performance and behavioral aspects during long ascending evacuation in stairs, stopped and moving escalators (Ronchi et al., 2015). This research serves as a reference point for the methodological aspect regarding simulations in section 3. However, as previously stated in the limitations section, several differences are pointed out between the laboratory set-up and the conditions presented in the aforementioned project. For instance, the stair dimensions have an impact on the leg extensor power (LEP) needed to fulfill the stair-climbing movement. In the physiology field, correlations have been made between LEP and flat surface walking speed (Bassey et al., 1992) which leads to subsequent researches where it was found that the higher the step rise, the greater is the power requirements to complete the motion (Fujiyama et al., 2004). Another difference to point out is the effect of the stair-gradient, as horizontal walking speeds may have a linear relationship with this (Fujiyama et al., 2004) pointing out the importance of consider stair characteristics as a factor influencing people's performance.

A second study, presented by Halder, aimed to develop and validate a method to evaluate stair ascending physical work capacity using combined VO_2, heart rate (HR) and EMG measurements (Halder, 2017); this test is taken as reference for the methodology followed for the experimental part of this thesis. Both studies included laboratory and field experiments with people ascending through escalators and stairs. Part of the results of the first study, showed that people tend to pause when they feel tired during long ascending evacuations. Regarding the second study, it was found that a continuous ascent can last in between 2 to 6 minutes at 90% of the maximum capacity; these results serves a reference point for the experimental phase and evacuation simulations methodology, and also as a guide to interpret relevant parameters

1.3.3 Importance of the evacuation modelling tools

Even when the probability of potentially noteworthy fires in metro systems may be in the order of a few fires a year, and considering most of these fire are more likely to be self-suppressed before reaching their full potential (Poon and Lau, 2007) these fires must not be understated. Fire in metro stations are not uncommon to happen, and they have multiple ignition sources that might be out of scope during the first stages of designing fire-related measures. For instance, the 1987 fire at the King's Cross underground station, where 31 persons lost their lives and 100 resulted injured started within 1 of the 4 escalators available in the facility (Crossland, 1992), the 2003's fire in the Daegu subway, where 192 fatalities were recorded and another 151 persons resulted injured, was catalogued as an arson fire (Jeon and Hong, 2009), the Moscow metro station fire in 2004 that which resulted in 39 fatalities, was cataloged as terrorist bombing (Balog, 2006). These cases remark the importance of using evacuation modelling tools to avoid fatalities by creating a safe design for all the metro users whilst including as many factors as possible into the task.

Nowadays, prescriptive design forms part of the normally used strategies to build facilities which ensure life safety within them. However, modern facilities may need different approaches due to new architectural trends and the characteristics of the fuel packages in them. For these reasons, prescriptive designs are usually working hand-by-hand with a performance-based design.

Performance-based design is defined as "an engineering approach to fire protection design based on (1) agreed upon fire safety goals and objectives, (2) deterministic and/or probabilistic analysis of fire scenarios, and (3) quantitative assessment of design alternatives against the fire safety goals and objectives using accepted engineering tools, methodologies, and performance criteria." (SFPE, 2007). The first part of this definition remarks the importance of the stakeholder's involvement during all the stages of a project. The second part involves the design basis of the building, e.g. fire loads, occupant characteristics, this is considered as design fire scenarios. The third part of the definition involves engineering analysis to evaluate if the proposed design strategies provide the proposed level of safety for the design fire scenario; for fulfillment of the latest part, an ASET ≥ RSET analysis is done.

An ASET ≥ RSET analysis is a comparison between the required safe escape time (RSET) and the available safe egress time (ASET); In other words, it shows if the proposed design provides the necessary time for a safe egress. In terms of safety regulations, NFPA 130 indicates the platform evacuation time, ASET in case of metro stations, as a maximum of 4 minutes (NFPA, 2017). To estimate the required time for egress, the use of engineering tools and hand calculations is well known; however, for most of the hand calculation methods, it is necessary to include the movement period, which can generate non-accurate results as it assumes that the facility's occupants are not in direct contact with fire or smoke (Purser, 2003) this is not a clear representation of reality, as smoke is also present causing a reduction in people's movement speed. For this reason, engineering tools for evacuation simulations are highly used in the fire-safety field; they facilitate the simulation process by including several aspects of human behavior, with the possibility to intertwine the results with fire conditions (calculated with a fire simulator or by hand calculations); this, serves as a support for the designers to determine the exact times where the pre-stablished tenability criteria is not met, resulting in better representations of real fire scenarios.

1.3.4 Human behavior in fire

The SFPE Engineering Guide for Human Behavior in Fire, in its second edition, gives a set of updated guidelines to understand human behavior in emergency situations. In this document, three main areas are identified as primordial in terms of human behavior in fire: 1) behavior that causes or prevents fires, 2) behaviors that affect fire, and 3) behaviors that increase or reduce harm from fires (SFPE, 2017). A focus on the third area is needed when discussing influencing factors related with evacuation or refugee seeking in case of fires; this factors include occupant characteristics such as age, familiarity with the building, social and cultural roles, presence of others, and commitment to activities, alertness, physical and cognitive ability (SFPE, 2017).

Each of the factors have been studied and developed over the years. For instance, a study showed that movement speed, inherent to the population characteristics, and the flow constrains can create a bottleneck in emergency situations (Fridolf et al., 2013). The affiliative model predicts that in situations of potential entrapment, people tend to move towards familiar places or people (Sime, 1985), meaning that people tend to take the route in which they entered the facility. New studies support Sime's results, but also add the concept of exit design as it influences people's choices, for example, people tend to use the nearest exit, disregarding if they receive strong visual indicator of an alternative egress route (Nilsson, 2009). Wood's questionnaire studies, found that women are more likely to evacuate faster than men, who initially tend to fight the fire, implying that decisions also relate to gender roles (Wood, 1972). However, according with the observations made for the People Project II, people's reaction might be a result of their roles rather than their gender (Bryan et al., 1981) showing the complexity of the analysis of human behavior.

The decision-making process and the behavior on people also varies depending if they are in the presence of other persons or if they are alone, this also applies to their response to fire alarms or cues; when an ambiguous cue is presented to a person who is alone, the response tends to be more rapid in comparison to their reaction when they are in presence of one or more persons, this is known as the bystander effect (Darley and Latane, 1968). Both, the affiliation theory and the bystander effect, are factors that will affect people's response in case of emergencies and an evacuation from a deep metro station is no exception.

When discussing human behavior in fire, times must be addressed as an essential factor as it is crucial for a correct ASET>RSET analysis. The Protective Action Decision Model (PADM), provides an outline to the information flow and decision-making process that impacts a person to take protective actions in response to natural and technological disasters (Lindell and Perry, 2012). In this model, people take time sensing the cues from the physical and social environment, paying attention to them and attempting to understand them, to then process them as threats to make a decision on their next move towards safety (SFPE, 2017). Depending upon how the threat is processed a person will either: a) seek additional information, b) engage in actions to protect people or property, or c) resume normal activities. Figure 1-2, shows an idealized process of decision-making fire situation.

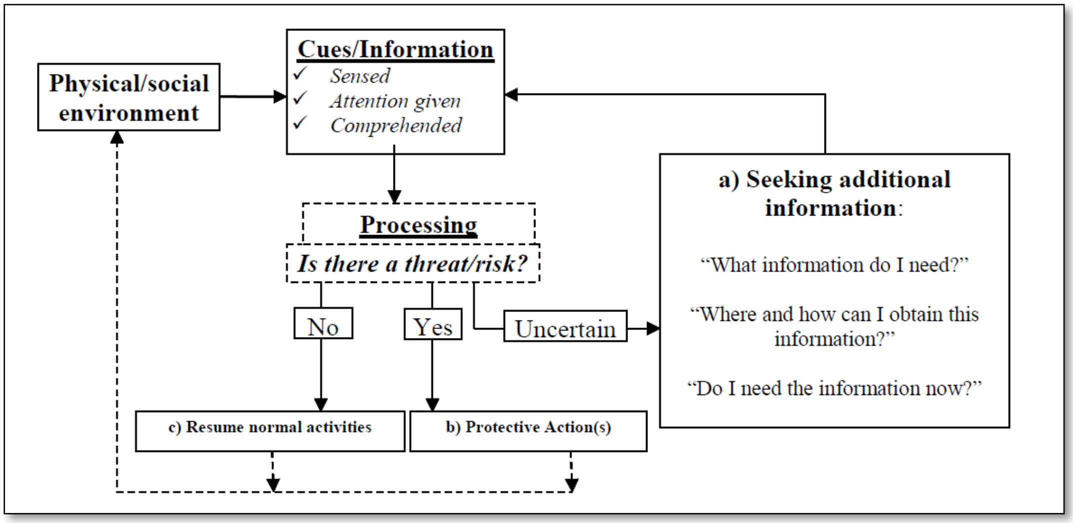


Figure 1-2: The Protective Action Decision Model, Redrawn and Adapted to Building Fires (From SFPE, 2017)

1.3.5 Human behavior application to evacuation modelling

When it comes to evacuation simulations, the application of human behavior theories is included in different levels. For instance, two general types of models can be considered: 1) Those which only contemplate human movement and 2) Those which attempt to link movements with behavior. The first type of model is called "ball-bearing" and it treats the individuals as unthinking objects responding automatically to external stimuli ceasing any other activity besides the ones related to evacuation; it also considers the direction and speed of egress by physical considerations like population densities or exit capacities. (Gwynne et al., 1999) The second type of model considers the physical characteristics of the enclosure while treating the individual as an active agent, this is done by considering his response to stimuli such as hazards and individual behavior such as personal reaction times and exit preferences. (Gwynne et al., 1999)

Besides the two models discussed beforehand, it is important to mention that even when all models aim to simulate evacuations, they can handle this in the following three main different ways: 1) by optimization, 2) by simulation, 3) by risk assessments. On one hand, the models by optimization do not consider any individual behavior but treat the agents as a homogenous collective; on the other hand, the models by simulation, attempt to represent behaviors and movements usually noted during evacuation with the aim to obtain realistic quantitative results by replicating paths and decision-making processes. The models by risk assessment identify the hazards attempt to quantify risks, they perform repeated runs and assess the statistical variations generally by changing the compartment characteristics or the fire safety features within it. (Gwynne et al., 1999)

There are other issues considered within the evacuation modelling, as the representation of the geometry, however, these will not be discussed in this work as it moves away from the focus on population and behavioral perspectives. For instance, it is of more interest for this thesis to state that most models now allow to assign physical and behavioral attributes, which are used in the movement and decision-making process of the agents, generating independent results. This independent-thinking does not exclude the group behavior that influences the individual decision and it is crucial to obtain more realistic results.

Numerous evacuation models are available in the market. According with the technical note 1471 by NIST made in 2005, there were up to 14 models available to the public, including Simulex (IESL, 2014), and STEPS (Mott MacDonald, 2010); other 7 seven models were available on a consultancy basis, e.g. PathFinder (Thunderhead, 2018); by that moment, 6 more models were not released, 5 were no longer in use and 2 more were cataloged with an unknown availability (Kuligowski, 2005). Several reviews of these models have been made throughout the last years, including comments about their performance to represent situations in underground facilities and high-rise buildings (Gwynne et al., 1999; Kuligowski, 2005; Ronchi, 2016; Ronchi and Nilsson, 2014) and even user's experiences and needs (Ronchi and Kinsey, 2011). However, the effects of physical exertion and the impact that adding extra load has over a stair-ascent motion, is not included in these reviews, pointing out once again, the need to continue the research in this field.

Exertion effects during evacuations is still a developing topic, a limited amount of modelling studies have been conducted regarding this subject; for instance, a study was developed in 2014, with the aim to model and estimate the effects of mental disorientation and physical fatigue on evacuation times (Koo et al., 2014). Exertion has also been studied over the years in other fields that can work as compliment for evacuation modelling; for example, a model estimating the vertical speed was developed in the human kinetics field (Kuklane and Halder, 2016) and the effects of clothing weight on the wearer was studied in the environmental science field (Goldman, 1981); in the biomechanics field, the effects of ascending and descending movements have also been studied (Amirudin et al., 2014). These studies are relatively new, and they show the importance of considering physical exertion as a factor influencing people's performance during an evacuation, as it will have an effect on the calculations made within the modelling evacuation tools.

Limitation for the evacuation models are also present when the scope of fatigue is limited to a physical concept. As stated before in section 2.3.1, when talking about fatigue, there is also a psychological aspect to consider (Borg, 1998). The omission of considering the effects of physical exertion, people's perception of tiredness, and the effect of carrying loads when doing a stair-ascent motion, can produce an optimistic and non-realistic result, endangering the life safety inside metro stations. For this thesis, Mass Motion is taken as an example of agent-based model, as it allows to simulate movement and behaviors to adjust them to the ones commonly used for fire-safety related designs in metro stations.

1.3.6 Mass Motion: An example of evacuation modelling tool.

Mass Motion (MM) is a pedestrian simulator and crowd analysis software developed by Oasys, that uses behavioral profiles for agents in a 3D environment to simulate evacuations in different scenarios. With this tool, the agents have several options to select from in order to arrive to their destination based on a predefined origin; they are able to identify congested areas thus, they consider alternative escape routes adapting to the on-going scenario. The route choice is generally indicated as based on quickest time, however it can also be chosen according to distances (shortest path) or by a conditional path (Bladström, 2017). MM offers tools to create and modify 3D environments, to define operational scenarios while executing dynamic simulations with the option to extract the results (e.g. charts, graphs). MM allows to import 3D geometrical designs (e.g. designs from Sketchup, AutoCAD) and 2D drawings that can be edited and converted into "scene" objects. The tool also includes the possibility to change any scene conditions; for example, gates can be either opened or closed according with the population density of a room. Agents can inspect and react to their surroundings according a predefined-set of characteristics and goals; the characteristics of the agents include size, speed and route options.

The tool also allows to apply different tasks to the agents (e.g. moving to a portal destination, evacuating a zone, executing a sequence of subtasks), allowing the representation of human behavior theories into the model. The way to execute these tasks is based on the Navigation and Movement intelligence system, and forms part of the behavioral pattern set to them.

Within the navigation system, the agent can choose the best way to fulfilling a given task. For instance, agents can determine the best route to an exit portal when given the “evacuate” task; this is done by a surrounding-awareness, including evaluation of distances and congestions of the exits, which can lead to the change of route after a periodical re-evaluation. Regarding the movement system, it relies on a modified version of the Social Forces algorithm (Helbing and Molnár, 1995); this allows the agents to be influenced by a series of forces that are based on factors like: the chosen egress route, the agent’s location, the movement and location of other agents, and the position of obstacles. The goal of this system is to determine the agent’s speed by summing the forces at every time step.

Other variables included into MM relate to the way agents choose their route, which is done by a local target feature, by costing routes, and by including two stochastic elements. The local target feature, allows the agents to select their egress route by considering only the immediate floor they are located, meaning that the conditions of other floors (e.g. congestion) are not considered for the immediate decision. Meanwhile, the costing route process consider several components (e.g. downstream horizontal distance, weighted downstream vertical distance, near horizontal distance, queue times, opposing flows). The various components are then summed up producing the total cost for the route and therefore, giving the optimal one to the agents. Regarding the adaptation of the cost to represent different conditions, MM multiplies the vertical displacement components by a factor based on the type of object (e.g. stair, escalator, ramp).

The agent’s speed is defined as the speed at which the agents will walk on a flat surface and uncongested environment, however this speed is influenced by the population density (Seyfried et al., 2005), the type of object, and the object’s speed limit property. The relation used for MM is based on the Fruin’s research (Fruin, 1971) and can be also modified to match other agent profiles or to adapt the speeds to other parameter outside the basic options. Table 1-2 shows the diverse profiles with their correspondent speeds.

Table 1-2: Agent's speed profiles in Mass Motion

Code	**Short description (*)**	**distribution**	**Speed for each agent profile [m/s]**			
			Minimum	Maximum	Average	Standard deviation
FC	Fruin commuter	Normal	0.65	2.05	1.35	0.25
PD7974	PD 7974	Constant	-	-	1.19	-
NPRM	Non-PRM	Normal	1.1	1.9	1.53	0.13
WC	Wheelchair	Constant	-	-	0.58	-
MI	Mobility Impaired	Constant	-	-	0.8	-
SL	Small Luggage	Normal	1.1	1.9	1.53	0.13
LL	Large Luggage	Normal	0.65	2.05	1.53	0.23
HL	Heavy Luggage	Normal	0.9	1.8	1.32	0.15
AC	Adult with Child	Normal	1	1.9	1.37	0.15
(*) Reference not stated in the model documentation – values extracted directly from the software						

The travel speed of the agents is also influenced by the stair angle and the direction of travel. Table 1-3 shows the speeds profiles modification according to the stair angle. Based on Fruin's observed speeds, MM assigns agent stair speeds as a function of the flat surface unimpeded walking speed. For example, an agent moving up a staircase with an angle of 27 degrees will move at an average of 0.574 m/sec if their natural flat walking speed is 1.34 m/sec. (Rivers et al., 2014) It is noted that the described speed does not refer to the vertical component but only to the horizontal one.

Table 1-3: Agent's speed modification in Mass Motion considering stair angle (From Mass Motion User Guide

Surface type	**direction**	**Angle (degrees)**	**Mass motion agent speed as a percentage of natural speed (%)**
Stair	Up	0 < X < 27	42.6
		27 ≤ X ≤ 32	Interpolate between 42.6 and 37.8
		32 < X	37.8
	Down	0 < X < 27	57.4
		27 ≤ X ≤ 32	Interpolate between 57.4 and 49.8
		32 < X	49.8

2. Methodology

In alignment with the research questions and considering that a full-scale experiment was not viable due to the limitations stated in section 2.2, the methodology for the development of this research has been divided in the following categories: 1) Literature review, 2) Laboratory experiments, and 3) Evacuation modelling.

A literature review was made to compile information that enables the analysis of the data obtained in the laboratory experiments and the definition of the experiments themselves. The review included the search of papers regarding: kinetics, fatigue, exhaustion, perceived exertion, evacuation, ascending evacuation, and evacuation modelling tools. This literature review was based on online searches in different databases and on literature recommendations from this thesis supervisors. The online databases included: ResearchGate [www.researchgate.net], ScienceDirect [www.sciencedirect.com], and Elsevier [www.elsevier.com]. The material used for the literature review was divided in: human kinetic, physical and perceived exertion, previous experimental studies, and material regarding evacuation modelling. This literature review can be found in section 3 of this document.

As introduced in section 2.3.2, two research papers have been taken as reference points for the methodology, due to their recent publication and the similarity on the analysis for factors in question. The experimental phase of this thesis, is based on researches made in Stockholm and Lund, Sweden, to propose a methodology that evaluates stair ascending physical work capacity using combined VO_2, heart rate (HR) and EMG measurements (Halder, 2017; Ronchi et al., 2015). Meanwhile, the simulation phase of this thesis takes values from Ronchi's field experiments to apply them into an evacuation simulation using Mass Motion as the evacuation modelling tool.

2.1 Laboratory experiments

This section intends to describe the experimental procedure followed to gather the relevant data for the subsequent analysis in section 5. It includes the laboratory equipment used, the characteristics of the participants, and the methodology used in the experimental sessions.

2.1.1 Laboratory equipment

A controlled experiment inside a laboratory has been performed. The experiment was conducted using a stair machine (Stair Master, SM5, Vancouver, WA, USA); this machine represented the escalators found in a metro station evacuation route, as this investigation required a controlled setting and given the limitation of the equipment in use; the stair-machine steps have fixed-step dimensions (20.5 cm height and 25 cm in depth) it has 20 step-rate levels to choose from, ranging from 24 to 162 steps per minute which were different for each participant according to their individual sub-maximal test results. A heart rate transmitter (RS400, Polar Electronics, Finland) was used to measure the heart rate of participants. The oxygen uptake was measured with a cardiopulmonary exercise testing system (Metamax 3B-R2, Cortex Medical GmbH, Germany).

