Maintaining balance on a moving bus: the importance of three-peak steps whilst climbing stairs

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Abstract

In a previous work of the authors, the impact of bus acceleration in level walking was presented. However, climbing stairs is physically more challenging than level walking and results in a high number of falls, hence substantial medical costs. Understanding the impact of a dynamic environment, such as that of a bus, on people's gait whilst walking on stairs, would enable the reduction, or even the elimination of balance-loss falls.

The gait of 29 healthy and regular bus users (20-80 y.o.) was monitored whilst ascending and descending a static and "moving" staircase. The tasks took place in a real double-decker bus which was initially stationary. When the bus was moving, ascending was tested during medium acceleration (+1.5 m/s^2), while descending during medium deceleration (-1.5 m/s^2), reproducing the most common movements aboard buses. Examining healthy people enables the identification of differences in gait that are accounted for the alteration in the bus environment and gives the opportunity to further consider the challenges mobility impaired passengers are experiencing.

After applying the method established in level walking, *chi-square* tests were performed on participants' step type (resulting from the ground reaction force profile), taking into account participants' age and gender and the bus acceleration. The outcomes revealed that age and gender affect people's gait in a dynamic environment. Moreover, there is a significant correlation between the increase of acceleration and the type of steps passengers use to sustain their balance, as the number of three-peak steps was increasing with the increase of bus acceleration. Hence, the bus environment forces people to use a walking style other than their natural one and older people in particular, unconsciously increase the contact area between their foot and the floor (three-peak steps) to increase balance. Surprisingly, males appear less able than females to control balance. People's stair walking in a moving vehicle was investigated for the first time and has opened-up new horizons for gait analysis in dynamic environments.

Keywords: dynamic environment, bus acceleration, gait analysis, stair climbing, step type, three-peak steps

1 Introduction

As people grow older, they tend to have reduced body capabilities and balance, and therefore fall more frequently (Chong et al., 2009; O'Sullivan et al., 2013). In the UK, one in three people over 65 (3.4 million people) suffer a fall (AgeUK, 2010), with falls from stairs or steps (20%) being the most common reason for hospitalisation in older as well as in younger adults (Canadian Institute for Health Information, 2013). The older people become the more likely they are to suffer from fear of falling, which affects their quality of life and health. They might avoid undertaking activities and socialisation and as a result their physical and mental well-being reduces.

The World Health Organisation (2015) defines a fall as "an event which results in a person coming to rest inadvertently on the ground or floor or other lower level". There are some 424,000 deaths per year directly due to a fall - thus falls are the second global cause of unintentional injury death - and 37.3 million falls that are severe enough to require medical attention. This introduces a substantial cost to societies as a result of medical treatment and loss of earnings (AgeUK, 2010;Centers for Disease Control and Prevention, 2015). In the People's Republic of China, for every death resulting from a fall, there are four cases of permanent disability and 690 cases requiring medical care and missing work or school. Nevertheless, the vast majority of falls go unreported and often, even where medical treatment is provided, the injuries will not be recorded as fall-related.

In the UK, falls on buses are common, and reported to be in the region of 800 per day for those 65 years old and over (AgeUK, 2009) and one of the most common risk factors for transport operators in London (Transport for London, 2015). However, although the WHO definition is clear that a fall is "coming to rest", actually it is only the last stage of a sequence of events, starting with some form of loss of balance - a stumble, or trip for example - caused by some poor response to a stimulus (e.g. an unexpected change in floor/ground surface or a change in acceleration imposed by a moving object, such as a vehicle). A fall only occurs when the body's responses fail to recover from the resulting loss of balance, so it is important to consider the effects of such stimuli in terms of the initial loss of balance, rather than just when they result in an actual "fall".

Level walking is an activity that requires a level of stability, as a controlled fall is generated whilst the body weight is transferred from one limb to the other. The recurrent events of level walking in a static environment have been the focus of many biomechanical studies (Karekla, 2016) and the effect of the surrounding environment, especially when this is dynamic, have also been described elsewhere, using the example of a moving bus (Karekla and Tyler, Under revision). In this environment it was shown that people's walking style consists of seven types of steps, the most important one of which is the three-peak steps, which is considered as an unintended balance mechanism. Increasing the contact area between the plantar and the ground increases the support base and provides additional stability.

Climbing the stairs is more demanding than level walking, as it requires more body capabilities for the centre of mass (CoM) to be moved vertically within a support base that changes between an upper and a lower stair (Mayagoitia and Kitchen, 2009). Younger people appear to be more confident during stair negotiation, especially during stair ascending, whereas older people use more muscle strength at the ankle and knee joints during both stair ascent and descent and stand on one leg for longer during stair descent (Maganaris et al., 2018). In addition, older adults present smaller foot clearance between their swinging foot and the edge of the stair (Kunzler et al., 2018), which results in slower transitions from one stair to another (De Asha and Buckley, 2015). In general, people with poor balance and reduced grip strength, such as the older members of the society, present difficulty to ascend the stairs, and there is a higher likelihood for falls for those who find stair descending difficult (Verghese et al., 2008).

For a large proportion of the literature, the interest was turned towards the motor coordination of the body and the synergies of muscles it engages at each joint (ankle,knee and hip) during stair walking, and the forces generated at each of these joints, as a result of the ground reaction forces, were of equal interest. Analysing some of these studies (detailed description can be found in Karekla (2016)), it was found that during stair ascending the ground reaction force (GRF) applied on the heel and toes was not significantly different between males and females. However females apply more force during mid-stance than males. During stair ascending, females apply more GRF on the heel and toes compared to males. No significant differences in GRF were observed between middle-aged and older people whilst they were ascending a staircase, however during stair descent, older people apply three times the force middle-aged people apply on their heel and toes.

Balancing on a static support surface is not as demanding for the body's sensory system as balancing in a moving environment, such as on a tilting or rotating surface. External perturbations on a flat surface, where subjects have been mechanically forced to agitation either by an external force or by the transformation of the support surface, have shown that older individuals are less able to maintain the centre of mass within the support base (information collected after reading the whole material of Lord et al., 2007). In the case of perturbed gait during stair negotiation of a static staircase, older people appear to adopt a more conservative walking pattern compared to younger people Christina and Cavanagh, 2002.

