Reducing non-collision injuries aboard buses: passenger balance whilst climbing the stairs

Karekla, Xenia* and Tyler, Nick

Department of Civil Environmental and Geomatic Engineering

Centre for Transport Studies

University College London

Gower Street, London WC1E 6BT, UK

**Corresponding author. E-mail address: x.karekla@ucl.ac.uk*

Abstract

In a previous work of the authors, the impact of acceleration on people's walking on the lower deck of a bus was examined. The importance of investigating the impact of bus acceleration when people are walking on the bus staircase is also recognised. As many falls occur on steps or stairs, especially during stair descending, eliminating non-collision bus injuries will attract more people to active means of transportation and will contribute towards healthier societies.

Twenty-nine healthy and regular bus users (20-80 yrs.), took part in this study. Their natural gait on a static staircase was monitored in a laboratory and was compared to their gait on the staircase of a moving double-decker bus. When the bus was in motion, the most common movements aboard buses were studied: stair ascending during bus acceleration and stair descending during bus deceleration. The examined acceleration levels (low - 1.0 m/s^2, medium - 1.5 m/s^2, high - 2.5 m/s^2) were set in the range of accelerations experienced by passengers on the real bus service in London.

ANOVA tests were conducted considering the changes in double support time (DST, gait event indicative of balance) between tasks and levels of acceleration. Participants' age and gender were also variables informative of the significance of the differences in DST. The results revealed that passengers start their journeys with an inherent disadvantage due to the bus staircase design, which worsens their ability to maintain balance as acceleration increases. To eliminate falls aboard buses, the current acceleration level should be decreased.

Keywords: non-collision injuries, bus acceleration, stair ascending, stair descending, balance, accessibility

1 Introduction

Buses form a cost effective means of mobility for people of all age groups that is increasingly used by the elderly as society is ageing (Transport Committee, 2013), and even though passenger cars are still the most preferred mode of travelling (83.4%), a large number of people chooses bus networks for their everyday movements, activities, and social encounters. In fact, in 2014, 9.1% of passenger journeys in Europe were done by buses and coaches compared to 7.6% of journeys recorded on rail networks. However, in-land transportation use reduced by 5%, and bus journeys by 1%, between 2004 and 2014 (Eurostat Statistics Explained, 2017). In England in particular, bus journeys in the year 2016-17 reduced by 1.6% compared to those undertaken in the same period in the year 2015-16 (Department for Transport, 2017).

Comparing the collision and casualty rate of a bus to that of a car, it can be seen that travelling by bus is much safer than travelling by car. Taking casualties during traffic accidents in Greater London as an example, the 2016 statistics show that car passengers account for 39% of all casualties, whereas bus passengers account for only 5% of all casualties (Transport for London, 2017*b*). A similar trend is observed for the whole of the European Union: 45% of all recorded fatalities are related to car users (mainly drivers) and 1% of all recorded fatalities are related to bus users (European Union Road Federation, 2017). Therefore, safety alone is not the basis for people choosing their private cars over a safer means of transport, such as the bus, for their everyday movements.

Accessibility and the smoothness of the bus movement are factors that score high when bus passenger satisfaction is questioned (London Travel Watch, 2010). However, older members of the society avoid using the bus service as they find it inconvienient and poorly designed for their needs (Green et al., 2014), whereas the astonishing number of 800 falls reported every day on buses in the UK by those over 65 year old magnifies their fear of falling (Age UK, 2009; Zijlstra et al., 2007). Bus passenger non-collision injuries in London, which required hospitalisation, increased from 128 in 2014, to 703 in 2015 (+82%), to 796 in 2016 (+12%) (Transport for London, 2017*a*). Even though a downward trend is observed between 2016 and 2017 (-6%), the number of hospitalised injuries is still at high levels (749 people in 2017). The authors acknowledge that the great increase in the number of hospitalised injuries between 2014 and 2015 (82%) can be subject to the personal initiative of reporting a fall or injury.

Non-collision injuries during bus journeys can occur at any stage of a journey. Bus passengers can be injured by slipping or by losing their balance when trying to board or alight the vehicle, when the bus is stationary at a bus stop or at traffic lights. When the bus is moving, accidents can happen either because the driver does not wait for the passengers, especially elderly and disabled ones, to find a seat or due to hard accelerations/decelerations (Bird and Quigley, 1999; Björnstig et al., 2005).