Figure 2-3: Stair machine SM5 used for experimental sessions 2 and 3 (From: User Guide Manual)

Figure 2-3: Heart rate sensor RS400 used for all experimental sessions (From: Manufacturer's web page)

Figure 2-3: Metamax 3B-R2 used for sessions 2 and 3 (From: Manufacturer's web page)

2.1.2 Participants

A total of 21 participants were recruited for the experimental phase from the student and staff population at Lund University. Participants were asked to refrain from ingesting food, alcohol, caffeine or using tobacco products within 3 hours before testing. They were also asked to be rested before the assessment, avoiding significant exercise at least 24 hours before the test. They were requested to bring their own sport clothes and to choose an attire that allowed freedom of movement, including walking or running shoes. To limit the bias in the data collection phase, they were asked to bring the same outfit for all sessions.

People with disabilities or with cardiac history were not considered as suitable to participate in the experiments. A declaration of health was required to be part of the experimental sessions. The health declaration was a self-assessment based on AHA/ACSM Health/fitness Facility Pre-Participation Screening Questionnaire and it was filled in by the participants during session 1.

The recruitment of participants was done through social media by sharing a Google Form which they filled in to confirm their contribution to the experiments. Final confirmation was done through Google Calendar. Table 2-1 shows the characteristics of the experimental group.

Table 2-1: Characteristics of experimental group

Number of participants	**Male**	**Females**	**Age**			
			Min	Mean	Max	SD
21	13	8	21	27	33	4

2.1.3 Experimental procedure

The experiment was divided in three sessions. The total number of experimental sessions was 63 (3 per participant), these sessions were completed in one month and a half (mid-February to end-March 2018). To organize sessions 2 and 3, participants attended individually if preferred, thus, two modalities were considered in this report: Individual and by pairs. Session 1 consisted in a sub-maximal test. This test helped to estimate the maximum oxygen uptake (VO_{2max}) needed to calculate the step rate at which participants were going to perform the stair-ascending exercise during experiments in sessions 2 and 3. The specifics of this test are mentioned in section 3.1.4 of this document.

During sessions 2 and 3, participants VO_2 and HR were recorded depending on the test-modality chosen by them. These modalities were designed by the investigator to respect the participant's right to privacy and to reduce bias in data collection. The modalities considered are: 1) Individual modality - Session 2: Participant performed weight bearing test (8 kg) Session 3: Participant complete non-weight bearing test (0 kg), 2) Pair modality - Session 2: Participant 1 performs weight bearing test while participant 2 performs non-weight bearing test (0 kg) - Session 3: Participant 1 fulfill the non-weight bearing test while participant 2 performs weight bearing test (8 kg)

The experimental procedure was based on previous studies performed in Sweden (Halder, 2017; Ronchi et al., 2015) with simplifications in terms of technical measurements, as this project focusses on the aforementioned relevant parameters (heart rate, oxygen uptake, and perceived exertion). In addition to the previous experiments, this project's novelty is the measurement of the relevant parameters while adding weight to the same sample population. The additional weight was 8 kg. This weight was selected according with the standard weight allowed in airplanes for cabin luggage and also, by considering the expected average weight of an 8 months old child (WHO, 2006)

Before starting with the experiments, a written informed consent was acquired. Participants were informed to terminate the experiment at any point in case of perceiving signs of serious discomfort (e.g. dizziness, nausea) however, they were encouraged to lower the step rate instead of ending the experiment before the stipulated time. During sessions 2 and 3, participants were not allowed to lower the step rate before 2 minutes after the session started. This time-threshold is set according to the findings in a precedent experiment, in which the steady state values for VO_2 was reached in between 20-30% of a normalized ascending period for a 109 m building taken as the reference experiment (Halder, 2017).

The perceived exertion was qualitatively measured with Borg's Scale (Borg, 1998) every 60 seconds after starting the experiments and at any moment when the participants decided to lower the step rate. The Borg's RPE scale was selected to measure the perceived exertion as it allows an easier comparison with selected physiological variables (HR and VO_2). The Borg's scale to be used during the sessions, was presented to the participants in 2 occasions: 1) while reading the experimental guide through the enrollment form, and 2) while listening to the experimental procedure during the preparations for session 1. A reminder of the procedure was made before sessions 2 and 3.

Participants were only allowed to reduce the step rate if their perceived exertion was between 14 and 17 in the scale; A 14 RPE Borg's scale has been selected as the initial value for the threshold as, from experiments conducted in stairwells, it was found that participants tend to adjust their ascending speed to stabilize their perceived exertion between 15-17 in the Borg's Scale (Ronchi et al., 2015), however, they also show a faster increase in the perceived exertion when ascending through escalators. This last criterion fits better the current study and it is used as a parameter for lowering the threshold 1 point in the scale. A 17 in the RPE Borg's scale is the maximum value that participants were intended to reach in the scale as, in alignment with one of the thesis goals, fatigue is supposed to be avoided at any point during all the controlled ascent. If at any point participants reached 17, the person in charge of monitoring the stair machine could reduce the step rate by 1 level. As safety measure, two investigators were always available inside the laboratory during the tests. Emergency contacts were listed in case of any unexpected situation involving the participant's safety. An emergency aid kit and water were always available inside the laboratory.

Session 1: Sub-maximal test

In order to measure the cardiorespiratory fitness, it was necessary to measure the individual's maximal oxygen uptake (VO_{2Max}). This can theoretically be obtained by a maximal or a sub-maximal exercise testing. To perform a maximal test, the participants are exposed to exercise until the point of exhaustion requiring medical supervision and emergency equipment. Even though more accurate values can be obtained through a maximal test, for the scope of this project, a sub-maximal test is selected to obtain an estimated VO_{2Max}. For this thesis, the participants performed a sub-maximal test according to Åstrand (Astrand et al., 1986) on a mechanically braked cycle ergometer.

Using a sub-maximal test allows easy adjustment of the work rate of the ergometer and reduces participant's anxiety while using it (ACSM, 2010). Once the preliminary information was collected during the session 1, the investigator calculated the step rates for each participant to use during sessions 2 and 3. The aim of the sub-maximal test is to find the theoretical step-rate which allow participants to finish the 5-minutes stair-climbing exercise in sessions 2 and 3; The tables used for these calculations and the protocol form for the sub-maximal test can be found in Annex 5.2: Step reduction for each participant

Session 2 and session 3: Stair-machine exercise

Participants attended session 2 according to the modality chosen (individually or by pairs). If they attended by pairs, a counter-balanced measure design was followed to reduce biased in the data-collection step; meaning that if the first subject performed the test with the backpack, the second subject would perform without it. For this, participant 1 was given an 8 kg backpack to carry during the session, and participant 2 conducted the experiment without the 8 kg backpack. If the participant attended alone, the 8 kg backpack was provided. As soon as all the relevant equipment was in place and the participants agreed with the initiation of the session 2, the stair climbing was programmed at the previously calculated step rate. In order to replicate the expected response of people during ascending egress, which consist in slowing down instead of stopping completely (Ronchi et al., 2015) , participants were told to reduce the step rate of the stair master when perceiving a level of exertion within the previously defined threshold (14-18 in the RPE Borg's scale), however, as explained in section 2.1.3, they were not allowed to slow down during the first 2 minutes of testing. Participants were not expected to reach exhaustion as the stair machine step rate was selected according to the results of the sub-maximal test, nevertheless, they were told to stop the sessions if they sensed any major discomfort (e.g., dizziness, nausea, extreme weakness). Participants were asked to indicate their level of perceived exertion on Borg's scale each 60 second but also every time they decided to slow down their step rate. This cycle was repeated until reaching 300 seconds of non-stop stair climbing.

Session 3 was performed 24 hours after session 2; This time was selected to ensure full muscle recovery and to avoid biased results from the effects of session 2. The step-by-step of this session also depended on the test-modality selected. If they attended by pairs, participant 1 conducted the experiment without the 8 kg, and participant 2 will conducted the experiment with the 8 kg backpack. If the participant attended alone, the non-weight bearing test was completed. After each experimental session, participants were asked to complete a questionnaire via google forms inside the laboratory. The questionnaire can be found further in this document. The general scheme for the methodology followed for the experimental phase of this thesis, is found in Figure 2-4.

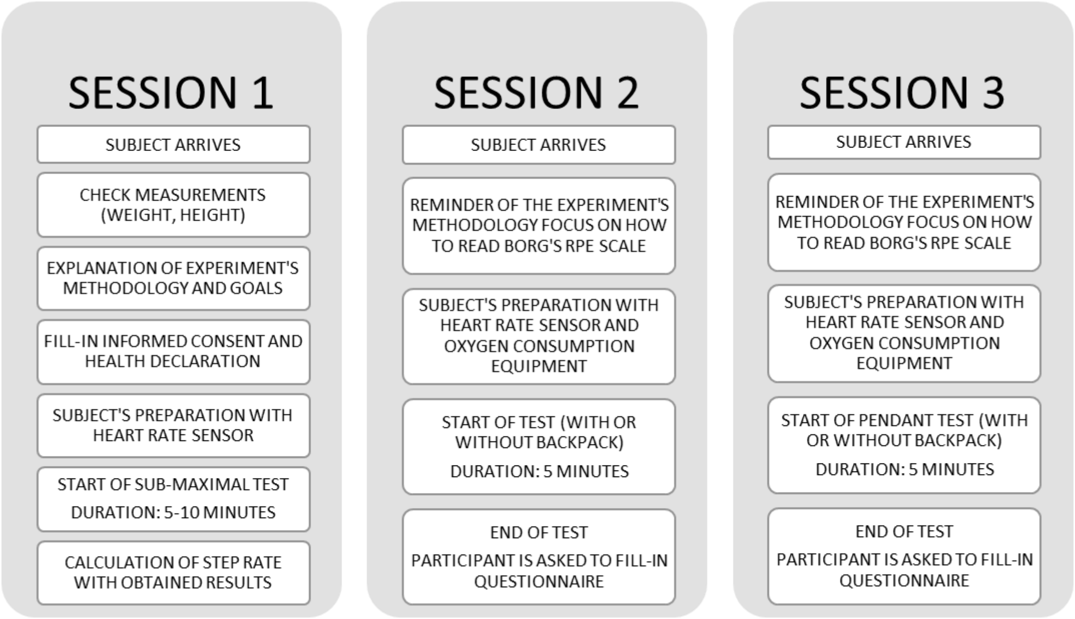


Figure 2-4: General scheme for the experimental phase

3. Experimental laboratory results

This section describes the results obtained from the experimental phase of the thesis that includes the sub-maximal test and stair-climbing exercises with and without the influence of additional weight (8 kg backpack)

3.1 Sub-maximal test

A total of 30 persons enrolled the test via Google Forms, however only 21 completed all three experimental sessions; from the remaining 9 persons who were not able to finish the experiments, 4 underwent the submaximal test, however their heart rate was higher than the values included in the Astrand nomograms in Annex 2, which shows a maximum of 170 bpm; therefore, they were not required to join the subsequent sessions involving the stair machine. The remaining 5 persons excused themselves for participating due to personal time constraints.

A total of 21 persons did complete the sub-maximal test using a braked ergometer. As indicated in section 2, with this test, the researcher aimed to measure the oxygen intake capacity of the participants, by using the Astrand nomograms in annex 2, that correlate Hear Rate (HR) and Oxygen Uptake (VO_2), the results are then used to calculate the step-rate of the stair machine for sessions 2 and 3, that would theoretically allow the participants to finish the 5-minutes stair-climbing exercise. Participants were asked to maintain a velocity of 60 RPM during the necessary time for their heart rate to stabilize; the parameter used to recognize such stable-state was a difference of 2 bpm between each 1-minute measurement. With the sub-maximal test, the researcher aimed to estimate the step-rate which allows the participants to endure the 5-minutes stair-climbing exercise; the implications of these calculations to resemble real conditions are thoroughly explained in the discussion section.

Table 3-1, shows the minimum, maximum, mean value and the standard deviation obtained from the sub-maximal test of all participants. These values were used to calculate the step rate for sessions 2 and 3 shown in Table 3-1. Important to mention, the tables in annex 2 used to calculate the VO_{2Max} showed liters/min as unit, and a conversion of units is needed to obtain mL/min/kg; such conversion considers two kg measurements per participant: 1) VO_{2max1}: Participants weight, and 2) VO_{2Max2}: Participants weight + 8 kg. This is used to compare the predicted Metabolic Rate (M) and the calculated value after sessions 2 and 3. Ratios between the additional load (8 kg backpack), the participant's body mass, and height are also included.

Table 3-1: Physiological parameters of participants during sub-maximal test

Statistical measurement	Weight [kg]	Heart Rate [bpm]	Corrected VO_{2max} [l/min]	VO_{2max1} [ml/kg/min]	VO_{2max2} [ml/kg/min]	Load/ BM	Load/ Height
Minimum	57.1	123	1.75	19.64	18.02	0.08	0.04
Average	72.9	149	2.52	34.97	31.40	0.11	0.05
Maximum	99.5	168	3.75	48.16	43.30	0.14	0.05
Standard deviation	12.4	14	0.61	7.79	6.92	0.02	0.002

For the calculation of the step rate (SR), a prediction equation was used. This equation is taken for a new proposed prediction model, which was developed and validated with laboratory experiments between the years 2016 and 2017 (Halder, 2017). For the prediction of the metabolic rate (M), Pandolf's equation was used (Pandolf et al., 1977). The prediction formulas for the SR and M, are:

$$SR: -108.8633 + 2.0121 * VO2\max + 1.3289 * \%VO2max \qquad \text{(Eq.1)}$$

Where:

- VO_2 max: Oxygen Uptake [mL/kg/min]
- $\%VO_{2max}$: 100% assuming participants using all their physical capacity to meet real-life conditions where they are influenced by the need to reach a safe place as soon as possible.

$$M = 1.5 * W + 2 * (W + L) * \frac{L}{W}^2 + \eta * (W + L) * (1.5 * V^2 + 0.35 * V * G) \qquad \text{(Eq. 2)}$$

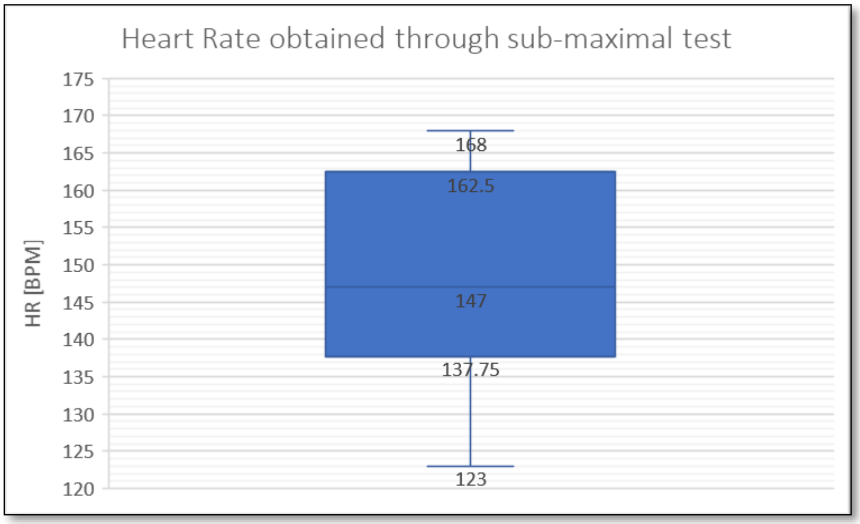
Where:

- W: Participants weight [kg]
- L: External load [kg]
- V: Walking speed [m/s]
- G: grade of slope – 82 for all cases considering stair machine slope
- η: Terrain coefficient – 1 for treadmill

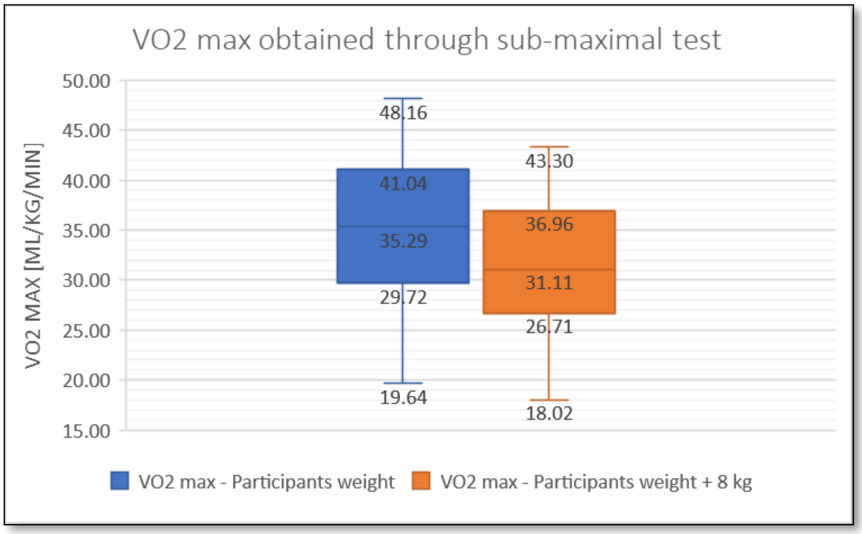
The predicted minimum, maximum, average and the standard deviation of the predicted step rate (SR), vertical displacement, and metabolic rate (M) are shown in Table 3-2. A visual representation of the results is found in Graph 3-1, Graph 3-2, Graph 3-3, and Graph 3-4; results shown by participant performance and predictions can be found in annex 5.1

Table 3-2: Predictions based on sub-maximal tests

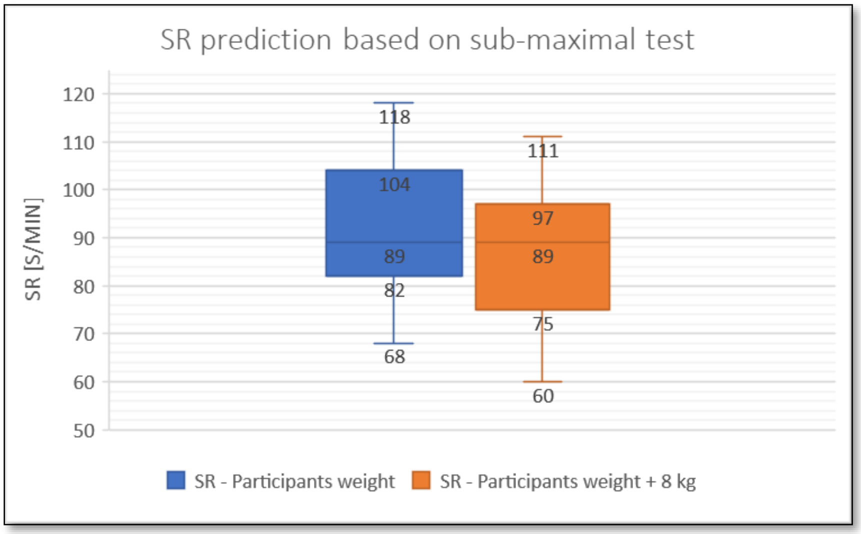
Statistical measurement	**Without influence of additional weight (0 kg)**			**Influence of additional weight (8 kg)**		
	Step Rate [steps/min]	Vertical displacement [m]	Metabolic Rate [W]	Step Rate [Steps/min]	Vertical displacement [m]	Metabolic Rate [W]
Minimum	68	69.70	558.66	60	61.50	482.58
Average	92	94.10	654.02	86	88.10	602.05
Maximum	118	120.95	822.15	111	113.78	822.15
Standard deviation	15	15.04	78.24	14	14.21	93.53



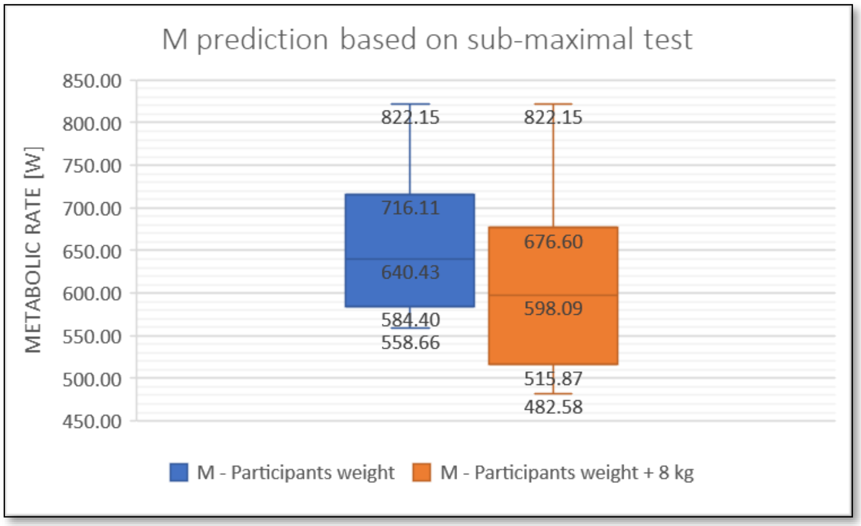
Graph 3-1: Min, max, average and standard deviation for HR obtained during sub-maximal test



Graph 3-2: Min, max, average and standard deviation for VO2 obtained during



Graph 3-3: Min, max, average and standard deviation for the SR predictions based on sub-maximal test



Graph 3-4: Min, max, average and standard deviation for the M predictions based on sub-maximal test

3.2 Sessions 2 and 3: Stair-climbing exercises

All the participants of the laboratory experiment were able to complete the 5 minutes stair-climbing exercise while carrying a backpack, except one man; he asked the researcher to stop de machine after 3 minutes of exercise due to high discomfort while breathing. All participants completed the 5 minutes stair-climbing exercise without carrying the backpack.