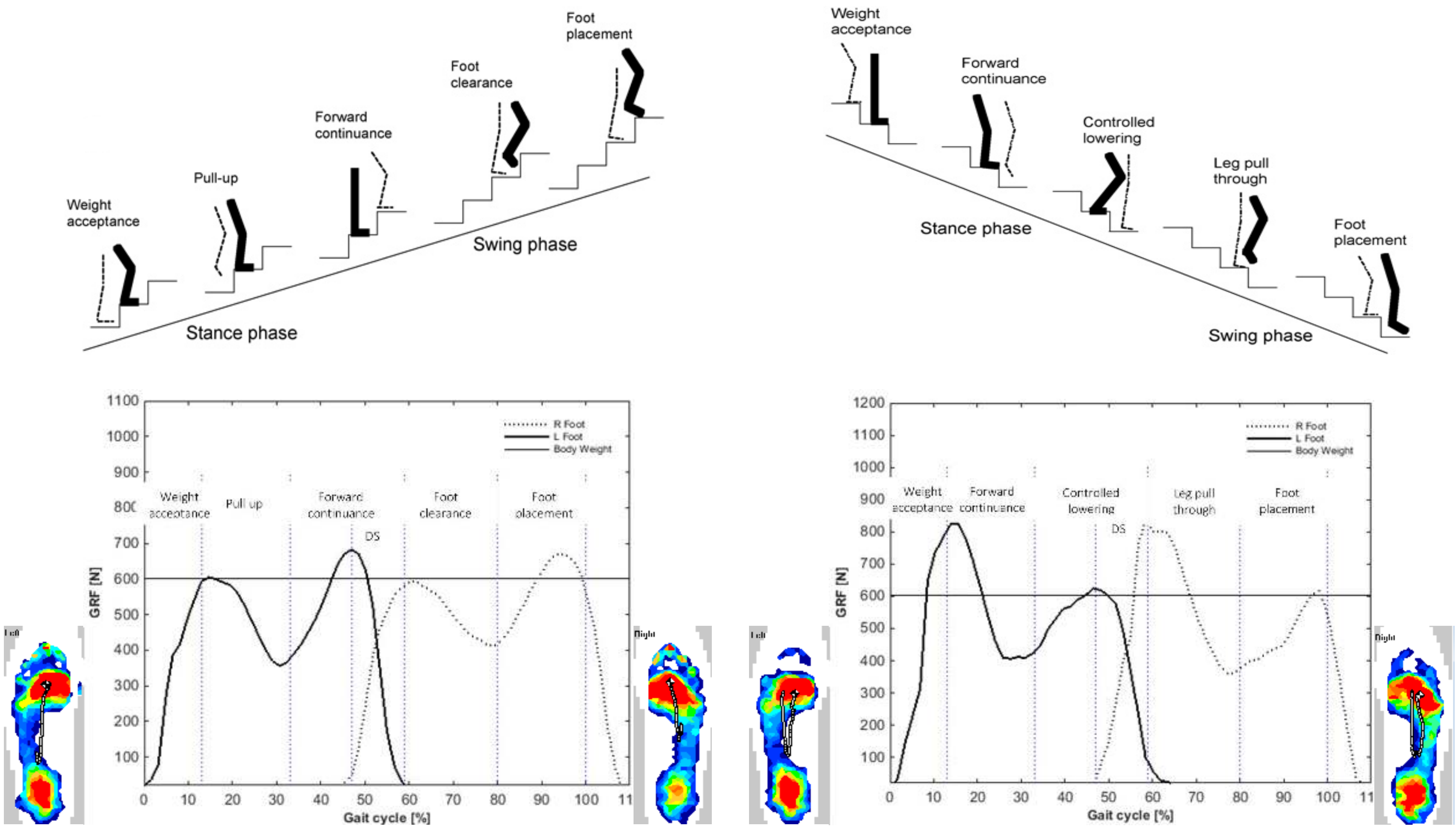
Although gait perturbation on a static staircase has been studied previously, to the authors' knowledge there has not been previous work on people's gait on a staircase that is subject to exogenous motion. A search on Google Scholar using the term “moving passenger on bus staircase” returned 24,200 results unrelated to the negotiation of dynamic staircases, whereas the term “person on moving staircase” returned 67,500 unrelated results. Hence, this reveals a gap in the research field of gait variability whilst negotiating dynamic staircases, a task undertaken by and affecting a great number of people every day.

The balance mechanisms people adopt during stair walking in dynamic environments are expected to be more distinct than in level walking. Using the peak-detection algorithm described in (Karekla and Tyler, Under revision), this paper aims to identify people's walking style when they are negotiating stairs, in a static and a dynamic environment. The dynamic environment chosen for this work is a double-decker bus, a transport mode that many people in cities use for their everyday movements, especially in cities with intense bus services, such as London, Hong Kong, or Singapore. Despite the amount that buses are used, people - especially older - are unsatisfied with the level of service provided and report many incidents of loss of balance. This work is discussing the way the bus environment, in terms of its layout and acceleration, affects the natural way people walk on staircases when no external forces hinder their movement. The walking style observed in each environment will also be presented and the differences between age groups and genders will be discussed.

1.1 Natural gait during stair walking

The gait cycle during stair walking is similar to that of level walking, in the sense that it involves recurring movements of the two limbs. Just like in level walking, the force that a person applies to the ground during walking generates an equal and opposite force (reaction) from the ground to the person's plantar (Newton's third law). Ground Reaction Forces (GRF) have two components, a horizontal and a vertical one, but the main interest in this paper focuses around the vertical component.

Although during level walking the two peaks that define the M-shape curve of the GRF are of similar intensity (Karekla and Tyler, Under revision), in stair ascent the second peak has a larger intensity than the first (Figure1, a), whereas in stair descent the first peak has a larger intensity than the second (Figure1, b). Both ascent and descent consist of five phases (Shumway-Cook and Woollacott, 2007; McFadyen and Winter, 1988). However, some actions processed by the body in each phase differ between the two tasks (Table 1).