Loss of balance is more likely to happen whilst climbing stairs, as more body capabilities are required to elevate the centre of mass to a higher step (Mayagoitia et al., 2002). Therefore, people with lower muscle strength, such as older females, present higher difficulty in climbing stairs and more balance loss incidents, particularly during stair descent (Verghese et al., 2008). The bus movement enhances this instability by applying vertical, fore-aft and lateral forces to the human body. Hence, people that are moving inside a bus, not only have to overcome their natural instability that increases with age (Hsue and Su, 2014), but they also need to counteract the forces generated by bus acceleration. A free-standing passenger can withstand accelerations of up to 0.9 m/s^2, whereas in the case they use a handrail, passengers are likely to avoid a fall if acceleration does not exceed 2.0 m/s^2 (a list of publications that refer to these thresholds can be found in Karekla, 2016). Surprisingly, accelerations and decelerations on the London bus service, which serves as this work's case study, reach, and in some cases exceed, 2.5 m/s^2.

The rate of bus acceleration, or the smoothness of the bus movement as it is also referred to, is another significant factor that affects people's balance Levis (1978). This is in line with the passenger satisfaction surveys mentioned above. Acceleration rates below 0.9 m/s^3 offer a comfortable journey to passengers (Castellanos and Fruett, 2014), with an acceleration rate of 0.6 m/s^3 being ideal for passenger comfort (Vuchic, 1981). Although the acceleration rate is an important factor affecting passenger comfort, the complexity of the experiments in this study did not allow its investigation. As this work is the first studying real passenger movement in the real environment, limiting the controlled factors was necessary, hence the work presented in this paper focuses on the impact of bus acceleration on passenger gait and balance. Further work will need to be done on the effect of acceleration rate on passenger movement.

The described problem is one encountered by bus passengers worldwide, especially in cities with intense bus services, such as London, Ottawa, Hong Kong, or Singapore, that use double-decker buses. Therefore, passengers' ability to cope with the accelerations developed on a bus will be assessed, together with their capability to retain balance whilst moving inside the moving vehicle. The objective of this work is to define an acceptable level of acceleration that would provide an accessible bus service to users of all age groups, and would be safe by allowing them to climb the bus staircase naturally, whilst avoiding injuries. The influence of the design of the bus staircase is also being investigated and the alterations it imposes or not to people's natural gait are discussed. Participants' balance is assessed using double support time (DST), a gait characteristic that defines the time a person keeps both feet on the ground and relates to a person's stability (Reid et al., 2011). Participants' age and gender are also considered when comparing their walking styles in different environments and acceleration levels.

2 Methods

As this is still an unexplored area of research, there is a need to establish some basic principles about the problem, which are supported by quantified evidence. In order to find out the trends of the relative motions of a person and the bus on which they are travelling, some form of repeatable experiments is needed, which will be carried out under controlled conditions and during which a person's movement will be tested against different, known, bus movements. This means in effect that it is necessary to have a set of controlled experiments in which appropriate data can be collected to describe both the bus and the person movements in relation to time. This paper reports the results of such a set of experiments, carried out in the UCL Pedestrian Accessibility Movement and Environment Laboratory. Twenty-nine regular bus users, between 20 and 80 years old, were recruited to undertake these experiments. Participants were divided into three age groups; the size, physical and demographic characteristics of each group, the devices used and the condition of the road are mentioned in Karekla and Tyler (2018).

At first, it was necessary to monitor participants' movement in a static environment, where no external force is applied. From this, the natural way of walking, unconstrained by any environmental circumstance, of each of the participants was drawn. This part of the experiment served as the baseline of the experimental process, against which participants' walking pattern in other environments was compared. In the static environment, participants were asked to ascend and descend a five step staircase, the dimensions of which comply with regulations for public buildings (Office of Public Sector Information, 2013): 175 mm riser, 240 mm tread and 1140 mm width.

The dynamic tests were undertaken in a real bus. First, stair ascending and descending tests in the stationary bus were undertaken when the engine of the bus was running, causing it to vibrate lightly. This allowed the comparison to the static environment and would highlight whether passengers start their journeys with an inherent disadvantage due to the bus environment itself. Then, the same tests were examined whilst the bus was in motion, at a 'low' (1.0 m/s^2), 'medium' (1.5 m/s^2) or 'high' (2.5 m/s^2) acceleration rate, in order to understand whether passengers are forced to alter their gait due to the acceleration of the bus. Bus driver training was organised before the experiments to ensure that these levels of acceleration were consistently achieved. The range of bus acceleration that participants were exposed to at each examined acceleration level during the experiments and their distribution are included in Table 1. The bus staircase consisted of seven stairs with a riser of 240 mm, tread of 220 mm and free width of 550 mm. Participants were advised to ascend and descend only the straight part of the staircase. The starting and ending point of each task is shown in Figure 1.