For this section of the thesis, the results point out the comparison between the participant's performance while performing the stair-ascent exercise in the two beforementioned conditions: 1) not carrying weight (0 kg), and 2) carrying weight (8 kg); To offer a more comprehensible order of ideas, this section is divided in the following points: 1) Velocities, 2) Displacements with focus on vertical distances, 3) HR/VO_2, 4) Metabolic rate, 5) variables correlations, and 6) Borg's scale. All the sections consider predicted values and the values obtained from the laboratory results, made known in terms of minimum, maximum, averages and standard deviation.

3.2.1 Velocities

Participants were asked to slow down the step rate when they considered it as beneficial to complete the 5-minutes exercise. For the stair-climbing exercise without carrying weight (0 kg), in average, participants needed to reduce the step rate 2 times, the first reduction was noted at an average of 3:00 minutes, meanwhile the second reduction was observed at an average of 3:35 minutes into the exercise. Out of 21 participants, 17 did not reduced the step rate during the 5-minutes exercise.

In contrast with the same exercise while carrying weight (8 kg), participants needed to reduce the step rate at an average of 3 times, the first reduction was noted at an average of 3:03 min, a second one was recorded at an average of 3:37 min, and the third reduction was observed at average of 4:21 min into the 5-minutes exercise. Out of 21 participants, only 3 did not reduce the step rate during the session length, and 18 participants slowed down the step rate almost after 2 minutes into the exercise. Table 3-3, shows the aforementioned time-reductions (in seconds) for each experimental set-up (0 kg and 8 kg), considering minimum, maximum, average, and standard deviations.

Table 3-3: Time reductions during stair-climbing exercises

Time [seconds]	No Backpack (0 kg)		Backpack (8 kg)		
	1st reduction	2nd reduction	1st reduction	2nd reduction	3rd reduction
Min	135	175	120	154	250
Max	240	245	292	252	271
Average	179.75	215	183	217	261
SD	44.27	36	47.29	32	15

The initial velocity of the participants is obtained with the step rate calculated in the sub-maximal test. Every time the participants asked to slow down the step rate, the ascending velocity also changed with respect to the prediction. Table 3-4 shows the minimum, maximum, average, and standard deviations for the predicted values of the velocity (named as Initial Velocity – Vo), times of reduction of step rate, and final velocities (Vf). These results are displayed for the two conditions: 1) not influenced by additional weight (0 kg), and 2) influenced by additional weight (8 kg). The step reduction of each participant can be observed in annex 5.2

Table 3-4: Velocity decrease during stair-climbing exercises – diagonal component

Statistical measurements	Initial (Vo) [m/s]	Final (Vf) [m/s]		Decrease velocity [%]		
		Vf1 (0 kg)	Vf2 (8 kg)	Vo vs Vf1	Vo vs Vf2	Vf1 vs Vf2
Min	0.37	0.37	0.26	-	22.05	22.05
Average	0.49	0.49	0.43	1.50	12.45	11.12
Max	0.64	0.64	0.64	-	-	-
SD	0.08	0.08	0.08	-	-	-

3.2.2 Displacements

By comparing the experimental results obtained after the participants climbed the stairs while carrying a backpack during one session, and not carrying it during a subsequent session, it has been found that: people can climb an average of 92 m when they are not carrying the backpack, in comparison with 84 m when they are influenced by the additional weight; this represents a performance reduction of 8.52% for this specific sample and experimental conditions. The predictions indicated a reduction of 6.38% for the participants performance, however, the laboratory experiments show an actual reduction of 8.52%. Table 3-5 shows the comparison values between the predictions made with the sub-maximal test, and the laboratory results during the stair-climb exercise.

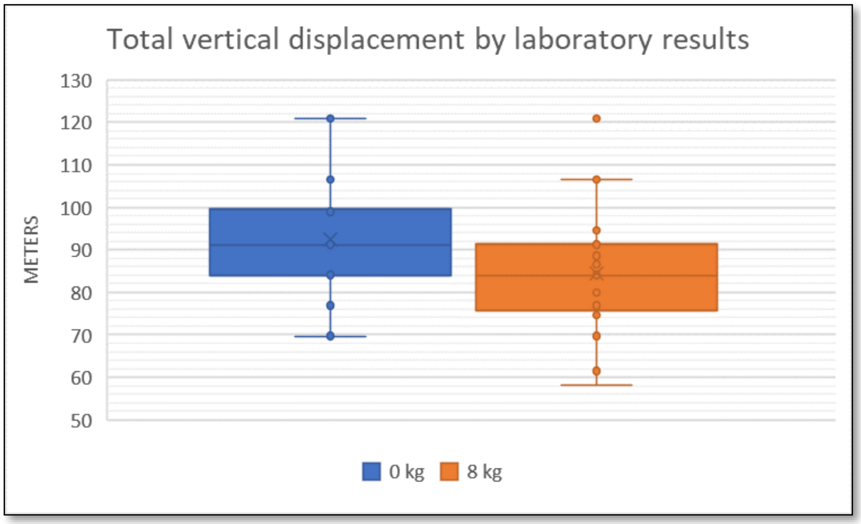
Table 3-5: Predicted vs experimental results for the vertical displacement of participants

Statistical measurements	**Predicted**			**Laboratory experiments**		
	0 kg	8 kg	performance reduction	0 kg	8 kg	performance reduction
Minimum	69.7	61.5	11.76%	69.7	58.15	16.57%
Maximum	120.95	113.78	5.93%	120.95	120.95	0.00%
Average	94.105	88.1	6.38%	92.3968	84.52	8.52%
Standard deviation	15.04	14.21	-	14.1832	14.9869	-

Regarding the vertical displacement before reducing the step rate, it has been found that people can reach a vertical distance of 57.93 m before reducing their step rate when they are not carrying a backpack; results also shows a tendency to reduce the step rate at a distance of 42.75 m when they are carrying the additional weight of 8 kg. These results show that people, in average, request for the first step-rate reduction 15.18 m before when carrying weight, representing a reduction of 26.20% on the participants performance, considering a healthy and young sample under specific experimental conditions. A summary of these results can be found in Table 3-6 and are illustrated in Graph 3-5. Additional tables including diagonal and horizontal displacements are displayed in Annex 5.3

Table 3-6: Vertical displacement comparison - 0 kg vs 8 kg

Statistical measurements	**Vertical displacement**		
	0 kg	8 kg	performance reduction
Minimum	44.74	32.80	26.69%
Maximum	72.98	67.84	7.04%
Average	57.93	42.75	26.20%
Standard deviation	11.78	20.21	-



Graph 3-5: Total vertical displacement for the stair-climbing exercise

3.2.3 HR/VO_2

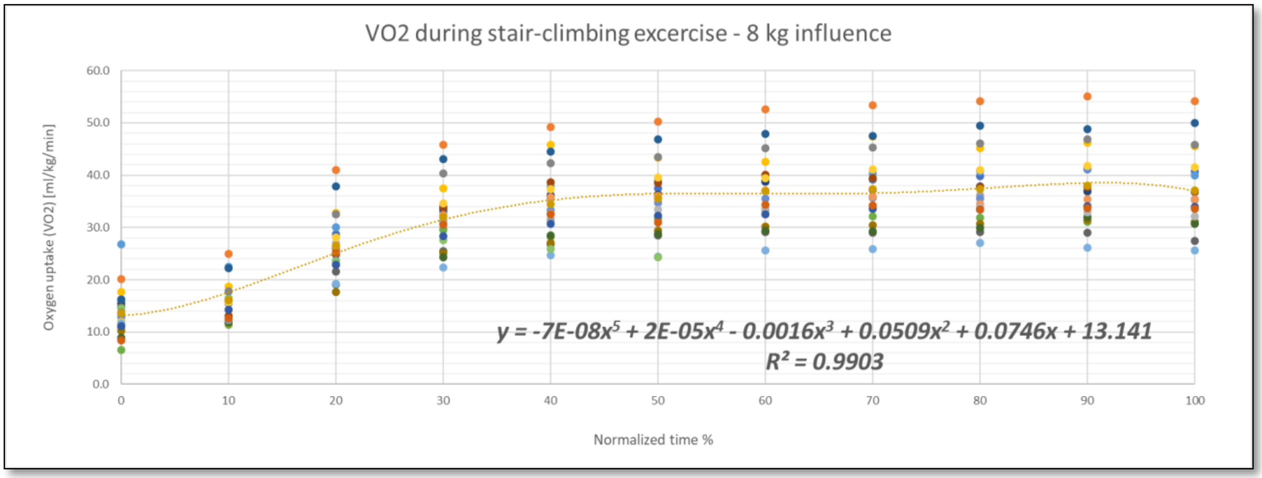
The stair-climbing exercise lasted 5 minutes for each participant, however the VO_2 values are not taken exactly at the same moment for each experiment, thus, a normalization of time must be made. In average, an increase of 4% in the VO_2 and the HR is found when the influence of the 8 kg backpack is included. For both cases (0 kg and 8 kg), steady state can be observed around interval 40% and 50% of the normalized time, this matches with 120 – 150 seconds of a non-stop stair-climbing exercise.

According with the sub-maximal results, the average maximum VO_2 is 34.97 mL/kg/min, this value is reached at different moments for both cases (0 kg and 8 kg); in the case of not having the influence of the weight (0 kg) the value is in average reached in the 60% normalized time-interval, corresponding to 160 and 180 seconds after the exercise initiated; when considering the effect of the additional 8 kg, the value was in average reached in the 40% normalized time-interval, corresponding to 100 and 120 seconds into the stair-climbing exercise. General results can be found in Table 3-7

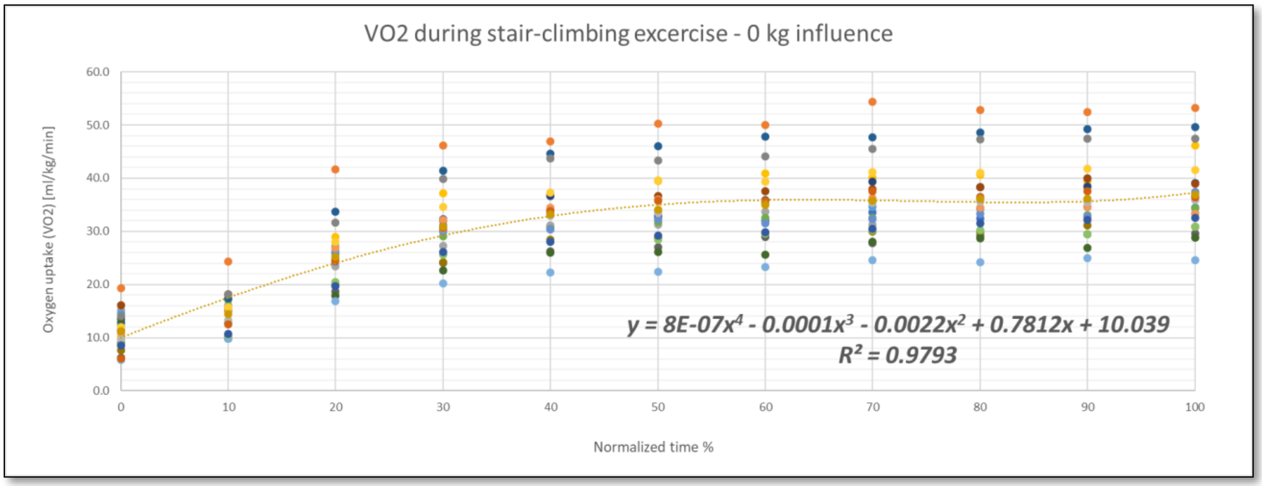
Table 3-7: VO_2 and HR comparison resulting from laboratory experiments

Statistical measurements	**0 kg**		**8 kg**		**Increase 8 kg/0 kg**	
	VO_2	HR	VO_2	HR	VO_2	HR
Min	11.21	102.62	13.58	108.35	17.41%	5.29%
Max	37.44	174.84	38.59	178.79	3.00%	2.21%
Average	31.77	158.64	33.13	165.34	4.10%	4.05%
SD	6.87	18.51	6.81	17.68	-	-

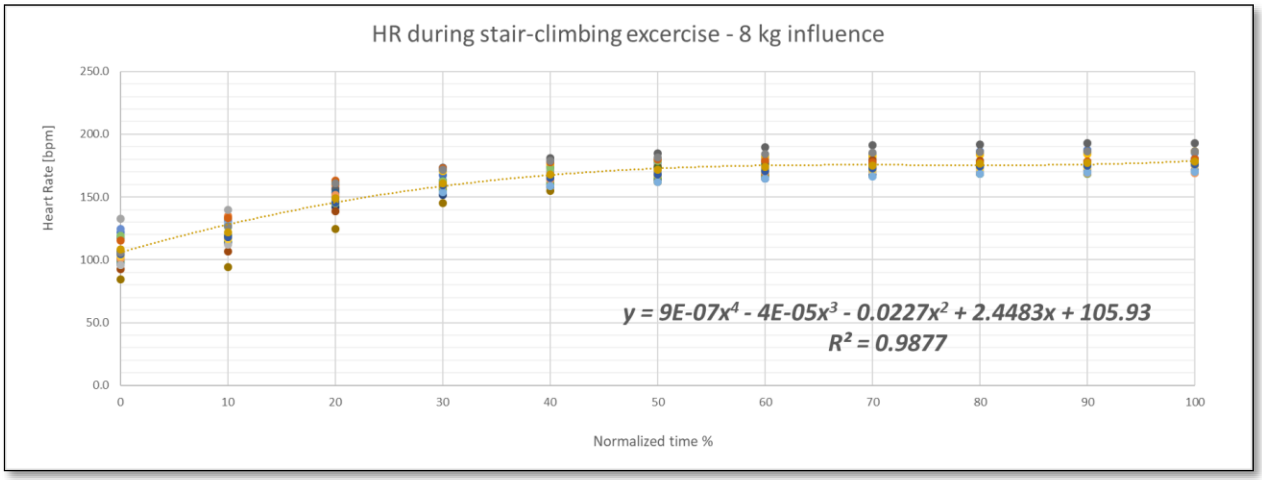
Patterns for VO_2 and HR during the exercise can be found in Graph 3-6 and Graph 3-8for the participant's performance without the backpack and in Graph 3-7 and Graph 3-9 for their performance with the backpack. Patterns observed in a minute-by-minute basis for participant's performance with and without the 8 kg backpack can be found in annex 5.4



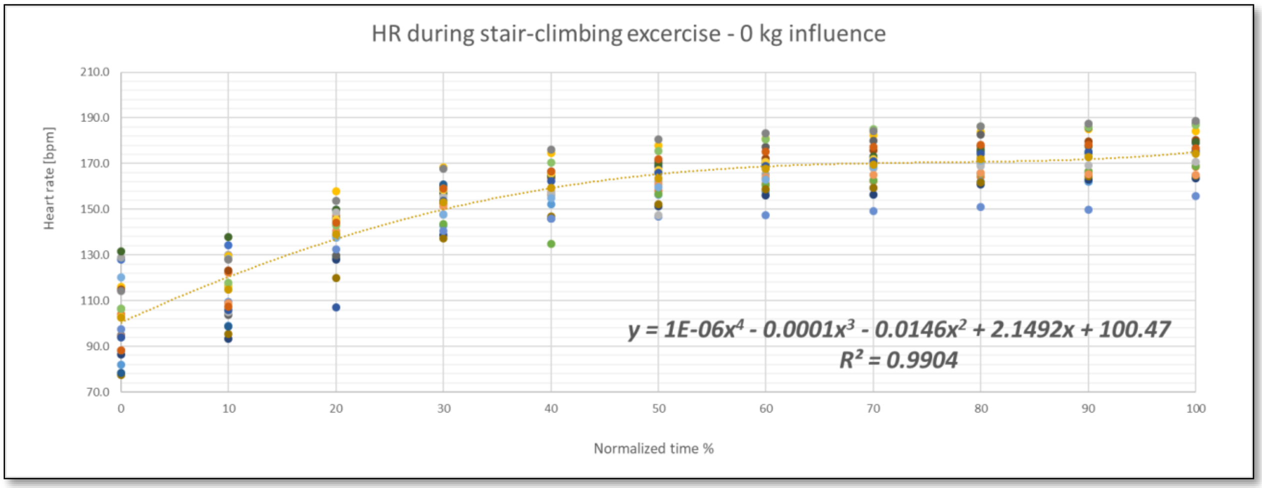
Graph 3-6: Oxygen uptake pattern during stair-climb exercise with the influence of extra weight



Graph 3-7: Oxygen uptake pattern during stair-climb exercise without the influence of extra weight



Graph 3-8: Heart Rate pattern during stair-climb exercise with the influence of extra weight



Graph 3-9: Heart Rate pattern during stair-climb exercise without the influence of extra weight

3.2.4 Metabolic Rate

Bearing in mind equation 2 results for the predicted metabolic rate (W) in section 4.1, a comparison is made with the calculated results out of equation 3.

$$M = 5.874 * (0.23 * R + 0.77) * VO2STPD * 60/ADu \qquad \text{(Eq. 3)}$$

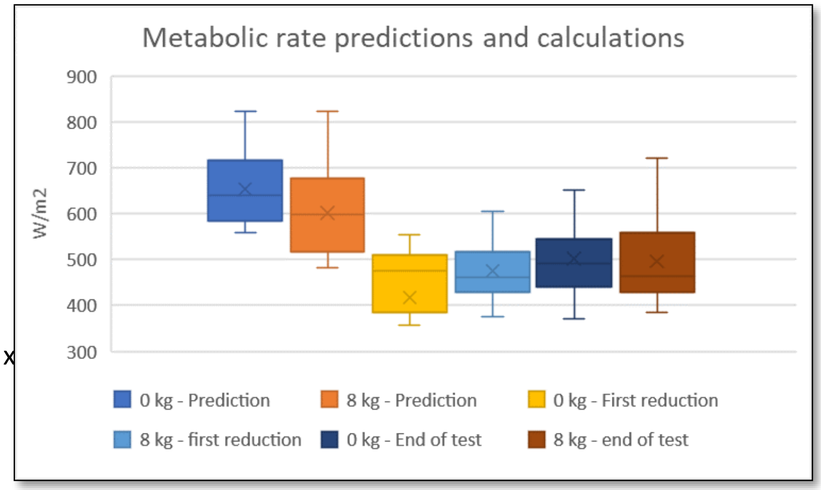
Where:

- R: Respiratory quotient (if R>1, then R=1)
- VO_{2STPD}: Corrected VO_2 [l/min]
- ADu: Body Area [m^2]

Predictions and calculations for the metabolic rate have been made based on each step rate reduction. Graph 3-10 and Table 3-8 show the predicted and calculated values for the metabolic rate after each reduction throughout all off the experimental time (5 minutes); For this selected time, the prediction of the metabolic rate was higher than the calculated value in all cases. When looking at the calculated metabolic rate for the first reduction, it has been found that in average there is a higher M by 1.28% when subjects are carrying a backpack. When looking at the “end of test” calculations in minute 5, it is noticed a reduction of the calculated M. These values must be further discussed as several factors influence the calculations for these cases.