(a)

(b)

Figure 1: Gait cycle (top, picture taken and adapted from Novak et al., 2010 and GRF profile (bottom) whilst ascending (a) and descending (b) the stairs. The pressure maps illustrate the plantar areas under load during the presented steps.

Table 1: Gait cycle events during stair walking

Occurrence	Stair Ascend	Stair Descend
	Stance	
0 - 10%	**Weight acceptance:** the front part of the leading foot is in touch with the stair.	
10 - 30%	**Pull up:** the plantar is in full contact with the stair, as body weight is supported by the leading leg. The other leg is moved towards the upper stair.	**Forward continuance:** the back part of the plantar is in contact with the stair as body weight is supported by the leading leg. The other leg is moved towards the lower stair.
30 - 60%	**Forward continuance:** a controlled fall is generated with the GRF of this phase being higher than those of pull up, as the CoM has to be moved to a higher level. Double support is achieved towards the end of this phase.	**Controlled lowering:** the CoM is lowered in order for the swinging leg to reach the stair. GRF of this phase are lower than those in forward continuance. Double support is achieved towards the end of this phase.
	Swing	
60 - 80%	**Foot clearance:** the leading foot becomes the swinging foot which is not loaded as it is being moved towards a higher stair.	**Leg pull through:** the leading leg becomes the swinging leg and the CoM is stabilised between the moving support base. The plantar is not in contact with the stair.
80 - 100%	**Foot placement:** the swinging foot is placed on the next stair and is being prepared to accept the body weight in order to proceed with the movement.	

Note: Occurrence is given as the percentage of gait cycle

2 Methods

As people's stair walking in a moving vehicle is investigated here for the first time, it was crucial to invite healthy people to take part in this study. Any mobility difficulties of the participants will provide obscure outcomes of the real challenges of passengers during bus journeys.

Thus, 29 healthy and regular bus users, between 20 and 80 years old, were recruited for this study. Participants were divided into three age groups following Steenbekker and Van Beijsterveldt's analysis on balance (Steenbekkers and Van

Beijsterveldt, 1998): young (20 to 39 years old); middle-aged (40 to 59 years old) and older (over 60 years old). More information on the sample size and the physical characteristics of each age group are included in Table 2 below. In addition to being regular bus users, all participants stated that they would like to travel upstairs on a bus if they could (Karekla, 2016).

Table 2: Physical and demographic characteristics of the examined sample, mean (SD)

Characteristic	Young (n=12)	Middle-aged (n=8)	Older (n=9)
Gender (M/F)	7/5	4/4	5/4
Age (years)	31.1 (5.2)	49.8 (5.5)	66.7 (4.9)
Height (cm)	176.6 (10.0)	171.1 (9.8)	169.6 (11.2)
Weight (kg)	68.6 (17.7)	74.5 (13.9)	77.1 (12.1)
UST (sec)	30.1 (21.6)	7.7 (12.3)	7.4 (9.6)
TUAG (sec)	12.0 (1.8	11.8 (1.5)	12.6 (2.0)
Step width (cm)	26.9 (9.4)	29.1 (5.7)	26.9 (7.4)
Step length (cm)	69.9 (8.7)	63.2 (10.1)	65.3 (10.9)
Leg power (Watt)	125.9 (84.0)	109.4 (54.9)	78.2 (46.2)
Arm Length (cm)	72.5 (5.0)	71.8 (5.0)	71.1 (5.5)
Grip strength (kg)	42.3 (13.4)	34.1 (11.3)	29.3 (7.1)

Note: Unipedal Stance Time (UST) test indicates risk of falling, Timed Up and Go (TUAG) test reflects balance deficits in gait.

A university laboratory (PAMELA, UCL) constituted the static environment. PAMELA, or in other words the Pedestrian Accessibility Movement Environment Laboratory (`www.cege.ucl.ac.uk/arg/pamela`), is located in London, UK and it is a multisensory laboratory where the built environment can be simulated for the assessment of pedestrian movement. In this laboratory, participants were asked to negotiate five stairs, the dimensions of which comply with the regulations for public buildings (Office of Public Sector Information, 2013): 175 mm riser, 240 mm tread and 1140 mm width. The staircase was not constructed specifically for these experiments, but it is part of the platform set up in the PAMELA laboratory. The dynamic environment was simulated in a real double-decker bus, owned by UCL, that was driving on a public road, but was not affected by the city traffic. The bus staircase consisted of seven stairs with a riser of 240 mm, tread of 220 mm and free width of 550 mm.

Participants repeated each task three times and were free to use handrails if needed. Their gait throughout the experiments was recorded by an in-shoe plantar pressure system (F-Scan mobile system, Tekscan Inc., Boston, USA, error order: ±3%). The bus was initially stationary (0 m/s^2), which allowed comparisons between the natural gait (static environment) and the walking style adopted due to the bus staircase design. The bus was thereafter moving at a "medium" acceleration rate (1.5 m/s^2) in a straight line, which revealed the effect of acceleration on passengers' gait. The bus acceleration was monitored using a 3D motion wireless system (MTw, Xsens Technologies, Netherlands). The equipment set-up on the person and on the bus are shown in Figure 2. When the bus was in motion, ascending was tested during acceleration, simulating the real life situation during which a passenger is attempting to go upstairs when at the same time the bus is leaving a bus stop, whereas stair descending was tested during deceleration, replicating behaviours of when a passenger, who has been sitting upstairs, intends to alight whilst the bus is already pulling into the stop. The examined level of acceleration was set in the range of accelerations passengers experience on the current bus service in London and bus driver training preceded the experiments, to ensure that this was achieved. The acceleration rate was checked in each run to make sure it was in the required range and if it was not the run was terminated and then repeated.