Table 1: Descriptive statistics of bus acceleration at each examined level

Acceleration Level	N	Minimum	Maximum	Mean	Std. Deviation	Skewness	Kurtosis
Low	1574	-2.16	1.36	0.20	0.63	-0.52	-0.84
Medium	1543	-2.22	1.96	0.40	0.98	-0.67	-0.96
High	1494	-2.57	2.02	0.46	1.15	-0.88	-0.67

Note: SE of Skewness is 0.06 and SE of Kurtosis is 0.13 in all cases

In all experimental conditions participants were equipped with an in-shoe gait

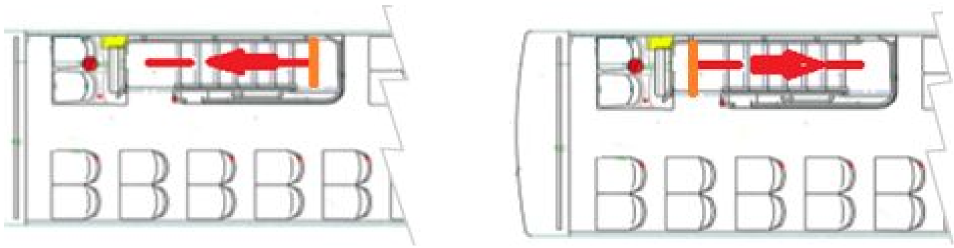

Figure 1: Experimental task of ascending (left) and descending (right) the straight part of the bus staircase. The starting point (orange/solid line), walking path (red/dashed line) and direction of participant movement are marked in the picture.

monitoring device (F-Scan mobile system, Tekscan Inc.) and were able to use the handrails when necessary, whilst the bus acceleration was monitored by a wireless accelerometer (MT SDK 3.8.1., Xsens Technologies) recording at 50Hz. Qualitative data were also collected through questionnaires. At the end of each task and acceleration condition, participants were asked to assess the difficulty of the experiment and report any balance loss incidents they experienced. The outcomes of the questionnaires are presented in Karekla (2016), whilst a brief reference is made here to strengthen particular points in the Results and Discussion sections.

As discussed in Karekla and Tyler (2018), participants were divided into three age groups, young (20-39 years); middle-aged (40-59 years) and older (over 60 years), and the changes and variation identified in gait patterns between different environments in regards to double support time (DST) were analysed. DST is a temporal gait parameter that is used to provide information about a person's balance whilst walking. It is used in the experiment reported here to enable comparison with walking in static environments and in a moving bus, but walking along a flat surface.

3 Results

3.1 Stair ascending during bus acceleration

A three-way independent ANOVA test was performed to reveal whether the three independent variables can account for any significant differences in double support time during stair ascending. The output of the test showed that age, gender and acceleration level have a significant effect on double support time ($p<.05$). Furthermore, the combined effect of age and acceleration, gender and acceleration as well as age, gender and acceleration on double support time was also significant ($p<.05$).

Table 2: Analysis of variance (ANOVA) for double support time (DST) whilst stair ascending during bus acceleration

Source	*Type III Sum of Squares*	*df*	*Mean Square*	*F*	*Sig.*
Corrected Model	5.180 [a]	29	.179	5.405	.000
Intercept	116.377	1	116.377	3521.107	.000
Age Group	.457	2	.229	6.919	.001
Gender	1.597	1	1.597	48.327	.000
Accel. Level	1.045	4	.261	7.905	.000
Age Group * Gender	.101	2	.050	1.528	.217
Age Group * Accel. Level	.567	8	.071	2.144	.029
Gender * Accel. Level	.477	4	.119	3.605	.006
Age Group * Gender * Accel. Level	.830	8	.104	3.139	.002
Error	81.108	2454	.033		
Total	209.756	2484			
Corrected Total	86.288	2483			

[a] R Squared = .060 (Adjusted R Squared = .049)

The mean DST value at each acceleration level was calculated considering all participants (Figure 2). In the static environment of the laboratory, the mean DST value, which represents people's natural duration of DST, was 0.24 sec. On the stationary bus, however, the mean DST was found to be lower (0.19 sec) than the natural DST. After conducting a *Gabriel post hoc* test on the mean DST values,