Table 3-8: Predicted and calculated Metabolic Rate

Statistical measurement	**Predicted**			**First Reduction**			**End of Test**		
	0 kg	8 kg	%	0 kg	8 kg	%	0 kg	8 kg	%
Minimum	558.66	482.58	13.62%	357.56	376.53	5.04%	369.78	384.90	3.93%
Average	654.02	602.05	7.95%	468.86	474.93	1.28%	501.74	496.41	-1.07%
Maximum	822.15	822.15	0.00%	554.59	604.04	8.19%	702.31	721.02	2.59%
Standard deviation	78.24	93.53		167.22	63.63		86.86	90.44	



Graph 3-10: Metabolic rate - prediction vs calculations

3.2.5 Variable correlations

The Pearson's correlation coefficient (r) has been used to present the relations between the physiological variables found during the experimental phase, and vertical displacements that influence the fire-safety designs.

Table 3-10 shows the results after three groups were determined to look for correlations. Column A shows the correlation between the variables using all the participants results, while column B shows the correlations for the below-average results, and column C shows the above-average results. The average used each variable are shown in Table 3-9.

Table 3-9: Averages and groups used for the regressions

Variable	Average value	N persons below average	N persons above average
Height	173 cm	10	11
Weight	73 kg	13	8
Vertical displacement	85 m	10	11
VO_2	2.63 l/min	11	10

Table 3-10: Correlation results

N	Variables	Pearson's correlation coefficient (r)		
		All subjects	< average	>= average
1	Load/BM vs metabolic rate (M)	0.29	0.52	0.41
2	Load/height vs metabolic rate (M)	0.13	0.15	0.33
3	Load/BM vs vertical displacement	0.28	0.33	0.53
4	Load/height vs vertical displacement	0.09	0.23	0.34
5	Metabolic rate vs vertical displacement	0.30	0.43	0.87
6	BMI vs first reduction time	0.47	0.33	0.49
7	BMI vs Oxygen Uptake (VO_2)	0.39	0.62	0.48
8	BMI vs Heart rate (HR)	0.19	0.28	0.02

The stronger correlation was found between the metabolic rate (M) and the vertical displacement (Vdisp) with an r=0.87; this indicates an increase of the energy expenditure when the subjects reached a higher position in the vertical direction. Meanwhile, the lowest correlation was found between the BMI and the HR, with an r=0.02. An interesting result can be found in correlation #3, where it can be seen that the impact of carrying weight, is higher for the participants carrying the 8 kg backpack that have a BM above the average, in comparison to those with a BM lower than the average. Further studies can include correlations divided by sex, age, fitness conditions, etc.

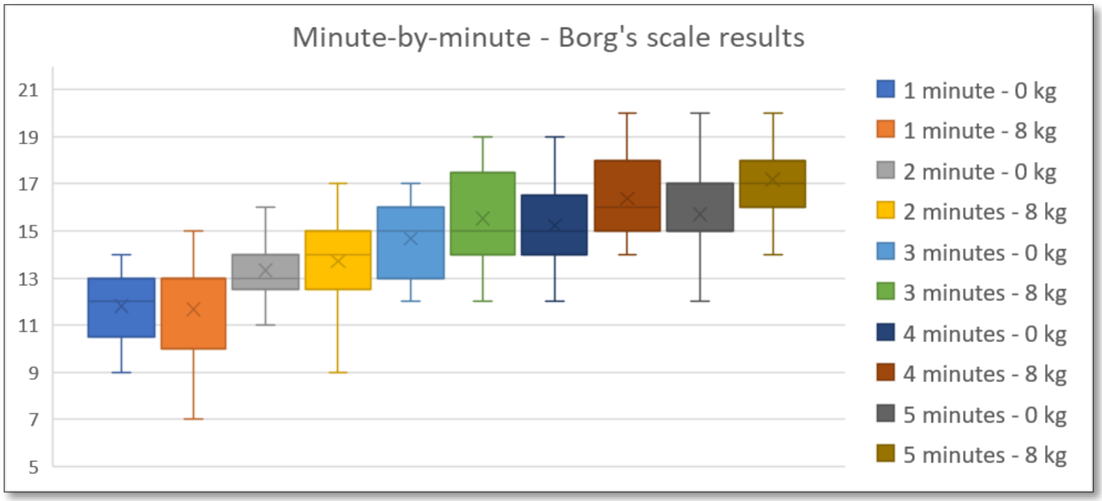
3.2.6 Borg's scale

For this set of results, minute-by-minute values are taken for both experimental configurations (0 kg and 8 kg). It was found that the Mode is the most representative statistical measurement to evaluate the participant's perception of fatigue.

During minute 1 and 2 of the stair-climbing exercise for both experimental conditions (0 kg and 8 kg), the most repeated value indicated by participants did not remarkably change and it remained in 13 of the Borg's scale, corresponding to a "somewhat hard" verbal anchor; during minute 3, the perception increases to a general 15 in the Borg's scale for both cases (0 kg and 8 kg), regarding the verbal anchor indicator, this represents a "Hard (heavy)" representation of the perceived exertion. Differences in between the influence of the 8 kg backpack start to be notorious at minute 4, when the perceived fatigue consensus is 16 of the Borg's scale, in contrast with the value of 15 of the Borg's scale noted without the influence of the backpack, this corresponds to a verbal anchor in between "Hard (heavy)" and "very hard" for the task including the 8 kg backpack. At minute 5, the general perception of fatigue reaches 18 of the Borg's scale for the set-up with a backpack, corresponding to a verbal anchor in between "very hard" and "extremely hard" for this task, meanwhile it remains steady in 15 of the Borg's scale when participant's performance is not influenced by the external weight. Table 3-11 shows more details about the distribution of values with minute-by-minute measurements for the perceived exertion using the RPE Borg's scale.

Table 3-11: Borg's scale rating results

Time		**1 min**		**2 min**		**3 min**		**4 min**		**5 min**	
Weight		0 kg	8 kg	0 kg	8 kg	0 kg	8 kg	0 kg	8 kg	0 kg	8 kg
min		9	7	10	9	12	12	12	14	12	14
max		14	15	16	17	19	19	19	20	20	20
Mode	Value	13	13	13	13	15	15	15	16	15	18
	# repetitions	8	10	6	5	7	7	5	6	8	6
	%	38	48	29	24	33	33	24	29	38	29
SD		2	2	2	2	2	2	2	2	2	2



Graph 3-11: Minute-by-minute Borg's scale ratings during experimental sessions

4. Evacuation modelling

A case study is developed to demonstrate the implications of fatigue on evacuation modelling. This was conducted using Mass motion as modelling tool example, as it uses the continuum approach into macroscopic modelling, which focuses on the behavior of pedestrian flows, with high applicability to large crowds (Xia et al., 2009). MM is a commercial model that has been involved in several projects of large scale, such as the full-scale simulation of the 15-minutes of the peak hour predicted for 2021 for Toronto's busiest metro stations: Union Station. The applicability of MM for metro-stations, its reliability and accuracy challenged several times (King et al., 2014), makes clear the motivation to use this modelling package for the develop of this thesis.

The geometry is based on the characteristics of the T-Sofia metro station, which nowadays is planned to start the constructions between the year 2018 and 2019 in Stockholm, Sweden. This metro station will be located under Saltsjön, and will be constructed entirely through rock (Aspengren, 2014). As clarification, T-Sofia vertical distance of 100 m is just taken as a reference of a scenario which is qualifies for a "deep metro station"; the actual egress means of T-Sofia are not discussed or taken into consideration for this thesis as it is out of the scope of this thesis; from this point of the thesis onwards the scenario based on T-Sofia dimensions will be named as "deep station"

4.1.1 Geometrical description

Three geometries were used to exemplify the differences of results when applying different walking speed distributions, these geometries are based on: 1) Vastra Skogen (33 m), 2) Deep station (100 m), and 3) hypothetical scenario (4 section). For all geometries the width of stairs is set as 1.2 m, the inclination of the stair is 30 degrees, and a group of 21 persons is considered (Ronchi et al., 2015). Geometries 1 and 2 consist of two levels connected via one escalator, meanwhile, the third geometrical configuration is proposed in line with the vertical displacements and diagonal speed components found after the laboratory experiments, when participants lowered the step-rate of the stair machine.

The configuration for the hypothetical scenario, consists in 4 shorter escalators, linked by 3 resting planes of 1.7 m, where each section had different velocities; such velocities are shown in section 3.2.2. it must be stated that the hypothetical case aims to show the differences in the evacuation times when compared to a benchmark case (field experiments parameters), this case does not intend to be an optimal design as it is taken from a controlled individual experiment, without considering group behaviour during a stair-ascent evacuation. Table 4-3, show the dimensions used for this scenario and Figure 4-1 shows the model used in MM for the simulations.

A total of 3 scenario configurations were examined within each geometry: 1) Default parameters in MM, 2) Laboratory experiments (0 kg and 8 kg) from the present work, and 3) Field experiments with no influence of additional weight (Ronchi et al., 2015) It is noted that for the current architectural plans, no escalator is considered accessing the station; in contrast, large express lifts are proposed to convey passengers (Aspengren, 2014); however for this research, a conservative approach is introduced by describing a worst-case scenario, stopped escalators are the only option for safe egress.

Each case was ran multiple times according with a proposed procedure to find the optimal number of simulation runs and investigating behavioural uncertainty, with a predefined acceptance criterion of 3% (Ronchi et al., 2014); A total of 310 runs were made, the resulting number of simulation runs per scenario can be found in Table 4-1. Table 4-2 shows the dimensions used for each scenario. Figure 4-2, and Figure 4-3 show the dimensions used in MM.

Table 4-1: Number of simulations ran per scenario

Scenario		**Default parameters**			**Laboratory experiments**		**Field experiments**
Parameter		Fruin	Small luggage	Adult with child	No backpack	Backpack	No backpack
Runs	**Deep station**	5	8	11	23	18	9
	Vastra Skogen	31	20	3	35	38	16
	Proposed scenario	7	7	24	8	8	39

Table 4-2: Dimensions used for the geometrical representation 1) Vastra Skogen (33 m), and 2) Deep station (100 m).

Geometry	**Deep station**	**Based on Vastra Skogen field experiment**
Vertical	100 m	33 m
Horizontal	173.2 m	66 m
Diagonal	200 m	73.8 m
Angle	30 degrees	30 degrees

Table 4-3: Dimensions used for the geometrical representation 3) hypothetical scenario (4 sections) based on the laboratory experiment

Geometry	**First escalator**	**Second escalator**	**Third escalator**	**Fourth escalator**
Vertical	42 m	18 m	18 m	22 m
Horizontal	72.75 m	31.18 m	31.18 m	38.11 m
Diagonal	84.00 m	36.00 m	36.00 m	44.00 m
Angle	30 degrees	30 degrees	30 degrees	30 degrees

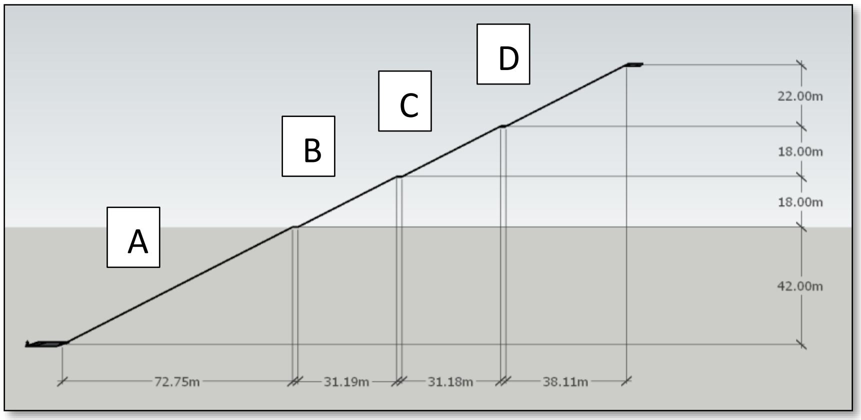


Figure 4-1: Geometrical representation of 3) hypothetical scenario (4 sections)

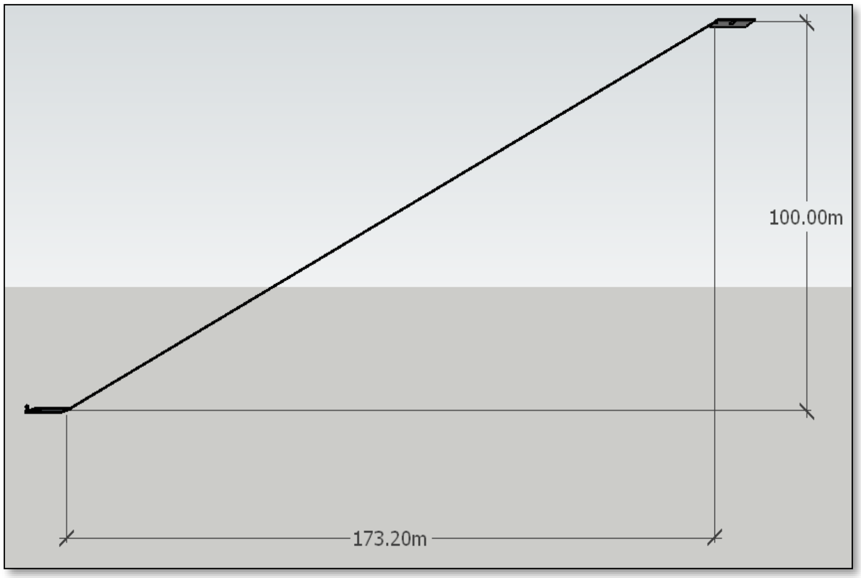


Figure 4-2: Geometrical representation for 2) Deep station (100 m)

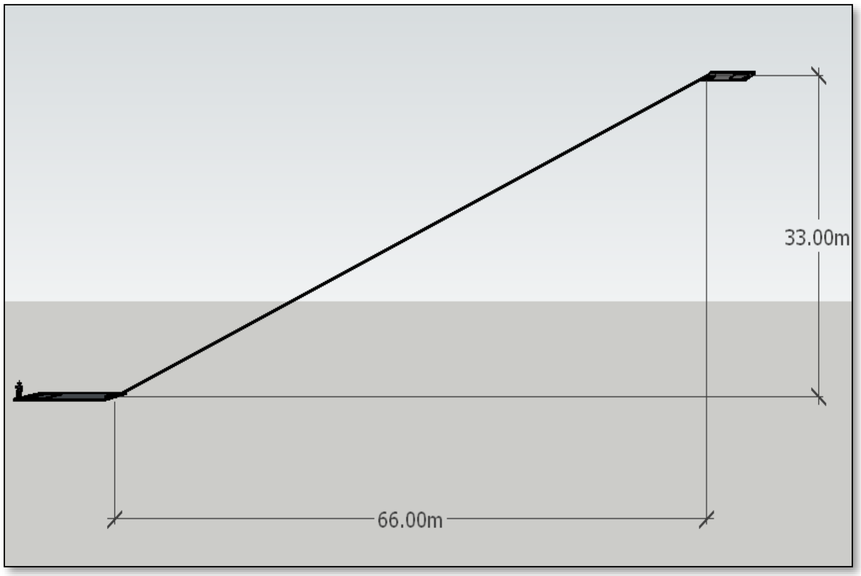


Figure 4-3: Geometrical representation for 1) Vastra Skogen (33 m)

4.1.2 Agents characteristics

The agent's characteristics taken for the default scenario are extracted from Table 1-2. The selected profiles are: 1) Fruin commuter, 2) Small luggage, 3) Adult with child. The first profile represents the experimental set-up where no backpack is carried by the participants, contrary to the second and third profile that represents the experimental set-up with participants carrying the 8 kg backpack. Table 4-4 show the component of speed used during the simulations in Mass Motion, meanwhile Table 4-5, shows the speed component used for each stair section for the proposed scenario based on the laboratory results; Taking Figure 4-1 as reference, a speed of 0.45 m/s is set for section A, 0.42 m/s for section B, 0.43 m/s for section C, and 0.42 m/s for section D.

Table 4-4: Agent speeds selection for evacuation simulation in MM

Scenario	Code	Walking speed distribution	Agents speed's component [m/s]			
			Min	Max	Average	Standard deviation
Default settings	D-1	Fruin commuter	0.65	2.05	1.35	0.25
	D-2	Small Luggage	1.1	1.9	1.53	0.13
	D-3	Adult with Child	1	1.9	1.37	0.15
Application of laboratory results with default settings	Lab1	Backpack – Lab results	0.29	0.64	0.43	0.08
	Lab2	No backpack – Lab results	0.37	0.64	0.48	0.07
Vastra skogen (group experiments)	FieldEx	No Backpack – Field experiment	0.44	0.60	0.52	0.08

Table 4-5: Diagonal component for the proposed scenario based on laboratory results, for each stair section separated by resting planes

	Diagonal component of velocity [m/s]			
Section	Min	Max	Average	SD
A	0.32	0.63	0.45	0.078
B	0.29	0.63	0.43	0.26
C	0.40	0.44	0.42	0.03
D	0.29	0.63	0.43	0.08

4.2 Simulations

The simulation results are examined according with the scenario they represent (0 kg – 8 kg), and the analysis is made regarding the evacuation time for a group of 21 persons; however, the simulations serves just as an example on how results change according with the parameters introduced to the tool, in this case, parameters including and excluding the influence of an 8 kg backpack.

Four main considerations must be addressed for the simulations : 1) the number of agents used for the simulations is not representative to a real-life situation under a metro station, where higher densities are expected; 2) the velocity parameters used for the simulations including the laboratory experiment results, are extracted from a healthy and young sample, which is not representative of a heterogenous population nor to the velocities expected for the metro-users; 3) the laboratory experiment present the results for an individual moving upwards in the stair-machine, meanwhile the field experiment show results for a 21-person group, therefore, social influence is not acknowledged for the laboratory experiment, but is still adapted to the condition of the field experiment; and 4) a stair configuration is chosen for the geometry in MM, as this represents better the conditions in the laboratory experiment, where participants performed an upward-motion contrary to the stair-machine downwards movement.