Before undertaking the above tasks, it was necessary to understand participants' preferences and requirements for a comfortable bus journey, in order to recognise the needs of bus passengers overall. Thus, participants were asked to respond to a pre-experiment questionnaire, which involved questions related to their travel frequency and scope, their seat preference, difficulty in performing tasks and comfort of the current service. After the completion of the experiments on the bus, participants

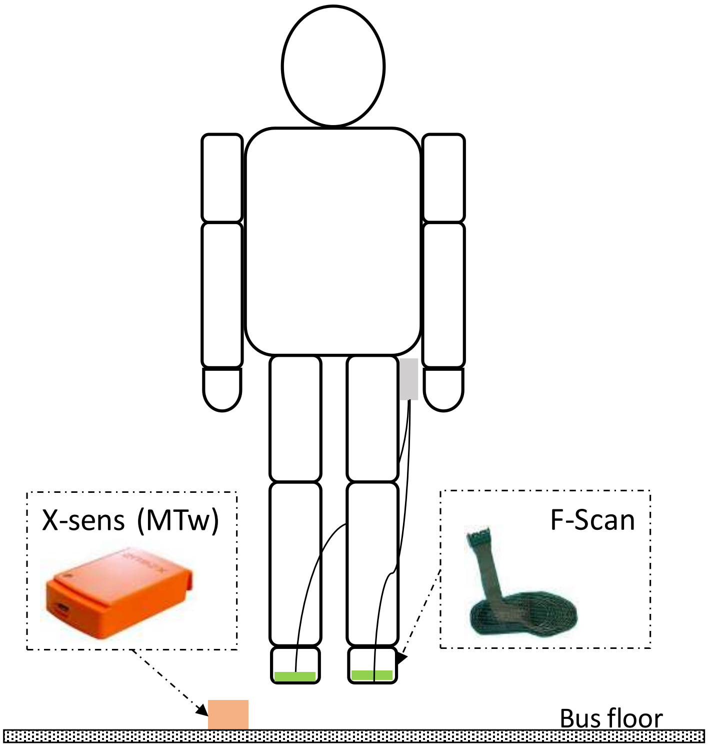


Figure 2: Experimental devices used for data collection

were asked to compare the examined service to the actual bus service as they had experienced it in London, to assess the simulation in terms of the examined acceleration and their difficulty in negotiating the stairs and to report any incidents of balance loss they experienced. The answers to the questionnaires are out of the scope of this paper, and details about the protocol and the outcomes can be found in Karekla (2016).

Data analysis followed the process described in (Karekla and Tyler, Under revision) to identify the step types used by participants in all tested environments. To avoid confusion, for the purpose of this study, a "step" refers to the alternating use of a person's lower limbs in order to achieve forward movement, whereas a "stair" refers to one of a series of steps a person needs to climb or descend in order to go from one level to another. Also, the term "stair negotiation" refers to the process of climbing or descending stairs.

Unlike level walking, in which the first, second and third peak of the GRF profile of each step were associated with the heel, middle-foot and toe area of the plantar, in stair walking, the first, second and third peak of the GRF profile of each step did not always correspond to the heel, middle-foot and toe area of the plantar respectively. Possible explanations for this are:

1. the different dimensions of the going of the two examined staircases (in the laboratory and on the bus),

2. the differences in foot size between participants which could enable some participants, especially women with small foot size, to place their entire plantar on the stairs of the static staircase, but leave part of their plantar hanging outside of the stair on the bus staircase or

3. that individuals have different techniques in negotiating stairs. For example, one person might use their heel as their first contact with the stair whilst descending, whilst another person might use their toes as the first contact when completing the same task.

Thus, to avoid bias in the results and to ensure that accurate comparisons can be made between environments and people, the seven different step types, that were identified in level walking, were grouped to one-peak steps, two-peak steps and three-peak steps when it came to stair negotiation. This is shown in Table 3. Furthermore, as with the similar experiments with level walking (Karekla and Tyler, Under revision) the data derived from each foot of each participant were treated as separate cases and were not averaged between runs. The data were processed in MATLAB 2014.

Table 3: Step types in level walking and stair negotiation

Definition	Level walking	Stair negotiation
Pressure is applied on the heel and toes. It is the most common step type in a healthy human's gait.	Normal	Two-peak
Pressure is applied on the heel and the middle of the plantar.	Back two-peak	
Pressure is applied on the middle of the plantar and the toes.	Front two-peak	
Pressure is applied on the heel only.	Heel peak	One-peak
Pressure is applied on the middle of the plantar only.	Middle-foot peak	
Pressure is applied on the toes only.	Toe peak	
Pressure is applied on the heel, the middle of the plantar and the toes. The entire plantar is under pressure.	Three-peak	Three-peak

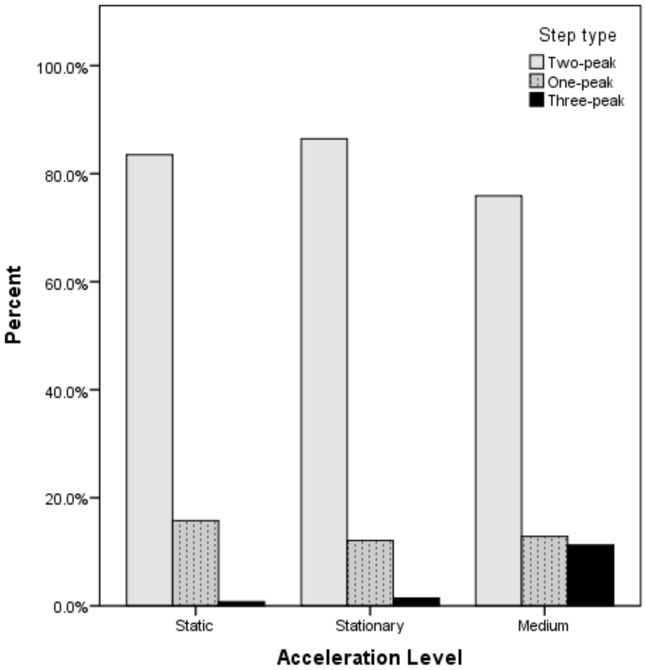
3 Results and Discussion

The influence of age, gender and acceleration level (categorical variables) on the observed step type was tested statistically by performing chi-squared tests (SPSS v.22). Each task (stair ascending and descending) was analysed separately and the results are discussed next.