Two groups are made for the simulation analysis: A) No influence of external load (D1, Lab2, and FieldEx), and B) Influence of external load (D-2, D-3, and Lab1). For the first association, default values (D-1) are compared with the ones obtained by the laboratory experiment without influence of additional weight (Lab2), meanwhile a third set values are introduced as result of a field experiment with similar characteristics (FieldEx). For the second association, no field experiment while carrying additional weight has been found in the literature to take as reference, thus 2 different default conditions are evaluated, small luggage (D-2), and adult with child (D-3) and then compared with the laboratory experiment results involving the effect of additional weight (Lab1).

Table 4-6, show the minimum, maximum, average and standard deviations after running the necessary simulations for the Deep station scenario, which required a vertical displacement of 100 m. When comparing the averages of the walking speed distribution for set A, it is observed that the D-1 result for the evacuation time is 59.65% faster than the value obtained from the FieldEx simulations; this corresponds to an earlier evacuation by 9:13 minutes; in contrast with the results from Lab2, that shows a slower evacuation by 10.35% corresponding to a slower evacuation by 1:47 minutes. When examining the results for set B, a similar evacuation times are found between the results obtained for both default cases, differing by 28 seconds; in contrary with the difference between the previously mentioned results and the evacuation time for Lab1, which differs from each other by 13:04 minutes. When comparing both experimental results each in set A or set B, it is observed an increase of 2:13 minutes in the evacuation time when the external load is applied. More comparative results can be found in Table 4-9.

Table 4-6: Evacuation time (hh:mm:ss) for the scenario based on a Deep metro station dimensions

	Set	Scenario	Min	Max	Average	SD	TETconv	Sdconv
Deep station [100 m]	A	D-1	0:04:05	0:08:44	0:06:14	0:01:19	1.89%	1.16%
		Lab2	0:13:26	0:18:57	0:17:14	0:02:18	1.40%	1.36%
		FieldEx	0:13:03	0:16:26	0:15:27	0:00:50	1.81%	1.74%
	B	D-2	0:04:34	0:05:54	0:05:28	0:00:25	1.83%	1.09%
		D-3	0:04:52	0:06:17	0:05:56	0:00:20	1.95%	1.47%
		Lab1	0:13:19	0:23:17	0:19:27	0:03:12	0.74%	6.53%

Table 4-7, show the minimum, maximum, average and standard deviations after running the necessary simulations for the Vastra Skogen scenario with 21 people, which required a vertical displacement of 33 m. When comparing the averages of the walking speed distribution for set A, it is observed that the D-1 result for the evacuation time is 58.58% faster than the value obtained from the FieldEx simulations; this corresponds to an earlier evacuation by 3:18 minutes; in contrast with the results from Lab2, that shows a slower evacuation by 8.15% corresponding to a slower evacuation by 30 seconds.

When examining the results for set B, a similar evacuation times are found between the results obtained for both default cases, differing by 6 seconds; in contrary with the difference between the previously mentioned results and the evacuation time for Lab1, which 3.41 times larger showing a different between them of 5:07 minutes. When comparing both experimental results each in set A or set B, it is observed an increase of 1:06 minutes in the evacuation time when the external load is applied. More comparative results can be found in Table 4-9.

Table 4-7: Evacuation time (hh:mm:ss) for the scenario based in Vastra Skogen dimensions

	Set	Scenario	Min	Max	Average	SD	TETconv	Sdconv
VASTRA SKOGEN [33 m]	A	D-1	0:01:41	0:03:04	0:02:20	0:00:20	1.42%	2.11%
		Lab2	0:04:17	0:06:53	0:06:08	0:00:37	2.06%	1.24%
		FieldEx	0:04:42	0:05:58	0:05:38	0:00:20	1.11%	2.88%
	B	D-2	0:01:28	0:02:15	0:02:01	0:00:12	2.95%	2.30%
		D-3	0:01:33	0:02:13	0:02:07	0:00:09	1.76%	0.08%
		Lab1	0:05:00	0:08:55	0:07:14	0:01:05	0.98%	1.23%

Table 4-8, show the minimum, maximum, average and standard deviations after running the necessary simulations for the deep station scenario, which required a vertical displacement of 100 m divided in 4 sections. When comparing the averages of the walking speed distribution for set A, it is observed that the D-1 result for the evacuation time is 58.12% faster than the value obtained from the FielEx simulations; this corresponds to an earlier evacuation by 8:46 minutes; in contrast with the results from Lab2, that shows a slower evacuation by 14.22% corresponding to a slower evacuation by 2:30 minutes. When examining the results for set B, similar evacuation times are found between the results obtained for both default cases, differing by 28 seconds; in contrary with the difference between the previously mentioned results and the evacuation time for Lab1, which 3.5 times larger showing a different between them of 14:15 minutes. When comparing both experimental results each in set A or set B, it is observed an increase of 3:20 minutes in the evacuation time when the external load is applied. More comparative results can be found in Table 4-9.

Table 4-8: Evacuation time (hh:mm:ss) for the proposed scenario based on the laboratory results

	Set	Scenario	Min	Max	Average	SD	TETconv	Sdconv
PROPOSED SCENARIO (4 SECTIONS)	A	D-1	0:04:26	0:09:15	0:06:19	0:00:57	0.36%	0.38%
		Lab2	0:12:04	0:18:47	0:17:35	0:02:25	1.61%	1.50%
		FieldEx	0:12:28	0:16:07	0:15:05	0:01:10	2.28%	1.42%
	B	D-2	0:04:15	0:05:55	0:05:30	0:00:24	0.16%	0.90%
		D-3	0:05:00	0:06:41	0:05:58	0:00:28	0.91%	1.29%
		LE-B	0:12:28	0:24:54	0:20:55	0:03:41	2.65%	1.52%

The times obtained through the simulation using the parameters from the field experiment, have been taken as the benchmark case to compare the rest of the results, due its similarity with a real-life scenario where a 21-person group performed an ascending evacuation in Vastra Skogen metro station (33 m); this results must be used only as comparative study which aims to compare how different parameters affect the simulations results, as the other conditions (default parameters and laboratory experiments) do not consider the same evacuation conditions as the field experiment.

The obtained values are shown in Table 4-9. In general, the results obtained by applying the default MM parameters represent a faster evacuation by 61.46% when compared with the benchmark case; meanwhile when applying the parameters obtained from the laboratory experiments, an increased time by 17.22% for both conditions (0 kg and 8 kg), however, it is observed that the evacuation times increase in 23.52% when the influence of the additional 8 kg is applied to the simulation.

Table 4-9: Comparative results taking field experiment (FE-NB) as benchmark case, default parameters are shown as "faster evacuation" and laboratory experiment parameters are "slower evacuation"

	Benchmark case - Field experiment	**Default MM parameter**			**Laboratory experiment parameters**	
Scenarios	FieldEx	D-1	D-2	D-3	Lab1	Lab2
T-Sofia (100 m)	0:15:27	59.65%	64.62%	61.60%	10.35%	20.57%
Vastra skogen (33 m)	0:05:38	58.58%	64.20%	62.43%	8.15%	22.12%
Hypothetical case (4 sections)	0:15:05	58.12%	63.54%	60.44%	14.22%	27.89%
Average	-	58.79%	64.12%	61.49%	10.91%	23.52%
	-	61.46%			17.22%	

Figure 4-10 shows the agent speed ratio graph, exported from MM for a Lab2 scenario considering Vastra Skogen as the geometry. The agents are numbered from 1 to 21 in the Y axis, and the simulation time is indicated in the X axis; The graph indicates the speed of each agent by a color scheme (Table 4-10) and it aims to shows the speed adjustments that each agent makes from the beginning of the simulation, until they reach a stablished exit point.

Table 4-10: Color scheme to interpret Agent speed ratio MM Graph

Color		**From**	**To**
Blue	🟦	1 m/s	∞
Sky blue	🟦	0.55 m/s	1 m/s
Green	🟩	0.45 m/s	0.55 m/s
Yellow	🟨	0.35 m/s	0.45 m/s
Orange	🟧	0.25 m/s	0.35 m/s
Red	🟥	-∞	0.25 m/s

Within the resulting graph, four zones are pointed out; zone 1 shows that agents 1-3 increased their velocity around minute 2, then they kept the same pace to only increase it around minute 19; zone 2 shows that agents 4-10 increased their velocity twice, once around minute 1 and the other around minute 2; agents 11-13 in zone 3 made several adjustments to their velocities between 2:30 minutes and 18:00 m minutes; and zone 4 shows agents 14-20 keeping the same velocity until the simulation ends.

When looking at the evolution of agent 8, marked with a blue arrow, it shows an initial velocity increase 1:30 min, a second increase at 2:00 min, and a decrease at 2:40 min maintaining this average velocity until finishing the travel time.

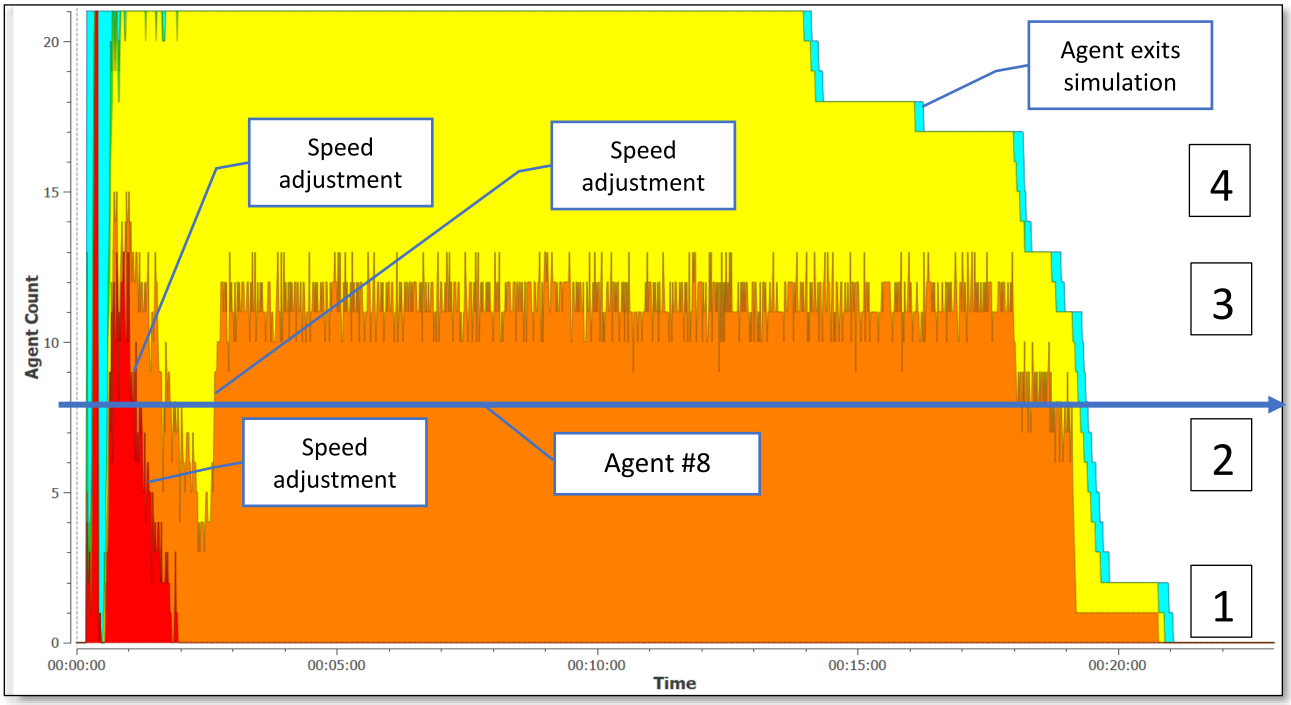


Figure 4-10: Agent speed ratio Graph - Vastra Skogen scenario - Walking distribution profile: LE-NB

5. Discussion

This section of the thesis serves as a discussion based on the results obtained during the different phases of the research work. The following order is trailed: 1) Limitations, 2) Laboratory experiment, 3) Evacuation simulations, and 4) future research.

The present study provides valuable information regarding the effects of applying external load to people while they are performing a stair-ascent motion. One central feature of the research is that methodology followed throughout the research, is based on previous and recent studies, whom main researchers served as supervisors during the development of this study. Several limitations regarding the methodology are present and affect the results and interpretation of the obtained data.

Sample characteristics – It is important to consider the sample's characteristics; the sample was formed by a young and healthy population, which can be considered as non-representative of the metro-user population. Participants were asked about their general health before enrolling the experimental sessions; for instance, participants with heart conditions or asthma were not allowed to enroll the experiment; again, this is not an accurate representation of real conditions for metro users where medical conditions can influence their performance while trying the evacuate. Participants were either fire-safety engineering students or acquaintances of the main researcher, which also influenced the age distribution and the fitness level of the studied population; this also suggests that the sample was more likely to have knowledge regarding evacuation and human behavior in fire than the general public. An additional factor to consider is the sample size; a total of 21 subjects were recruited as a sample-size calculation was not reasonable to apply since it would consider an estimate of the total number of metro-users, resulting in sample size outside of the feasible scope of this thesis framework, however this influences the representativeness of an expected population in metro stations, therefore this paper must be analyzed as an hypothetical case example with specific conditions and not to make conclusions for a broader application.

Pre-experimental conditions - Participants were asked to wear sports outfits, emphasizing comfortable shoe wear; they were also asked to avoid drinking coffee at least 3 hours before the sessions, and to avoid major physical activity that may create discomfort or could modify their normal performance. A limited number of research work was reviewed before the laboratory experiments; these researches show that several variables used for this thesis, have been measured individually but not as a whole. For instance, backpacks have been included into stair-ascent gait analysis (Hong and Li, 2005); energy muscle demand has been measured through EMG tests, (Moffet et al., 1993); a fit-sample was used to measure the energy expenditure while walking in the same level (Pandolf et al., 1977); this limitation affects the attempts to find general trends in how population's performance is affected by carrying weight during stair-ascent evacuations, as it is difficult to make direct comparison with previous researches.

Experimental set-up - To measure the oxygen consumption during sessions 2 and 3, participants were required to use a strap-on face mask connected to the main device; after the experimental sessions, most of the participants expressed negative opinions about it, indicating a level of discomfort due to the "lack of oxygen" or by feeling "limited to inhale as much air as they would normally do"; this condition could serve as an imitation of a fire scenario, where the available oxygen is gradually replaced by the smoke. The experiments also required to carry an 8 kg backpack, which, due to its characteristics, is not an actual representation of reality; for instance, participants were able to re-distribute the load by strapping the backpack in their hips and chest; again, this is not a reality for all metro users, where people can carry weight with one shoulder or with one hand (e.g. women with purses). The effects of using a stair-machine is also a limitation to obtain ecological results; the participants were not allowed to choose their own climbing step rate, this was determined through an initial calculation based on the sub-maximal test results. The stair machine used for the climbing exercise, counts with 20 different speeds with no intermediate levels, meaning that participants are not entirely free to modify their speed according to their needs. The climbing exercise starts at the maximum calculated step-rate, exposing the participants to their theoretical maximum capacity since the beginning of the exercise, when in reality, their climbing speed would be limited by factors like the population density (the more people in the stair, the slower they move towards the exit) and the stair characteristics (e.g. depth, height, inclination). By starting the experiment at the maximum capacity, people are exposed to a situation where their energy expenditure can-not be controlled by themselves, contrary to a real-life situation where they can evaluate and readjust according to their needs; this also is influenced by the 2-minutes threshold at the beginning of the experiment, where participants are not allowed to reduce the speed, forcing them to maintain a non-natural step-rate against what could be their natural response to such scenario.

Modelling ascending evacuations – For this part of the thesis, the reader must consider the assumptions used during all the simulation phase, starting by keeping in mind that the evacuation modelling has been made as an exercise, which had the purpose to show how the evacuation times are modified when applying different parameters; for these specific cases, the parameters obtained from the experimental results described in this document were compared to a benchmark case, which parameters are more realistic as they were obtained from field experiments, and therefore their comparison must be made with especial care, leading the researcher to state that further studies must be made in order to have more reliable data that can serve as the base to a mathematical model that can serve to enhance the evacuation modelling tools capability to replicate human behavior affected by fatigue during a stair-ascending motion. For instance, the parameters obtained from the field experiments (Ronchi et al., 2015) contain values for a group experiment conformed by 21 persons, meanwhile the results obtained in the laboratory experiment are taken from individual results. The radio of the agents remained the same for all agents for all simulations, meaning that there is no distinction between female and male agents, which indicates the use of a homogeneous sample for the simulations, in contrast with the heterogenous one obtained from the field experiment and expected in a real-life situation. The aforementioned number of agents used for the simulations, is an assumption that underestimates the number of possible metro-user, thus it can not be treated as a representation of reality and implies a non-crowed situation, in contrast with the usual circumstances found in a metro station which might include crowding. The values used in Table 1-2 regarding the agent speed selection for the simulations, show high values for the default settings (FC, SL, and AC), and even when the model's documentation does not show any reference about the source of these values, one may speculate they might be taken from the approximation values used un the SFPE Guide to human behavior for stair-climbing speed, showing a speed of 1.05 m/s for a velocity factor K of 1.25 m/s in stairs, therefore, they must be taken as not conservative in case of ascending-stair evacuations. Instead of escalators, a stair configuration is selected as part of the geometrical representation in MM, this is an assumption based on the laboratory set-up that includes a moving stair-machine with a downwards motion, while the test-participants make an ascending motion contrary to the stair-machine; must be mentioned that escalators are not meant to be treated as stairs, as people's performance (e.g. energy expenditure, gait) change according with the height and depth of each step, which are usually larger in the case of escalators, however, MM does not include the "stopped escalator" option as feature, thus stair are considered to be the best approximation.

Submaximal test – To identify the fitness level of each participant, a sub-maximal test with a bicycle ergometer was used; this is a source to biased results as it depends on the individual's physical condition which might be influenced by their preferred type of physical training; for instance, if a person is used to bike on a daily basis, their cardiorespiratory capacity can differ from a person who is not used to it or that focuses on strength-related exercises, therefore, the results obtained with the sub-maximal test, will differ between these two persons. To determine the stair-machine ascending step-rate, two values where considered as an input for the prediction formula: 1) participants body weight, and 2) participants body weight + 8 kg; The second calculation introduces a bias as during the sub-maximal test, the participants were not given the 8 kg backpack, thus, it is the work for future researches to determine if by doing two separate sub-maximal test the results vary considerably, according with the pre-stablished conditions. An error might be introduced in the resulting prediction from the sub-maximal test, as this is based on a $VO_{2max=100\%,}$ meanwhile in the reference research, this was commonly taken between 90-95%.

Stair-ascent exercise – This section of the discussion is divided in the main aspects evaluated during the experimental phase. The division goes as follow:

- Velocities/displacements: For both experimental conditions, without and with backpack, all participants were able to maintain the step-rate for the first 2-minutes of the data gathering threshold, however, one must keep into consideration that participants were told to not lower the step rate during this time threshold; in reality, people might adjust their velocity before reaching the 2-minutes limitation. Differences on the performance appeared, in average, after 3:02 minutes of the ascending exercise. For instance, during the session not involving the use of the backpack, 13 participants could finish the 5-minutes exercise at $VO_{2max=100\%}$ with RPE Borg's scale average value of 15, in contrast with their performance while carrying the backpack where only 3 participants could reach the 5-minutes goal without reducing the step rate and an average of 18 in the RPE Borg's scale. For the experimental session involving the influence of the weight, the final average velocity was 0.48 m/s (SD=0.07) and the average vertical displacement was 84.52 m (SD=15), in comparison with the experimental session without the backpack which was 0.43 m/s (SD=0.08) and 92 m (SD=14) as vertical displacement, this corresponds to a reduction of 10.42% in terms of velocity-performance and a reduction of 8.52% for the vertical displacement, when comparing the influence of external load at the end of each session. Different values were obtained in the reference research (Halder, 2017; Ronchi et al., 2015) were subjects reached an average of 109 steps/min (diagonal component = 0.59 m/s) and a vertical displacement of 95 m for an ascending time of 4.32 min at $VO_{2max=90\%.}$

- Borg's RPE scale: Recalling the pre-stablish threshold from 14 to 17 (section 3.1.3) when looking at the values expressed during the "no backpack session", only 2 persons indicated a RPE value higher than 17, corresponding to a perception in between "very hard" and "extremely hard", in contrast with 9 participants expressing values above 17 during the "backpack session", with 4 of them indicating 19 as the final number, which corresponds to an "extremely hard" perception of exertion. Values above 17 in the RPE scale started to appear after 3 minutes of the ascending exercise while participants where carrying the backpack, and after minute 4 without the influence of the backpack. For both results, high results for exhaustion are perceived by people. Even when most of the participants managed to finish the 5-minutes task, when examining the results from an ethical point of view, engineers must keep in mind the persons below the average who would not be able to complete the task if they do not count with the necessary means (e.g. resting planes, shorter vertical displacements) and the success of the design must also consider the metro-users experience while evacuating the station.

- VO_2/HR/M: In order to obtain the RPE during the stair-climbing exercise, participants were asked every 60 seconds and every time they required a step rate reduction; it was noticed that during the participants reply, the oxygen consumption measurement peaked seconds before their answer, as they take a longer inhalation before speaking; during this moment, participants were also distracted from their activity, which influenced their climbing strategy. At some points, during the RPE-reply, participants tripped due to distraction, altering the VO_2 measurement. For the experimental session involving the influence of the weight, the final average VO_2 was 33.13 mL/kg/min (SD=0.56), in comparison with the experimental session without the backpack which was 31.77 mL/kg/min (SD=0.55), this corresponds to an increase of 4.10% in terms oxygen uptake when comparing the influence of external load at the end of each session. When looking at the heart rate measurement results, the final average HR was 165.34 bpm (SD=8.78), in comparison with the experimental session without the backpack which was 158.64 bpm (SD=6.44), this corresponds to an increase of 4.05% in terms of heart rate influenced by carrying additional weight. In the reference research, the average maximum value for the VO_2 was 43.9 ml/kg/min (SD=7.8), while the maximum average for the HR was 184.9 bpm (SD=12.2) at a $VO_{2max=90\%}$, meanwhile the average maximum values for this thesis are 37.4 ml/kg/min (SD=7.28), 174.5 bmp (SD=8.8) without the influence of the additional weight, and 38.12 ml/kg/min (SD=7.21), 187.5 bmp (SD=6.67) when carrying extra weight; it must be pointed out that the reference research had a stair-machine level average value of 13 (SD=2) and participants were not allowed to reduce the step rate, differing with this research where reduction was allowed indicating a final stair-machine level average of 10 (SD=2) without the backpack and 8 (SD=2) while carrying the backpack. During the experimental sessions, a decrease of the oxygen uptake was observed every time the participants asked for a speed reduction, this was not the case with the heart rate, which did not decrease at the reduction moment, but showed an incremental tendency. Regarding the Metabolic rate, the maximum value obtained for the non-additional weight session was 702 W/m^2 (SD=87), and 721.02 W/m^2 (SD=90.44) for the session influenced by the additional weight; while in the reference research, the maximum average value varied in between 500 and 600 W/m^2. After the experimental sessions, several participants indicated an increased difficulty for their calves' muscles when the step rate was reduced, this may have an explanation with the sudden change in the gait cycle regarding the swing phase; when the individuals reduce the step-rate, they would also wait longer for the new foot placement while performing a pull-up motion with the opposite foot, which has already undergone the weight-acceptance phase, bearing all the load by itself. It was noted that only 2 participants did not used the handrails while climbing; this could be due to the sense of security that holding the handrails can offer while climbing a moving surface, especially when the velocity is not modified by the participants according to their needs, but by the researcher after the sub-maximal calculations; the handrails were also used to redistribute the load while climbing, especially around minute 3. This observation must be taken specifically for this experiment with a moving walking-surface, as for stairs or stopped escalators, people might use the handrail in a different way. The influence of the participants weight and height is also a factor to consider; for instance, taller participants may perceive the climbing task as easier than shorter subjects, this can be interpreted as the additional effort shorter participants must make with their legs to lift their body and achieve the same displacement in the pull-up motion that the stair height requires. A similar interpretation can be made with participants with a higher body mass, whom have to pull-up more weight than other participants with lower body mass. The sub-maximal test results used to calculate the estimation of the initial step-rate, might also influence the energy required to perform the tasks; by starting with the maximum step-rate, participants are not allow to balance their energy since the beginning, but are pushed to maintain the rhythm for at least 2 minutes; in real-life conditions, participants will adapt their speed according to their individual needs, influenced by external conditions (e.g. presence of smoke, presence of others, knowledge of the facilities), this leads to speculate that people might perform better in the long-term, if they are able to modify their speed according with their physiological needs and capabilities since the beginning of the climbing exercise.

Evacuation simulations - Three main geometrical configurations were studied as simulation case study, Vastra Skogen (33 m), Deep station (100 m), and an additional hypothetical scenario with a vertical displacement of 100 m, divided in 4 stair and 3 resting planes, based on the results obtained with the laboratory experiments when participants asked to reduce their step-rate after a 2-minutes threshold indicated by the researcher. Three sets of walking speed configurations were applied, default MM parameters, experimental results speeds (without accounting for people quitting the experiments), and field experiments speeds based on a reference research paper (Ronchi et al., 2015); these parameters were applied to a 21-person group in a 1.2 m wide stair. All the laboratory experiment participants were accounted to calculate the speed component to be used in MM; for instance, during the session involving the 8 kg backpack, only one person was not able to complete the 5-minutes climbing exercise, stopping at minute 3. Therefore, for this participant's speed during the last 2 minutes, an assumption of a 3-level reduction was made, in consistency with the maximum number of reductions requested by the rest of participants that were able to complete the exercise. As mentioned before, the evacuation modelling in this thesis has been made with several parameters as an exercise to show the reader, how the evacuation time changes when applying different values as the diagonal component of the ascending velocity is "affected" by fatigue therefore there is no direct correlation between the field experiment and the laboratory experiment; however when comparing the evacuation time results obtained by applying the laboratory experiment values, it can be noted that they are closer to the benchmark case in comparison with the default parameters of mass motion, yet the aforementioned limitations to the evacuation modelling must be considered.

When comparing the evacuation times, the simulations showed a better approximation between the times obtained by applying the laboratory results and comparing them with the field experiment results, than when compared with the default parameters of MM, this was observed in the three simulated cases with different vertical displacements in stairs. However, special attention must be directed on the application of the speed component taken from the laboratory results, as this value is based on the average result for 1 person (due to the experimental set-up) not counting with social influences; however when applying the results to a 21-persons group, the ascending speed will be modified by their presence; in order to get results that resemble more a reality, the experiment should be conducted in a real scale, ideally with the same sample under both experimental conditions – influenced and not influenced by additional weight. The results of the present simulation case study should therefore only be considered as an explorative relative comparison between existing model default settings and possible data from different sources of experiments. Nevertheless, given the nature of the experiments and their limitations (e.g. sample type, healthy young fit population, etc.), those results should not be considered of use from a quantitative point of view, as a real case would present a less fit population with a wider age spectrum.

According to NFPA 130:2017, the evacuation time from a station platform must be in 4 minutes or less, by examining the results, it is clearly that this requirement is only achieved in the Vastra Skogen scenario (33 m) when applying the default speed walking distributions of MM; this is not achieved with the field experiment results nor with the laboratory results, giving a first indication of the need to identify design solutions which do not consider such a huge physical strain on people; it is also observed an increase in the evacuation time when there is an application of weight-influenced walking speed distribution, in comparison with the results without the influence of additional weight. When plotting the agent speed ratio graphs for all scenario, none of these showed a speed adjustment considering the travelled distance by applying the MM default parameters. This feature needs to be implemented in future evacuation modelling tools. Such feature should possibly include both the reduction of speed due to fatigue, considering stair angle, vertical, and diagonal displacement, as well as a resting parameter, all of them accounting other behavioral aspects as social influence.

An additional hypothetical scenario is proposed for the study of a vertical displacement of 100 m. This scenario considers vertical distances recorded during the experimental phase of this research, specifically the average distances recorded when the participants required a step-rate reduction. An angle of 30 degrees was maintained, as the first vertical distance was set in 42 m, the second and third one were 18 m, and the last one was 22 m (Figure 4-1) however this might not be an optimal design, as before the first reduction request, the participants were already reporting an average VO_2 consumption higher than the maximum predicted with the sub-maximal test, a metabolic rate higher than 400 W/m^2, and a perceived exertion of 15 (or higher) in the Borg's scale, which leads to assume participants were already affected by the physical exertion when reaching to this point, perhaps to levels where recovery is not possible even when resting planes are provided ahead. For an optimal design of stairs, engineers should not only consider the beforementioned vertical distances, but designers must also consider the below-average performances of a more heterogeneous populations that lead to re-calculate the vertical displacements; for instance, a first vertical displacement of 32 m, recorded as the minimum vertical distance from the experiments, could serve to avoid exhaustion in the remaining travel distance. The perception of fatigue must as well be taken into account; from an ethical point of view, it is not ideal to design a solution that implies a possibility of metro-user reaching exhaustion levels before completing the evacuation or at the end, thus, vertical distances must be designed considering other physiological aspects.

5.1 Future research

Several factors serve as limitations for the applicability of the results obtained during the development of this thesis, thus, this section aims to guide the reader on to possible new researches regarding the influence of carrying weight while performing a stair-ascent evacuation in deep metro stations.

- The effects of carrying weight in different stair configurations, including stair height, depth, and inclination. This also applies to the experimental set-up, that in this case involved a stair-machine which resembles more to an escalator than to stairs. The data-gathering process should include a sample with wider spectrum of characteristics, which include age, as well as fitness level, and their career background. The influence of the prediction using a sub-maximal test based on a VO_{2max}=100% is suggested to be verified as it might impact the criteria to select the stair-machine level, and subsequently affecting the participants performance during the first minutes of the exercise.

- Additional indicators of muscle fatigue should also be included in future researches, for instance, EMG data and lactate measurement can be taken following the bases of the methodology shown in this thesis. This additional measurement can be suggested to be taken during a laboratory experiment and/or in real-scale field experiment.

- The impact of additional weight carried by the participants can be normalized in terms of percentage of their body mass, instead of using the same load. For instance, in this research a load of 8 kg was used for all participants, however, this weight is equivalent to the 13.33% of a 60 kg – person body weight, meanwhile it represents 8.9% of the weight of a 90 kg person; this could mean that both participant, even when given the same load, could be performing different according to their individual physiological capabilities. This variable should be further investigated.

- The load configuration must also be considered in future researches to resemble a real situation. For instance, a cross-shoulder bag can be use instead of a backpack, and this will change people's gait while climbing the stairs; another possible scenario is to use a mannequin imitating the shape and weight of a child, this way the gait-pattern change can also be documented and analyzed for further designing applications.

- The present study does not include the modification of mass motion source code, as the focus is on its application rather than its development; however, this is of high importance for designers, thus a comprehensive model must be presented that includes the effects of muscle fatigue for future changes, enhancing the evacuation modelling tool capabilities to resemble people's performance during deep metro evacuations. This model should allow the agents to adapt their speed according to the traveled diagonal and vertical distance, stair/escalator angle, the presence of resting horizontal areas, the stairs characteristics and the diverse metro-users characteristics, all under social influence instead of individual performance as limited by this research methodology.

6. Conclusions

Considering the aims and objectives stablished in section 2.1, the following conclusions are presented:

- The difference in people's performance while influenced by external weights, was measured through an experimental set up, by recording the oxygen consumption, heart rates, and energy expenditure (as physiological aspects), and with the RPE Borg's scale for the perceived exertion (as psychological aspect). The upper and lower limits for these measurements showed a decrease in the participants performance when they were given the additional weight, leading to conclude that the performance of people is affected negatively by the additional weight they are carrying, proving that this factor should be used in the fire-safety field when designing evacuation routes in deep metro stations.

- The relation between the perceived exertion and the acceptable exertion during an evacuation, should be considered by the designers when planning evacuation routes. Ethical aspects should be included, and metro-users should be given evacuation means that allow them to find a safety place without reaching the limits of their physiological capabilities. The success of an evacuation is a combination of the optimal usage of means and the users interaction and response with those provided means.

- Based on the laboratory experiments, the negative effect on the additional weight has been confirmed, showing a need to include these effects into the evacuation simulation tools modelling; this can be done by allowing the agents to modify their speed considering the travelled distances. The resulting values from the laboratory experiment, also show that the average of the sample is not the most appropriate statistical measurement to use, as it discards the bellow-average results for people that are not in the same fitness state than the average; this means that escape route design for deep metro evacuations must consider the 25th percentile of the sample.

- For the design, factors like the presence of resting planes and handrails must be included; the resting planes represent a change in the activity that leg muscle have to fulfil, this can be interpreted as a mini-rest for the muscle and will help the metro-user to momentarily recover from the repetitive motion of stair-climbing; handrails are used to change the load distribution. The importance of these factors relies on the change of physiological response and modification of the gate pattern that influence the success or failure of an evacuation design.

- The results obtained from this set of experiments, should be taken only as a reference to observe the differences on people performances during stair-ascending evacuations while carrying weight; the results obtained from the research are not to be used as designing values due to its many limitations, including lack of social influence, the use of an artificial environment, and the limited variability in the participant's characteristics (e.g. age, weight, fitness, academic background). More field research must be made to propose a mathematical model, that can include the effects of fatigue into the source codes of the engineering evacuation modelling tools.

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Annex 1: General information, informed consent, health declaration and final questionnaire.

International Master's in science of Fire Safety Engineering

Project: Experimental Evaluation of the Implications of Fatigue During the Evacuation of Deep Metro Stations

Institution: Lund University

Researcher: Alejandra Velasco

Background and objectives

The purpose of the thesis is to determine how performance during ascending stair evacuations is affected by exertion while evaluating two different conditions: carrying weight, and without carrying weight. This will be done by (i) measuring the oxygen uptake and the heart rate of the participants during the experiment and (ii), by measuring the perception of fatigue in different stages of the experiments. The experiments will be performed in three days agreed between the researcher and the participants.

Scenario

"Picture yourself on a platform in a metro station waiting for your train to take you home. You are 100 meters underground and suddenly you hear the fire alarm going off. A voice message starts playing mentioning the need to evacuate the metro station. You follow the indicated path until reaching the base of a stopped escalator. You start ascending towards the exit"

Experimental conditions, procedure and measurements

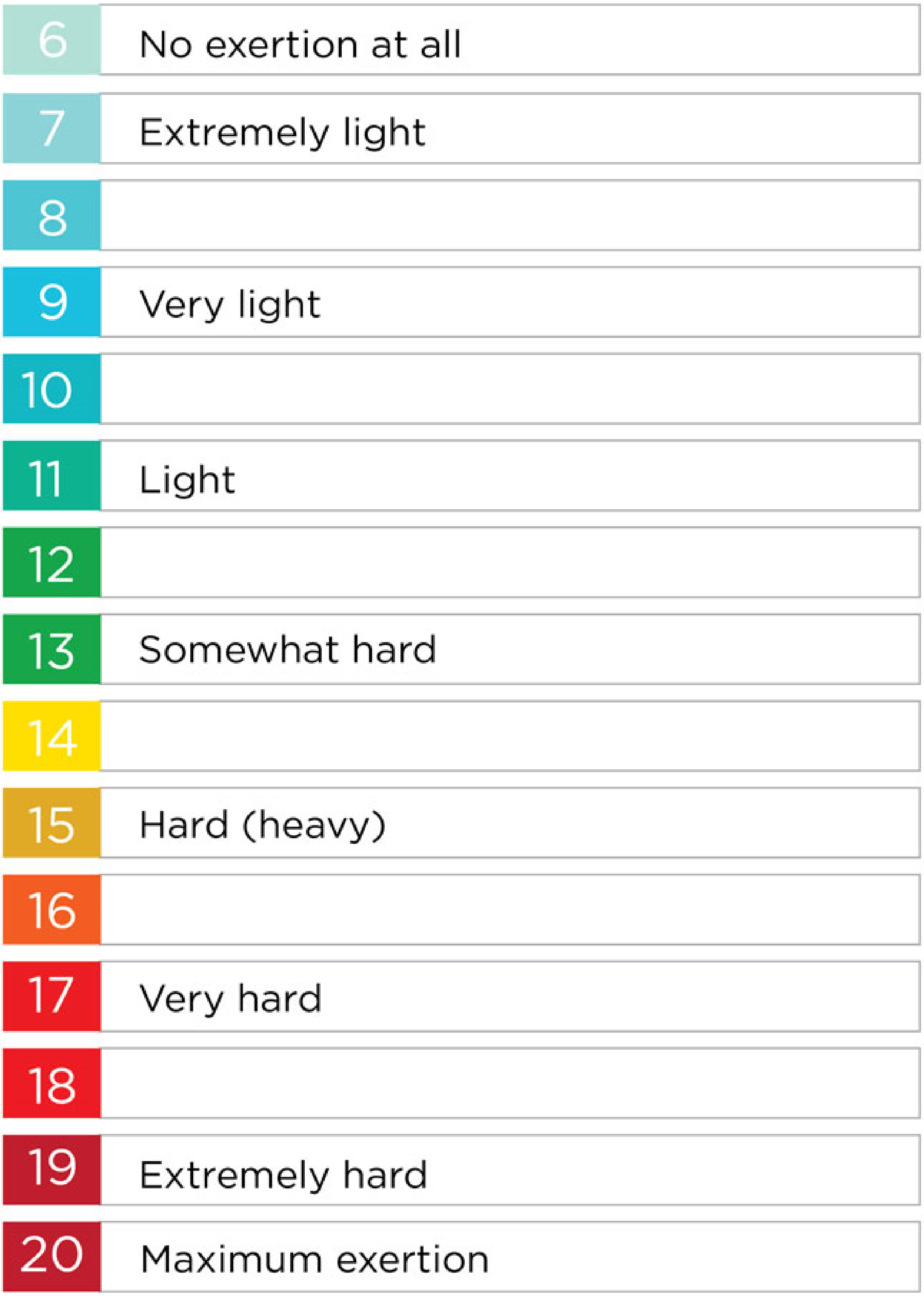
In order to be enrolled as a test person, you should be clinically healthy (e.g. absence of known cardiovascular, pulmonary, metabolic diseases and/or injuries). During session 1: you will perform a test on a cycle ergometer with purpose to calculate step rate at which you will not reach fatigue during the consequent experiments.