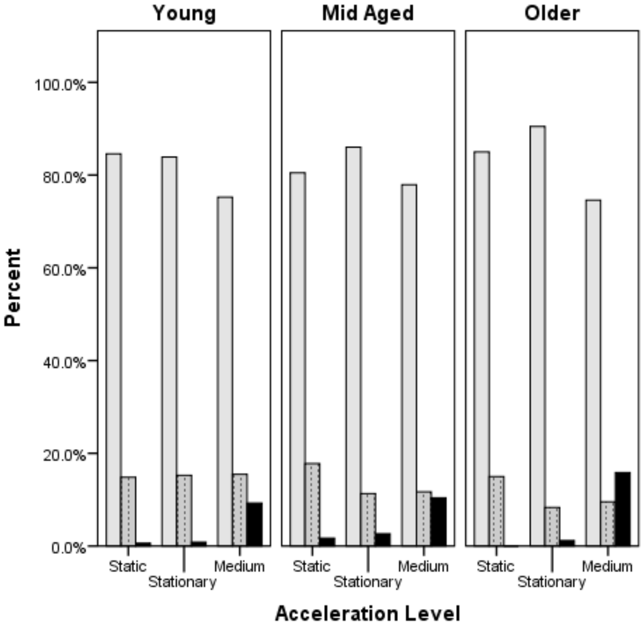
3.1 Stair ascending during bus acceleration

Age and acceleration level were found to associate significantly with changes in step type (0.05 confidence level), when participants were ascending the stairs. However, step type was not influenced by participants' gender. This are summarised in Table 4. The importance of different step types in this analysis is that the shift from one step type to another is beyond the participant's conscious control. It is a subconscious response to the challenge of maintaining balance when "normal" walking conditions cease to apply. In this case, the "walking conditions" were dictated by the change in motion of the bus and the "step type" response was recorded across all participant groups as a good observable response to the environmental challenge imposed by the motion of the bus. The percentage of step types identified at each acceleration level are presented in Figure 3.

In the static environment, over 80% of participants' steps were two-peak - which



(a) Overall



(b) Age Group

Figure 3: Step type distribution at each acceleration condition whilst ascending the stairs. The legend enclosed in graph (a) also applies to graph (b).

Table 4: Chi-square tests for step types observed in stair ascending during bus acceleration

	Age			Gender			Acceleration Level		
	Value	df	Asymp. Sig. (2-sided)	Value	df	Asymp. Sig. (2-sided)	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	133.38[a]	12	.000	7.26[a]	6	.297	169.32[a]	24	.000
Likelihood Ratio	140.69	12	.000	7.23	6	.300	196.57	24	.000
N of Valid Cases	2484			2484			2484		

a: 0 cells (.0%) have expected count less than 5.

include normal steps - whilst one-peak steps were used 16% of the time in this environment (Figure 3a). A trivial number of three-peak steps (0.75%) was observed whilst ascending a static stair, which shows that the dimensions of the stair, in conjunction to the stability of the environment in negotiation, did not require a person to engage extra support mechanisms in order to maintain their balance. In addition, the amount of one-peak steps used in the static environment, reveals that the task was within participants' comfort zone in terms of balance, and hence nothing was deterring them from using “less secure” step types.

On the stationary bus, participants were negotiating a narrower staircase with steeper stairs, compared to that in the static environment (Section 2). Although, just like in the static environment, the bus was not moving, it was observed that participants' gait consisted of more two-peak (+3%), fewer one-peak (-4%) and more three-peak (+0.7%) steps. The three-peak steps in particular were almost doubled on the stationary bus, but continued to be the least frequently used step type. Hence, the dimensions of the stairs on the bus forced participants to alter their natural way of walking, and in some cases to increase the level of stability, in order to avoid a fall. At the same time, the stationary bus staircase was not considered as a threat and participants sustained a level of confidence that they would remain in control of their balance, thus they continued using a considerable amount of the least stabilising step type (one-peak).

The acceleration of the bus (1.5 m/s^2), forced participants to alter their walking style further in comparison to the previous tasks (static and stationary). Their gait pattern in this case consisted of fewer two-peak (-10.6%), an equal number of one-peak and more three-peak steps (+10%) than in the stationary case. Three-peak steps in particular increased by 10.5% and by 9.8% compared to those observed during ascending on a static and stationary staircase respectively. This outcome shows clearly that the movement of the bus had an effect on participants' ability to control their balance and hence they were using steps that increased contact with the stair.

Young participants were substituting two-peak steps with three-peak steps as the difficulty of the task was increasing (Figure 3b). Being the strongest of the examined sample (Karekla and Tyler, Under revision), they used more one-peak steps than middle-aged and older participants overall. Middle-aged participants used around 2% more three-peak steps in the static and stationary environment than younger and older participants. The profile of two-peak and one-peak steps they used, followed the overall sample (Figure 3a), however they used fewer one-peak steps than younger participants. Older participants, on the other hand, used more two-peak and three-peak steps, but fewer one-peak steps than the other two age groups. Especially during medium acceleration, older participants used around 15% more three-peak steps than on the stationary stairs and 6.6% and 5.5% more compared to the younger and middle-aged groups respectively.

3.2 Stair descending during bus deceleration

Unlike ascending, the results for stair descending showed that gender is also a significant factor affecting step type. Age and acceleration level significantly affect a person's step type also during stair descending. The results of the *chi-square* tests are presented in Table 5.

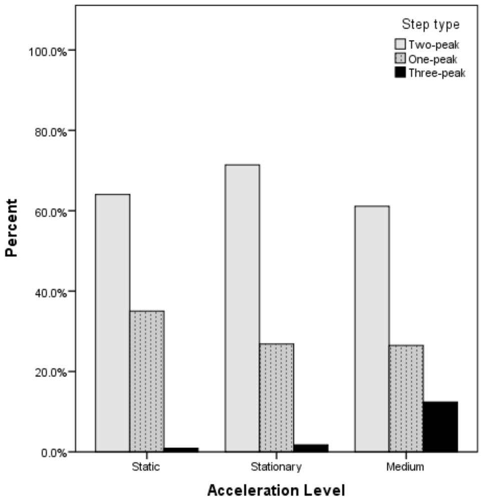
Table 5: Chi-square tests for step types observed in stair descending during bus deceleration

	Age			Gender			Acceleration Level		
	Value	df	Asymp. Sig. (2-sided)	Value	df	Asymp. Sig. (2-sided)	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	54.31[a]	12	.000	22.17[a]	6	.001	199.52[a]	24	.000
Likelihood Ratio	55.27	12	.000	23.76	6	.001	208.11	24	.000
N of Valid Cases	1900			1900			1900		

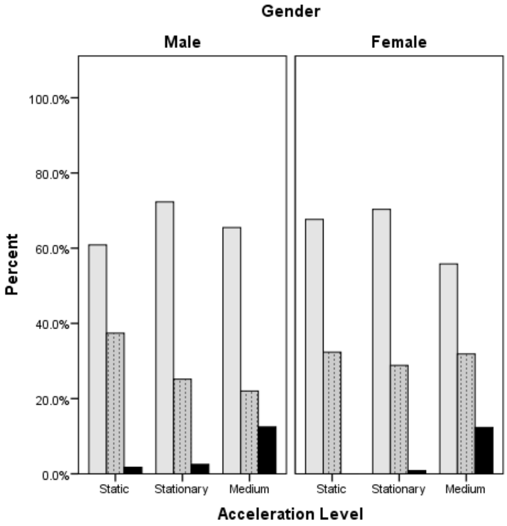
a: 0 cells (.0%) have expected count less than 5.

During stair descending in the static environment, 64% of the steps used by the general sample were two-peak, 35% were one-peak and only 1% were three-peak steps. Participants used the majority of one-peak steps on the static staircase, compared to the 27% of one-peak steps used on the stationary staircase and the 26.5% used during medium deceleration. This shows that naturally the most stabilising steps (three-peak steps) are not essential for these participants to descend a staircase and that they can sustain their balance even by using a considerable number of the least stabilising steps (one-peak steps).

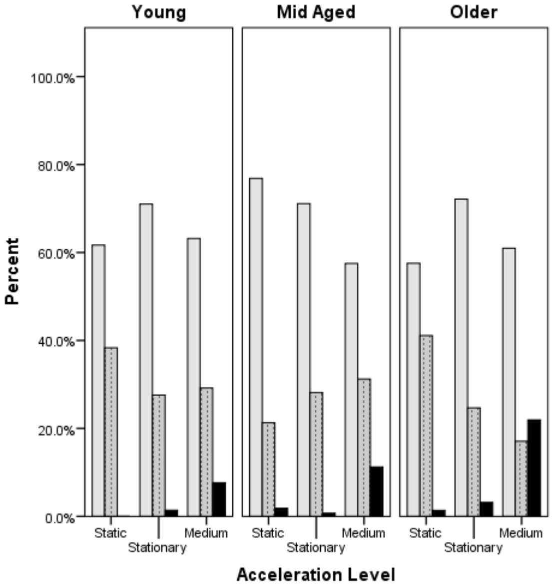
Moving to the stationary environment, the design of the bus staircase forced participants to to decrease the number of one-peak steps (-8%), which were substituted by two-peak steps that increased by 7% compared to the static environment. Three-peak steps were also increased by 0.8%. Hence, negotiating the stationary staircase, participants required extra support which they found by increasing the



(a) Overall



(b) Gender



(c) Age Group

Figure 4: Step type distribution at each acceleration condition whilst descending the stairs. The legend enclosed in graph (a) also applies to graphs (b) and (c).

area of their plantar that is in contact with the ground.

Compared to the stationary environment, a similar amount of one-peak steps was used during stair descending at medium deceleration. However, the number of two-peak steps reduced by 10%, roughly reaching the number of two-peak steps using in natural gait (61%). The rest of the steps (12.4%) were three-peak steps, revealing a 12% increase compared to the static and stationary environments. From this behaviour, it can be seen that descending a staircase during medium deceleration offers the least stability and participants compensate for their reduced balance by using steps that increase their contact with the ground and hence their support base.

Male participants appeared to have more difficulty controlling their balance than females (Figure 4b). Unlike females, they used three-peak steps in all conditions. While negotiating the stairs on the stationary bus, males used fewer one-peak steps (-7%) but more three-peak steps (+1.7%) compared to females. During medium deceleration, females used 10% more of the less stabilising steps (one-peak steps), but equal amount of three-peak steps as the males. This is an unexpected outcome which contradicts the existing literature, as males are generally considered to have better balance (Hsue and Su, 2014; Lord et al., 1996). However, it could be that one or more other factors, such as body weight, might be influencing this outcome and this should be investigated further. Male participants of the examined sample are heavier than female participants (Karekla, 2016) and it has been shown that increased weight reduces mobility and therefore balance (Gaur and Parekh, 2015).

Regarding participants' age, the young ones used the most one-peak and the least three-peak steps compared to the other age groups, whereas they required no three-peak steps on the static stairs. They have the best balance of the entire sample and hence they could afford to use step types of reduced level of support, as they could rely on their strong limbs to help them sustain balance. Middle-aged participants used two-peak steps more than the other participants. As the difficulty of the task was increasing between the static, stationary and moving bus cases, middle-aged participants were reducing the number of two-peak steps (-6% between the static and stationary environment and -14% between the stationary and moving bus) and were increasing the number of one-peak steps (+7% between the static and stationary environment and +3% between the stationary and moving bus). The reasoning behind this behaviour is questionable; as they have less natural balance than younger participants, one would expect them to seek more support as difficulty increases. This raises the question whether they used alternative balance mechanisms, such as handrail use, which should be investigated further. The older age group, just like middle-aged participants, used three-peak steps in all conditions, with the majority of them recorded during medium deceleration (22%). More precisely, during medium deceleration, they used 19% more three-peak steps compared to the stationary environment and 14% and 11% more compared to young and middle-aged participants respectively. At the same time, as the task difficulty was increasing, they were reducing the number of one-peak steps (-24% and -8% less than their natural gait and stationary bus respectively).

3.3 Comparison of the stair negotiation tasks

Considering the overall number of steps observed in the static environment between stair ascending (Figure 3a) and descending (Figure 4a), it can be seen that in descending two-peak steps were used approximately 20% less, whereas 20% more one-peak steps were observed compared to stair ascending. A similar number of three-peak steps was used in both tasks.