If you chose the "individual" modality for the session, you will use a stair machine for 320 seconds while carrying an 8kg backpack. For session 3, you will do as in session 2 but without carrying the backpack. Be aware that during sessions 2 and 3, you can slow down the stair machine as you consider necessary if level 14 in the Borg's scale has been reached. Every time you reduce the step rate, you will be asked to indicate the level of exertion a scale from 6 to 20. This cycle will be repeated until reaching 320 seconds of uninterrupted stair climbing. If you chose "in pair" modality, a counterbalance session will be arranged, meaning that you will carry the 8 kg backpack during session 2 while your partner will do it during session 3. After the experiment, you'll be asked to fill in a questionnaire.

Additional considerations:

- Refer to page 2 to get familiarized with Borg's scale.
- Read/sign the informed consent on pages 3 and 4
- Review/sign your health declaration on page 5

Perceived exertion (Borg's scale)



6	No exertion at all
7	Extremely light
8	
9	Very light
10	
11	Light
12	
13	Somewhat hard
14	
15	Hard (heavy)
16	
17	Very hard
18	
19	Extremely hard
20	Maximum exertion

Informed consent for test

1. **Purpose and explanation**

You will perform an exercise test on a bicycle ergometer. The exercise intensity will begin at a low work level and will be advanced in stages depending on your fitness level, we may stop the test at any time because of notorious signs of fatigue or major changes in your heart rate. It is important for you to realize that you can stop when you wish because of feelings of fatigue or any other discomfort.

2. **Attendant risks and discomforts**

There exists the possibility of certain changes occurring during the test, however these are not expected as a sub-maximal test has been performed in order to set the stair machine at a pace that avoids reaching fatigue. Every effort will be made to minimize these risks by evaluation of preliminary information relating to your health and fitness and by careful observation during testing. You should stop the test immediately if you feel any sign of physical risk or serious discomfort (e.g., dizziness, nausea, extreme weakness)

3. **Responsibilities of the participant**

Information you possess about your health status or previous experiences of heart-related symptoms (e.g. shortness of breath with low-level activity, pain, pressure, tightness, heaviness in the chest, neck, jaw, back, and/or arms) with physical effort may affect the safety of your exercise test. Your prompt reporting of these and any other unusual feelings with effort during the exercise test itself is very important.

4. **Inquiries**

Any question about the procedures used in the exercise test or the results of your test are encouraged. If you have any concerns or questions, please ask us for further explanations.

5. **Use of medical records**

The personal information obtained during exercise testing will be treated as privileged and confidential. It is not to be released or revealed to any person except your referring physician without your written consent. However, the information obtained may be used for statistical analysis or scientific purposes with your right to privacy retained.

6. Freedom of consent

I hereby consent to voluntarily engage in an exercise test. I understand that I am free to stop the test at any point if I so desire.

I have read this form, and I understand the test procedures that I will perform and the attendant risks and discomforts. Knowing these risks and discomforts and having had an opportunity to ask questions that have been answered to my satisfaction, I consent to participate in this test.

Date (YY-MM-DD) _________________	Place: __________________
______________________________ Test person signature	________________________________ Test person full name

Research responsible person and consent

I have read the attached information and have discussed with the test subject. • I have provided information about the test and related potential risks. • I have explained that the participation is voluntary and that the participant is free to discontinue participation at any time. • I have given the opportunity to ask questions and have also allowed time for consideration about participating.

Date (YY-MM-DD) _________________	Place: __________________
____________________________ Researcher signature	_______________________________ Researcher full name

Health declaration

Assess your health status by **marking all TRUE** statements

History

You have had:

☐ a heart attack
☐ heart surgery
☐ cardiac catheterization
☐ coronary angioplasty
☐ heart failure
☐ heart transplantation
☐ cogenital heart disease
☐ heart medications

Symptoms

You experience

☐ Chest discomfort with exertion
☐ Unreasonable breathlessness
☐ Dizziness, fainting, or blackouts

Cardiovascular risk factors

☐ You are a man older than 45 years
☐ You are a woman older than 55 years, have had a hysterectomy, or are postmeopausal
☐ You smoke, or quit smoking within the previous 6 months
☐ Blood pressure > 140/90 mmHg
☐ You take blood pressure medication
☐ You have a close relative who had a hearat attack or heart surgery before age 55 (father or brother), age 65 (mother or sister)
☐ You are physically inactive (i.e., you get <30 min of physical activity on at least 3 days per week)
☐ you are >9 kg overweight

Other health issues

☐ Diabetes
☐ Asthma or other lung disease
☐ Burning or cramping sensation in your lower legs when walking short distances
☐ Musculoskeletal problems that limit your physical activity
☐ You are pregnant

☐ **NONE OF THE ABOVE**

Annex 2: Protocol for Determination of Oxygen Uptake and Maximal Capacity

Sub-maximal test

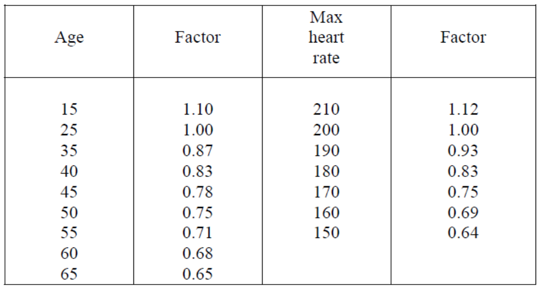
Objective: Estimation of VO_{2Max} according to a submaximal exercise (Astrand , 1964) corrected age.

General contact information

Name	
Email	
Age (years)	
Weight (kg)	
Body height (cm)	
Starting load (W)	
BMI	

Data collection

Time (min)	***Heart rate (bpm)***
1	
2	
3	
4	
5	
6	
7	
8	
9	
10	
Average (last 2)	



Age	Factor	Max heart rate	Factor
15	1.10	210	1.12
25	1.00	200	1.00
35	0.87	190	0.93
40	0.83	180	0.83
45	0.78	170	0.75
50	0.75	160	0.69
55	0.71	150	0.64
60	0.68		
65	0.65		

Table 2: Correction factor table - Astrand, 1964

Equation 1: Prediction equation SR (Halder, A. 2017)

$$SR = -108.8633+2.0121*VO_{2max}+1.3289*\%VO_{2max}$$

VO_{2max} (from table 1a for man and 1b for woman)	*Correction factor (table 2 - interpolated if needed)*	*Corrected estimation*	*Oxygen uptake/body mass (ml/kg/min)*	*Step rate*	*Stair machine initial level*

Non – Weight bearing

General session information

Name	
Starting stair machine level	
Date/time	

Non-weight bearing test

Data collection

Time (min)	*Borg's Scale*
1	
2	
3	
4	
5	

Change level

Time (min)	*Borg's Scale*	*Stair machine Level*

Weight bearing

General session information

Name	
Starting stair machine level	
Date/time	

Weight bearing test

Data collection

Time (min)	*Borg's Scale*
1	
2	
3	
4	
5	

Change level

Time (min)	*Borg's Scale*	*Stair machine Level*

*Table 1a: Table 3. Prediction of maximal oxygen uptake from heart rate and work load on a Bicycle Ergometer **(Man)** (from a nomogram by Åstrand. Acta. physiol. scand. 49 (suppl. 169), 1960, pp. 45-60.*

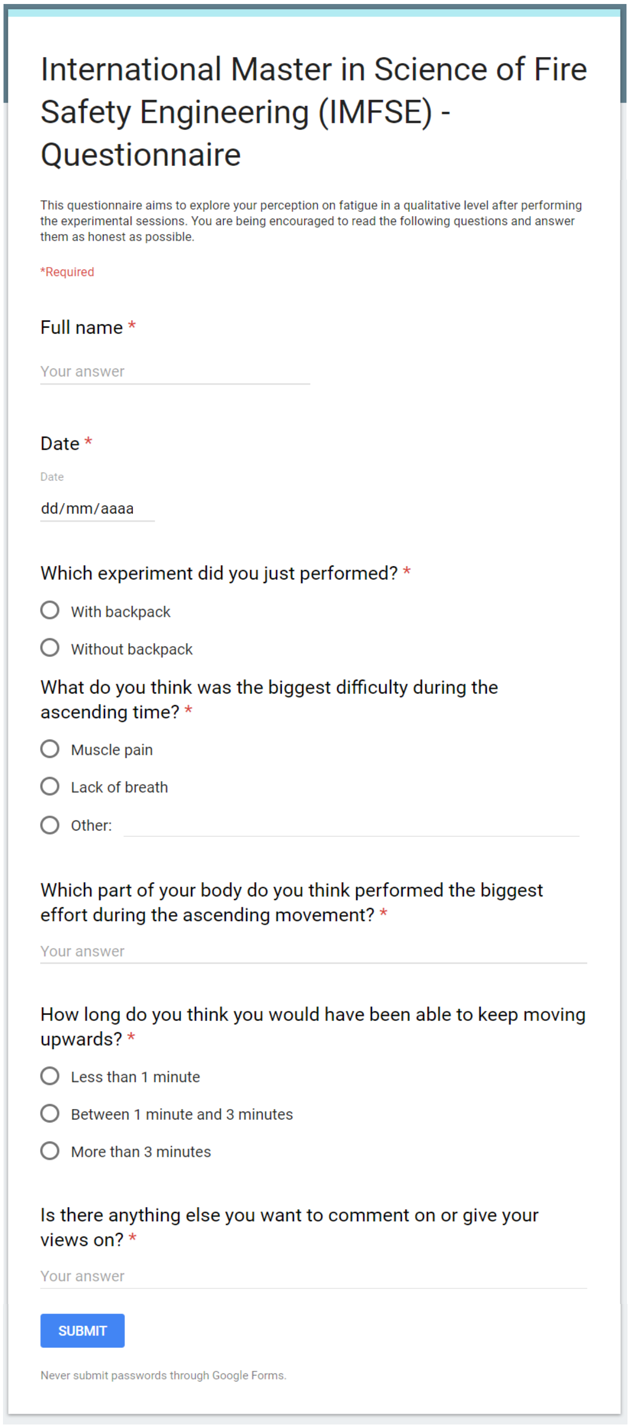
Heart rate	Maxial Oxygen Uptake litres/min.					Heart rate	Maxial Oxygen Uptake litres/min.				
	300 kpm/min	600 kpm/min	900 kpm/min	1200 kpm/min	1500 kpm/min		300 kpm/min	600 kpm/min	900 kpm/min	1200 kpm/min	1500 kpm/min
120	2.2	3.5	4.8			148		2.4	3.2	4.3	5.4
121	2.2	3.4	4.7			149		2.3	3.2	4.3	5.4
122	2.2	3.4	4.6			150		2.3	3.2	4.2	5.3
123	2.1	3.4	4.6			151		2.3	3.1	4.2	5.2
124	2.1	3.3	4.5	6.0		152		2.3	3.1	4.1	5.2
125	2.0	3.2	4.4	5.9		153		2.2	3.0	4.1	5.1
126	2.0	3.2	4.4	5.8		154		2.2	3.0	4.0	5.1
127	2.0	3.1	4.3	5.7		155		2.2	3.0	4.0	5.0
128	2.0	3.1	4.2	5.6		156		2.2	2.9	4.0	5.0
129	1.9	3.0	4.2	5.6		157		2.1	2.9	3.9	4.9
130	1.9	3.0	4.1	5.5		158		2.1	2.9	3.9	4.9
131	1.9	2.9	4.0	5.4		159		2.1	2.8	3.8	4.8
132	1.8	2.9	4.0	5.3		160		2.1	2.8	3.8	4.8
133	1.8	2.8	3.9	5.3		161		2.0	2.8	3.7	4.7
134	1.8	2.8	3.9	5.2		162		2.0	2.8	3.7	4.6
135	1.7	2.8	3.8	5.1		163		2.0	2.8	3.7	4.6
136	1.7	2.7	3.8	5.0		164		2.0	2.7	3.6	4.5
137	1.7	2.7	3.7	5.0		165		2.0	2.7	3.6	4.5
138	1.6	2.7	3.7	4.9		166		1.9	2.7	3.6	4.5
139	1.6	2.6	3.6	4.8		167		1.9	2.6	3.5	4.4
140	1.6	2.6	3.6	4.8	6.0	168		1.9	2.6	3.5	4.4
141		2.6	3.5	4.7	5.9	169		1.9	2.6	3.5	4.3
142		2.5	3.5	4.6	5.8	170		1.8	2.6	3.4	4.3
143		2.5	3.4	4.6	5.7						
144		2.5	3.4	4.5	5.7						
145		2.4	3.4	4.5	5.6						
146		2.4	3.3	4.4	5.6						
147		2.4	3.3	4.4	5.5						

*Table 1b: Table 4. Prediction of maximal oxygen uptake from heart rate and work load on a Bicycle Ergometer **(woman)** (from a nomogram by Åstrand. Acta. physiol. scand 4 (suppl. 169) 1960, pp. 45-60.*

Heart rate	Maxial Oxygen Uptake litres/min.					Heart rate	Maxial Oxygen Uptake litres/min.				
	300 kpm/min	450 kpm/min	600 kpm/min	750 kpm/min	900 kpm/min		300 kpm/min	450 kpm/min	600 kpm/min	750 kpm/min	900 kpm/min
120	2.6	3.4	4.1	4.8		148	1.6	2.1	2.6	3.1	3.6
121	2.5	3.3	4.0	4.8		149		2.1	2.6	3.0	3.5
122	2.5	3.2	3.9	4.7		150		2.0	2.5	3.0	3.5
123	2.4	3.1	3.9	4.6		151		2.0	2.5	3.0	3.4
124	2.4	3.1	3.8	4.5		152		2.0	2.5	2.9	3.4
125	2.3	3.0	3.7	4.4		153		2.0	2.4	2.9	3.3
126	2.3	3.0	3.6	4.3		154		2.0	2.4	2.8	3.3
127	2.2	2.9	3.5	4.2		155		1.9	2.4	2.8	3.2
128	2.2	2.8	3.5	4.2	4.8	156		1.9	2.3	2.8	3.2
129	2.2	2.8	3.4	4.1	4.8	157		1.9	2.3	2.7	3.2
130	2.1	2.7	3.4	4.0	4.7	158		1.8	2.3	2.7	3.1
131	2.1	2.7	3.4	4.0	4.6	159		1.8	2.2	2.7	3.1
132	2.0	2.7	3.3	3.9	4.5	160		1.8	2.2	2.6	3.0
133	2.0	2.6	3.2	3.8	4.4	161		1.8	2.2	2.6	3.0
134	2.0	2.6	3.2	3.8	4.4	162		1.8	2.2	2.6	3.0
135	2.0	2.6	3.1	3.7	4.3	163		1.7	2.2	2.6	2.9
136	1.9	2.5	3.1	3.6	4.2	164		1.7	2.1	2.5	2.9
137	1.9	2.5	3.0	3.6	4.2	165		1.7	2.1	2.5	2.9
138	1.8	2.4	3.0	3.5	4.1	166		1.7	2.1	2.5	2.8
139	1.8	2.4	2.9	3.5	4.0	167		1.6	2.1	2.4	2.8
140	1.8	2.4	2.8	3.4	4.0	168		1.6	2.0	2.4	2.8
141	1.8	2.3	2.8	3.4	3.9	169		1.6	2.0	2.4	2.8
142	1.7	2.3	2.8	3.3	3.9	170		1.6	2.0	2.4	2.7
143	1.7	2.2	2.7	3.3	3.8						
144	1.7	2.2	2.7	3.2	3.8						
145	1.6	2.2	2.7	3.2	3.7						
146	1.6	2.2	2.6	3.2	3.7						
147	1.6	2.1	2.6	3.1	3.6						

Annex 3: Questionnaire

Link to questionnaire: https://goo.gl/forms/qLlCUf6pQwwgEagP2



International Master in Science of Fire Safety Engineering (IMFSE) - Questionnaire

This questionnaire aims to explore your perception on fatigue in a qualitative level after performing the experimental sessions. You are being encouraged to read the following questions and answer them as honest as possible.

*Required

Full name *

Your answer

Date *

Date

dd/mm/aaaa

Which experiment did you just performed? *

○ With backpack
○ Without backpack

What do you think was the biggest difficulty during the ascending time? *

○ Muscle pain
○ Lack of breath
○ Other:

Which part of your body do you think performed the biggest effort during the ascending movement? *

Your answer

How long do you think you would have been able to keep moving upwards? *

○ Less than 1 minute
○ Between 1 minute and 3 minutes
○ More than 3 minutes

Is there anything else you want to comment on or give your views on? *

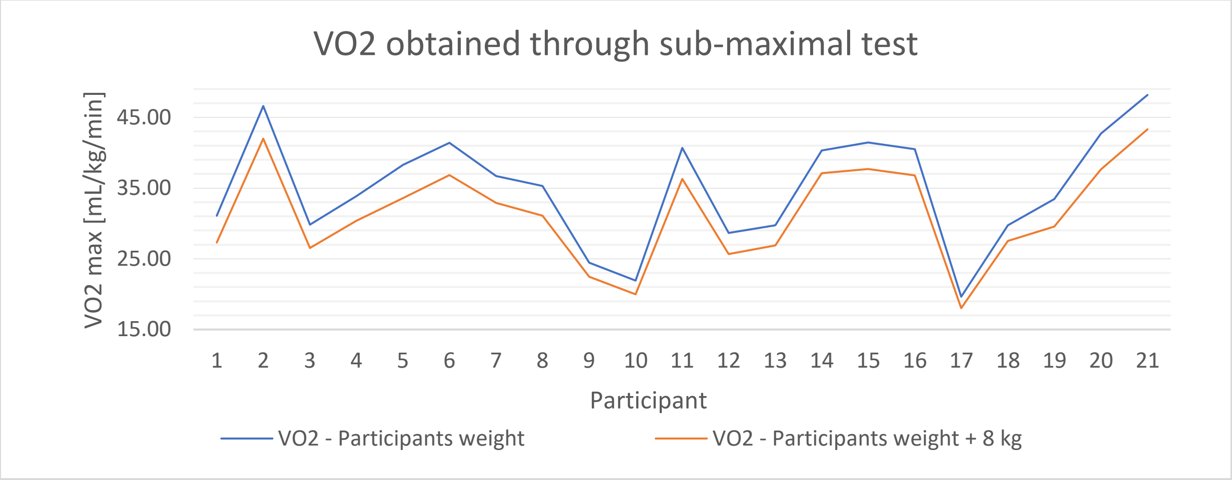
Your answer

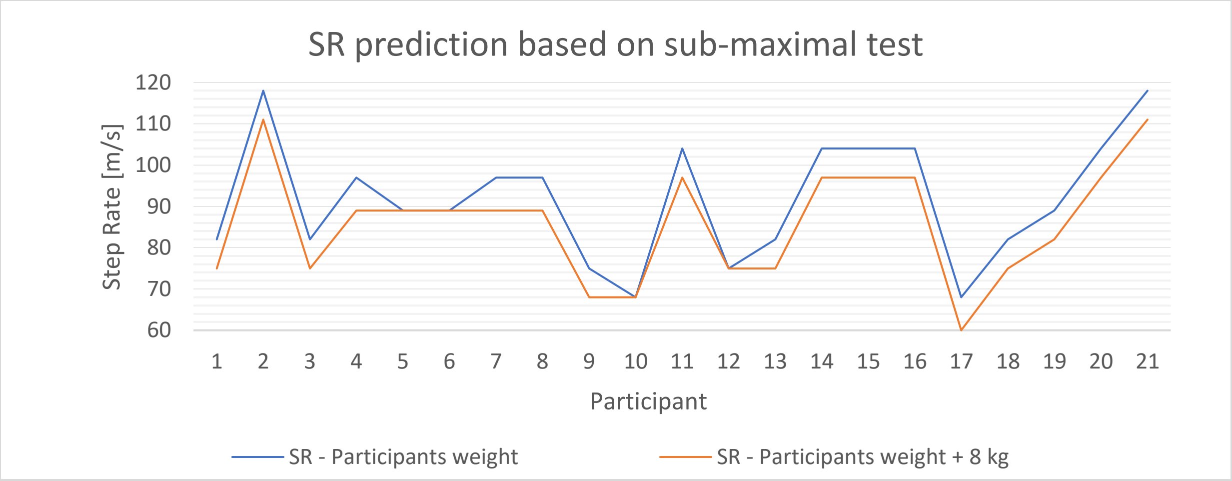
Never submit passwords through Google Forms.

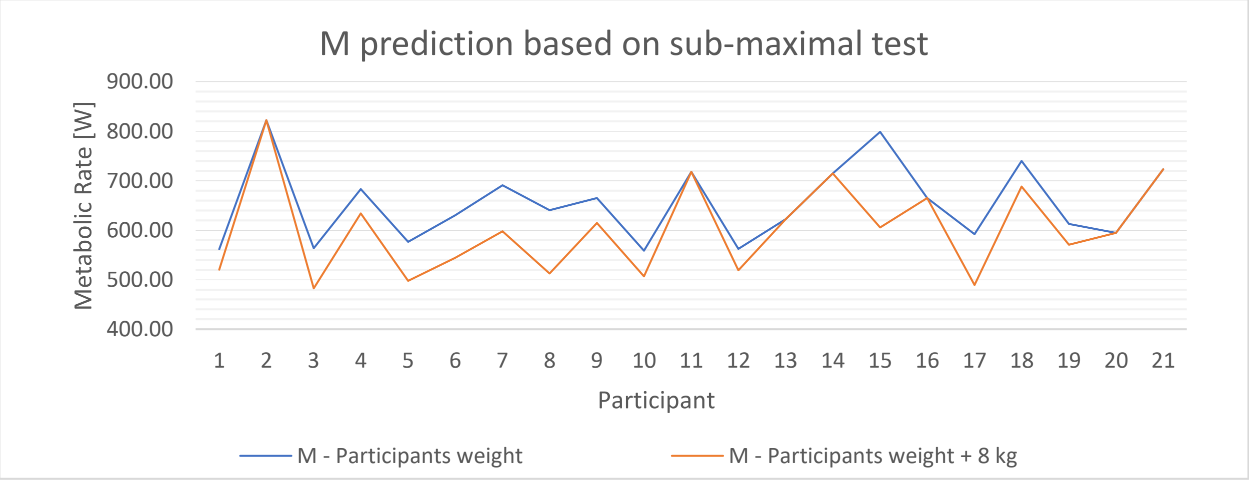
Annex 4: Experimental procedure to follow for experiments

Time	Activity
7:00 A.M.	Arrival of main researcher to laboratory. 15 minutes are considered to move all the related equipment from the storage room to the main laboratory.
7:15 A.M.	Start of calibration process
8:00 A.M.	Arrival of experimental couple 1
9:00 A.M.	End of experimental session 1. 15 minutes are considered for the preparation for 2nd experiment of the day
9:15 A.M.	Arrival of experimental couple 2
10:15 A.M.	End of experimental session 1. 15 minutes are considered for the preparation for 3rd experiment of the day
10:30 A.M.	Arrival of experimental couple 3
11:30 A.M.	End of experimental session 3. 30 minutes are considered for cleaning process and preparation for 4th experiment of the day (After lunch)
12:00 P.M.	Lunch break
13:00 P.M	Arrival of experimental couple 4
14:00 P.M.	End of experimental session 1. 15 minutes are considered for the preparation for 5th experiment of the day
14:15 P.M.	Arrival of experimental couple 5
15:15 P.M.	End of experimental session 5. 15 minutes are considered for the preparation for 6th experiment of the day
15:30 P.M.	Arrival of experimental couple 6
16:30 P.M.	End of experimental session 6. 30 minutes are considered for cleaning process and preparation for next day
17:00 P.M.	End of day

Annex 5.1: Submaximal results by participant







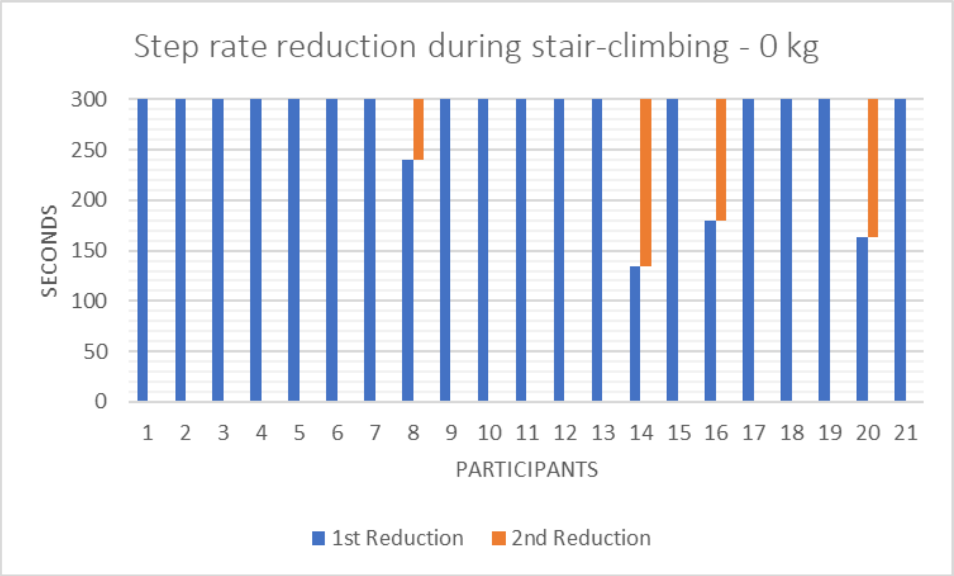
*Theses graphs are intended to show the difference in each participant performance when the physical parameters of interest (i.e. HR, VO2, and M) were affected (or not) by additional weight (8 kg)

Annex 5.2: Step reduction for each participant

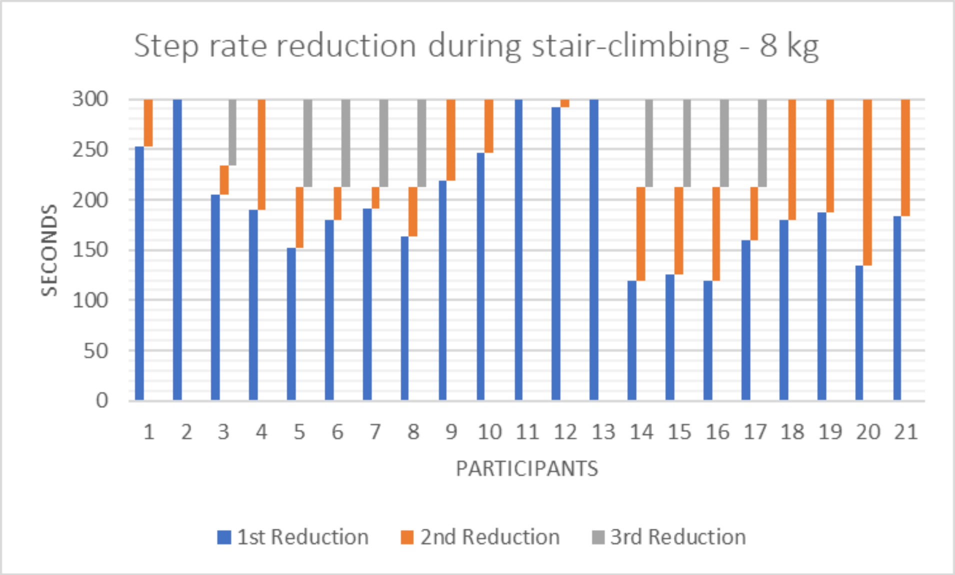
Vertical component						
Statistical measurements	Initial (Vo) [m/s]	Final (Vf) [m/s]		Decrease velocity [%]		
		Vf1 (0 kg)	**Vf2 (8 kg)**	**Vo vs Vf1**	**Vo vs Vf2**	**0 kg vs 8 kg**
Min	0.2323	0.2323	0.1811	0.00	22.04	22.04
Average	0.3137	0.3101	0.2746	1.15	12.46	11.45
Max	0.4032	0.4032	0.4032	0.00	0.00	0.00
SD	0.0501	0.0497	0.0516	-	-	-

Horizontal component						
Statistical measurements	Initial (Vo) [m/s]	Final (Vf) [m/s]		Decrease velocity [%]		
		Vf1 (0 kg)	**Vf2 (8 kg)**	**Vo vs Vf1**	**Vo vs Vf2**	**0 kg vs 8 kg**
Min	0.2833	0.2833	0.2400	0.00	15.28	15.28
Average	0.3825	0.3706	0.3404	3.11	11.01	8.15
Max	0.4917	0.4917	0.4917	0.00	0.00	0.00
SD	0.0611	0.0573	0.0589	-	-	-

In blue: Participants able to finish the experiment without decreasing the step rate during the 5 min exercise while NOT influenced by the 8 kg backpack. In orange: four participants whom decreased the step rate during the same experiment (no influence of additional weight)



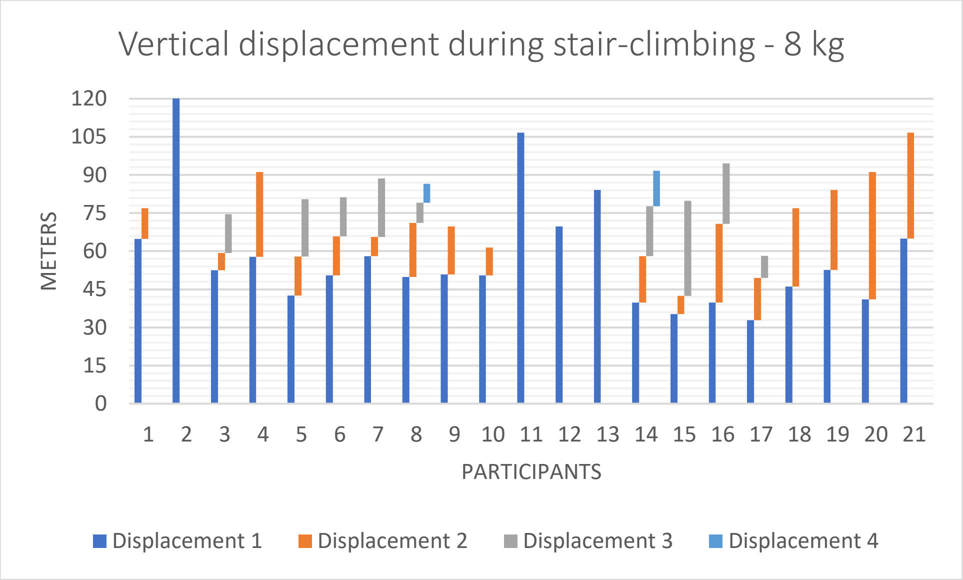
In blue: Participants able to finish the experiment without decreasing the step rate during the 5 min exercise while influenced by the 8 kg backpack. In orange: eighteen participants whom decreased the step rate during the same experiment (+ 8 kg) one time. In gray: nine participants whom decreased the step rate more than twice during the same exercise.



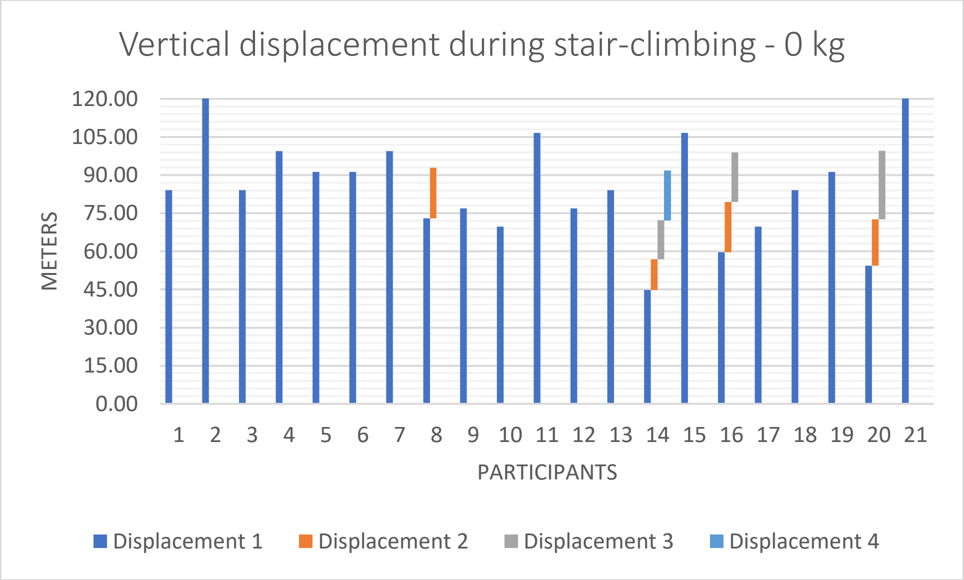
Annex 5.3: Vertical displacement for each participant

Statistical measurements	Diagonal displacement		
	0 kg	8 kg	performance reduction
Minimum	109.9231095	64.7415	41.10%
Maximum	190.7489253	190.7489	0.00%
Average	139.2559527	105.9424	23.92%
Standard deviation	24.72546194	34.26033517	

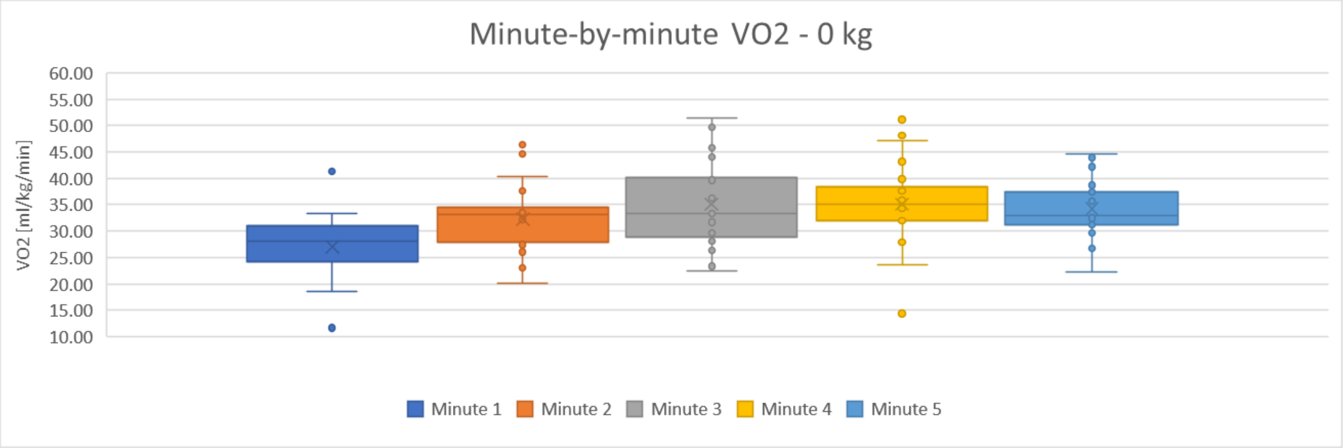
Displacement for each participant considering the time when a step reduction was asked in order to complete the stair-climbing exercise while carrying an 8 kg backpack.

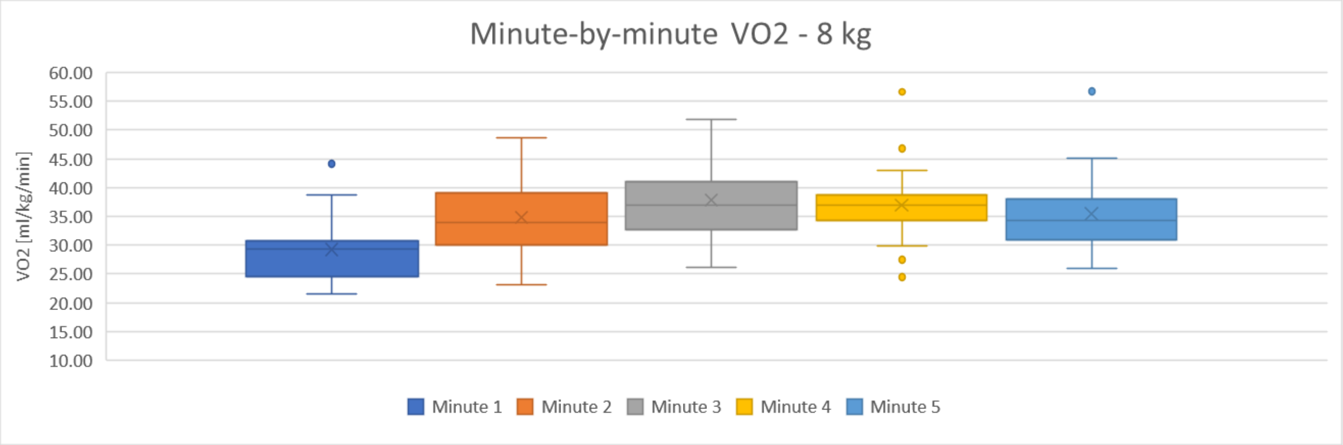


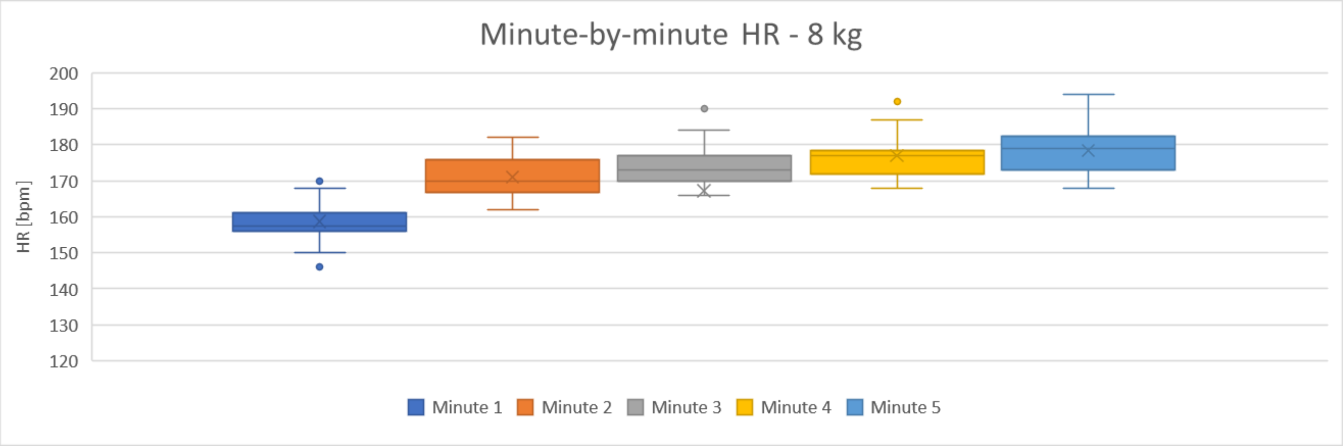
Displacement for each participant considering the time when a step reduction was asked in order to complete the stair-climbing exercise while NOT carrying an 8 kg backpack.



Annex 5.4: Minute-by-minute performance of participants VO_2 and HR






Minute-by-minute HR - 8 kg
HR [bpm]
200
190
180
170
160
150
140
130
120
Minute 1
Minute 2
Minute 3
Minute 4
Minute 5


Minute-by-minute HR - 0 kg
HR [bpm]
200
190
180
170
160
150
140
130
120
Minute 1
Minute 2
Minute 3
Minute 4
Minute 5

Annex 5.5: VO$_2$ and HR comparison between the two experimental conditions