Although the amount of steps used continued to be different between ascending and descending, the effect of the layout of the bus staircase (stationary) was observed to be the same: more two-peak, fewer one-peak and more three-peak steps. This is due to the dimensions of the bus staircase which forced participants to incorporate more stabilising step types into their walking compared to the one they performed on the static staircase. The reduction of one-peak steps in stair descending was double that observed in stair ascending, which reveals that participants were using a more cautious walking pattern whilst descending the stationary bus staircase. The need for an increased support base was amplified when the bus was decelerating at a medium level, as an 33% increase in three-peak steps was observed when compared to number of three-peak steps used whilst ascending the bus staircase during medium acceleration. The step type variability observed in the stationary environment compared to the natural gait in both tasks, has made it evident that bus passengers start their journeys with an inherent disadvantage due to the bus staircase design, and even when the bus is stationary, they need to alter their natural gait in order to remain balanced. In fact, the dimensions of the bus staircase fall into the category of stairs that increase risk of falling and are considered highly unsafe for public health (Johnson and Pauls, 2010). A design that considers increased staircase width and stairs with longer treads would provide more stability (Novak et al., 2016).

Based on the above, descending appears to be more difficult than ascending as participants were constantly and unintentionally using a combination of all three step types in order to successfully descend the stairs. In addition, and as it was observed in level walking (Karekla and Tyler, Under revision), the external forces generated by the bus movement force people to adopt a more stable walking pattern by increasing the contact area between their foot and the floor. This effect is more pronounced in older people, who used approximately 6% more three-peak steps during acceleration and 11% more three-peak steps during deceleration compared to the other two age groups. Considering the dimensions of the bus staircase, it seems impossible for any of the participants of this sample to have been able to place their entire plantar on the stairs whilst maintaining a forward facing posture. Thus, it can be speculated that participants were tilting their feet so as to fit on the stairs. This is a behaviour that has been observed in older people by previous researchers, who have been observed to alter their posture towards the direction of the handrail whilst negotiating stairs (Maganaris et al., 2018). Despite the fact that gender was not a critical factor associated with step type during stair ascending, males showed that they are in general less able to control their balance when the bus is moving, as they used less destabilising steps and more stabilising steps than females during stair descending. This result might be driven from the behaviour of the young and middle-aged males of the sample who used more one-peak steps than older participants. According to the results regarding double support time, a gait event that encloses information about people's stability, which are presented in Karekla and Tyler (2018) and were derived from these experiments, males of the middle-aged group presented the highest variability in their balance and seemed to be less able to control their balance when the bus was moving. A possible reason for this could be that middle-aged were the only ones from the general sample that increased the number of destabilising steps (one-peak steps) when the bus was moving compared to the other two environments (static and stationary staircase). This suggests that physical strength might be irrelevant when it comes to balancing in dynamic environments and that the literature around male stability needs to be updated.

Lower and higher acceleration levels were also tested as part of this experimental process (Karekla, 2016), but the results are not presented in this paper. It is important, however, to mention that three-peak steps were used less during low acceleration and more during high acceleration compared to medium acceleration, avoiding one-peak steps when possible. Therefore, as bus acceleration increases participants use a walking style that increases their contact with the ground, and therefore their stability.

4 Conclusions

The walking pattern of 29 healthy bus users, between 20 and 80 years old, was investigated whilst ascending and descending stairs. An excessive use of three-peak steps was identified throughout the experimental task, which led to the interesting observation that the bus environment and movement forces people to unconsciously alter their natural gait and increase the support base when negotiating stairs. To achieve better stability when the bus is moving, the dimensions of the staircase would need to be altered to comply with the buildings regulations for health and safety. However, the constraints imposed by the limited dimensions of the vehicle, required in order for it to function within an urban traffic stream, mean that it would be very difficult and costly to increase the width of the stairs. Even though the length of the bus, and therefore the tread of the stair, can be redesigned, the width of the bus staircase is constrained by the dimensions of the road, as the vehicle needs to fit into the dimensions of the traffic lanes. Modern buses (including the one used in these experiments) have reduced the number of turns in the stairs (thus reducing the number of stairs with different goings). Providing a completely straight staircase, for example, would necessitate the removal of several seats and loss of standing/wheelchair space on the vehicle. Therefore, altering the dimensions of the bus would solve only part of the problem, but changing the way the bus moves and setting a specific level of acceleration ($\pm1.0\ m/s^2$) above which bus drivers are not authorised to accelerate (Karekla and Tyler, 2018) will make buses safer and more accessible. Work is ongoing with a bus operator to assess the implications of such a control of acceleration, both for the journey times of the vehicle and also on driver behaviour. Transport operators could make use of these findings to increase passenger satisfaction, and hence demand, as by enabling people to walk naturally during their bus journeys will reduce fear of falling and more people will be using public transport systems for their everyday activities.

As with every scientific work that seeks solutions to problems following a microscopic approach, this work also suffers from some limitations that would need to be addressed in future investigation. The developed algorithm, through which the main variable of this work (step type) has been derived, was based on a limited sample size and bus movements. To increase the accuracy of the methodology a bigger sample in size and in age range, as well as mobility difficulties would need to be examined. The presented work focused on the vertical force applied to the plantar. However, the bus movement generated a force that has a horizontal and lateral component which also affect the way people distribute their weight onto their plantar. Thus, analysing gait in respect to these forces would also increase the accuracy of the results and would produce a more complete idea of the factors that govern the way people negotiate dynamic environments.

The fact that the outcomes of this study were derived after monitoring the gait of people who are able to walk unaided, reveals the importance of investigating the gait of those who naturally have difficulties in walking and to analyse the way they cope in such environments. This will enable us to further understand the challenges dynamic environments impose onto people and to reduce fall-related injuries for all. The type of steps people use during stair negotiation and whilst they carry shopping, luggage, or travel with accompanying persons is also worth exploring as many bus passengers travel under these circumstances on a daily basis. Furthermore, the presented environment is only a part of people's everyday life. Other dynamic environments would have to be investigated in order to provide further understanding around people's walking. This will enable the advancement of walking aids as well as the design of prostheses so that their users can walk naturally in any environment. The fact that even the most able participants had to alter the gait so as to remain upright can be taken into account by the footwear industry.

References

[1] AgeUK (2009), 'Get on board', https://www.transportforall.org.uk/files/id8562nationalfallsawarene (accessed 13-07-2016).

[2] AgeUK (2010), 'Falls in the over 65s cost nhs 4.6 million pounds a day', http://www.ageuk.org.uk/latest-press/archive/falls-over-65s-cost-nhs/. (accessed 28-07-2015).

[3] Canadian Institute for Health Information (2013), 'National trauma registry report 2013: Hospitalization for major injury in canada, 2010-2011 data', https://secure.cihi.ca/estore/productSeries.htm?pc=PCC46. (accessed 31-05-2016).

[4] Centers for Disease Control and Prevention (2015), 'Costs of falls among older adults', http://www.cdc.gov/homeandrecreationalsafety/falls/fallcost.html. (accessed 13-07-2016).

[5] Chong, R. K., Chastan, N., Welter, M.-L. and Do, M.-C. (2009), 'Age-related

changes in the center of mass velocity control during walking', *Neuroscience letters* **458**(1), 23–27.

[6] Christina, K. A. and Cavanagh, P. R. (2002), 'Ground reaction forces and frictional demands during stair descent: effects of age and illumination', *Gait & posture* **15**(2), 153–158.

[7] De Asha, A. R. and Buckley, J. G. (2015), 'The effects of walking speed on minimum toe clearance and on the temporal relationship between minimum clearance and peak swing-foot velocity in unilateral trans-tibial amputees', *Prosthetics and orthotics international* **39**(2), 120–125.

[8] Gaur, M. and Parekh, K. (2015), 'A study to determine the association of body mass index with performance-based measures of balance and mobility in young adults', *Int J Physiother Res* **3**(4), 1175–79.

[9] Hsue, B.-J. and Su, F.-C. (2014), 'Effects of age and gender on dynamic stability during stair descent', *Archives of physical medicine and rehabilitation* **95**(10), 1860–1869.

[10] Johnson, D. A. and Pauls, J. (2010), 'Systemic stair step geometry defects, increased injuries, and public health plus regulatory responses', *Contemporary Ergonomics and Human Factors* pp. 453–461.

[11] Karekla, X. (2016), Improving Accessibility of Public Transport Systems: the Influence of Double-Decker Bus Acceleration on Passenger Movement, PhD thesis, University College London.

[12] Karekla, X. and Tyler, N. (2018), 'Reducing non-collision injuries aboard buses: Passenger balance whilst walking on the lower deck', *Safety Science* **105**, 128–133.

[13] Karekla, X. and Tyler, N. (Under revision), 'Maintaining balance on a moving bus: the importance of three-peak steps whilst walking on the lower deck', *Transportation Research Part A: Policy and Practice* .

[14] Kunzler, M. R., da Rocha, E. S., Dos Santos, C. S., Ceccon, F. G., Priario, L. A. and Carpes, F. P. (2018), 'Should we consider steps with variable height for a safer stair negotiation in older adults?', *Work* **59**(1), 15–21.

[15] Lord, S. R., Lloyd, D. G. and Li, S. K. (1996), 'Sensori-motor function, gait patterns and falls in community-dwelling women', *Age and Ageing* **25**(4), 292–299.

[16] Lord, S. R., Sherrington, C., Menz, H. B. and Close, J. C. (2007), *Falls in older people: risk factors and strategies for prevention*, Cambridge University Press.

[17] Maganaris, C., Baltzopoulos, V., Jones, D., Di Giulio, I., Reeves, N., Gavin, J., Ewen, A., King, S. and Roys, M. (2018), *The New Dynamics of Ageing*, Vol. 1, Policy Press.

[18] Mayagoitia, R. and Kitchen, S. (2009), 'The use of stair ascent and descent speed to determine level of performance in older people', *Gait & Posture* **30**, S67.

[19] McFadyen, B. J. and Winter, D. A. (1988), 'An integrated biomechanical analysis of normal stair ascent and descent', *Journal of biomechanics* **21**(9), 733–744.

[20] Novak, A. C., Reid, S. M., Costigan, P. A. and Brouwer, B. (2010), 'Stair negotiation alters stability in older adults', *Lower Extremity Review* **2**(10), 47–51.

[21] Novak, A., Komisar, V., Maki, B. and Fernie, G. R. (2016), 'Age-related differences in dynamic balance control during stair descent and effect of varying step geometry', *Applied ergonomics* **52**, 275–284.

[22] Office of Public Sector Information (2013), 'Protection from falling, collision and impact', www.opsi.gov.uk. (accessed 01-06-2016).

[23] O'Sullivan, S. B., Schmitz, T. J. and Fulk, G. (2013), *Physical rehabilitation*, FA Davis.

[24] Shumway-Cook, A. and Woollacott, M. H. (2007), *Motor control: translating research into clinical practice*, Lippincott Williams & Wilkins.

[25] Steenbekkers, L. P. A. and Van Beijsterveldt (1998), *Design-relevant characteristics of ageing users*, Vol. 1, Delft University Press, The Netherlands.

[26] Transport for London (2015), 'Health, safety and environment report 2014/15', http://www.betterbuildingspartnership.co.uk/sites/default/files/media/attachment/TfL-health-safety-environment-report-2015.pdf. (accessed 13-07-2016).

[27] Verghese, J., Wang, C., Xue, X. and Holtzer, R. (2008), 'Self-reported difficulty in climbing up or down stairs in nondisabled elderly', *Archives of physical medicine and rehabilitation* **89**(1), 100–104.

[28] World Health Organisation (2015), 'Falls', http://www.who.int/mediacentre/factsheets/fs344/en/. (accessed 14-07-2015).

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We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

We confirm that we have given due consideration to the protection of intellectual property associated with this work and that there are no impediments to publication, including the timing of publication, with respect to intellectual property. In so doing we confirm that we have followed the regulations of our institutions concerning intellectual property.

We further confirm that any aspect of the work covered in this manuscript that has involved human patients has been conducted with the ethical approval of all relevant bodies and that such approvals are acknowledged within the manuscript.