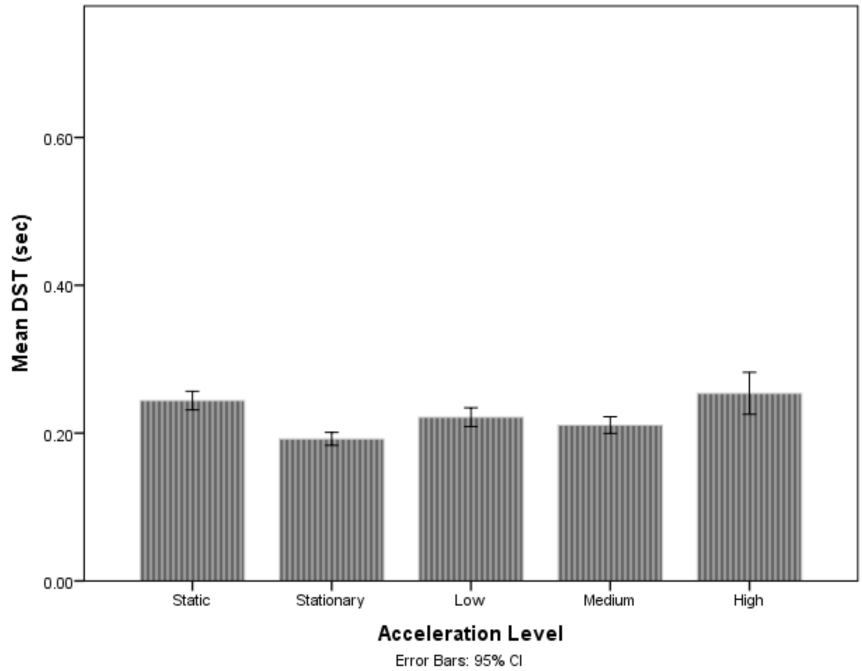

Figure 2: Mean DST and its variation during stair ascending at the five examined acceleration levels

it was shown that the difference of 0.05 sec observed in the two environments is significant (p <.001).

When the bus was moving at low acceleration, participants' mean DST was found to be 0.22 sec, whereas a lower DST value was found at medium acceleration (0.21 sec). Neither of the two mean values is significantly different from the mean DST value calculated in the static and stationary environment (p >0.05 - *Gabriel post hoc* on all multiple comparisons of the five acceleration levels). At high acceleration, on the other hand, the mean DST value was 0.25 sec. Although it is the highest value calculated in all environments, the difference is not significant when compared to the value found in the static environment (p >0.05), which shows that participants overall were sustaining a natural double support time.

Focusing on participants' age, when all acceleration levels were considered, a mean DST value of 0.21 sec was calculated for young participants, whereas for both the middle-aged and older participants a value of 0.23 sec was found. Therefore, no

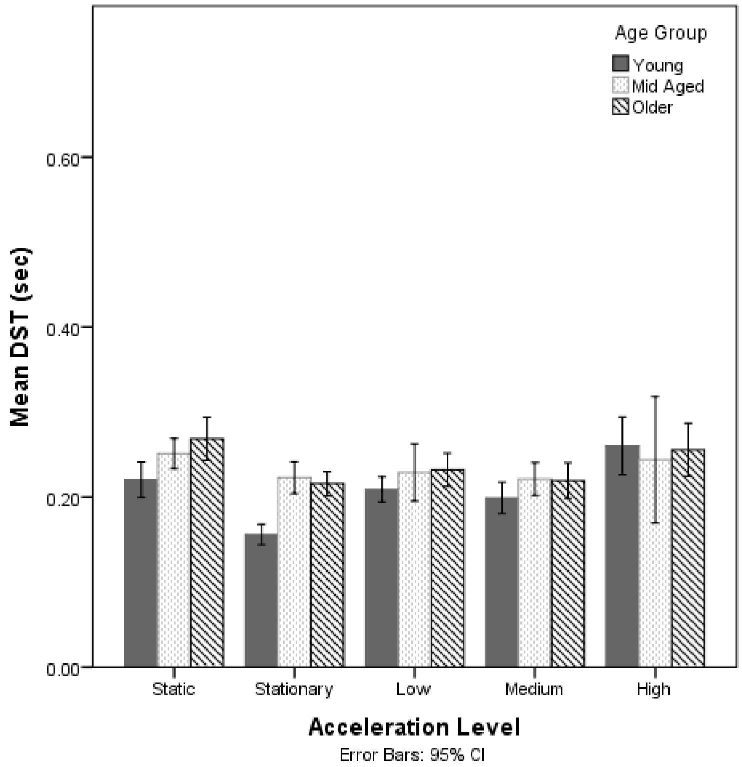

Figure 3: Mean DST and its variation for each age group during stair ascending at the five examined acceleration levels

significant difference was detected between the mean values of the middle-aged and older age group (p >0.05), however the mean DST of the younger age group was significantly lower by 0.03 sec (p <0.05).

Although young participants presented the lowest mean DST of all age groups overall, and hence at each acceleration level, at high acceleration their mean DST was higher (0.26 sec) than that of middle-aged and older participants (0.24 and 0.25 sec respectively). Nonetheless, the effect of acceleration on young participants was shown to be great (Figure 3) as their mean DST fluctuates between 0.15 sec (stationary case) and 0.26 sec (high acceleration) as the acceleration level increases. On the other hand, the increase of the level of acceleration had little effect on the mean DST of the older participants and very little effect on that of middle-aged participants, especially on the bus.

Male participants presented an overall higher mean DST value (0.25 sec) than

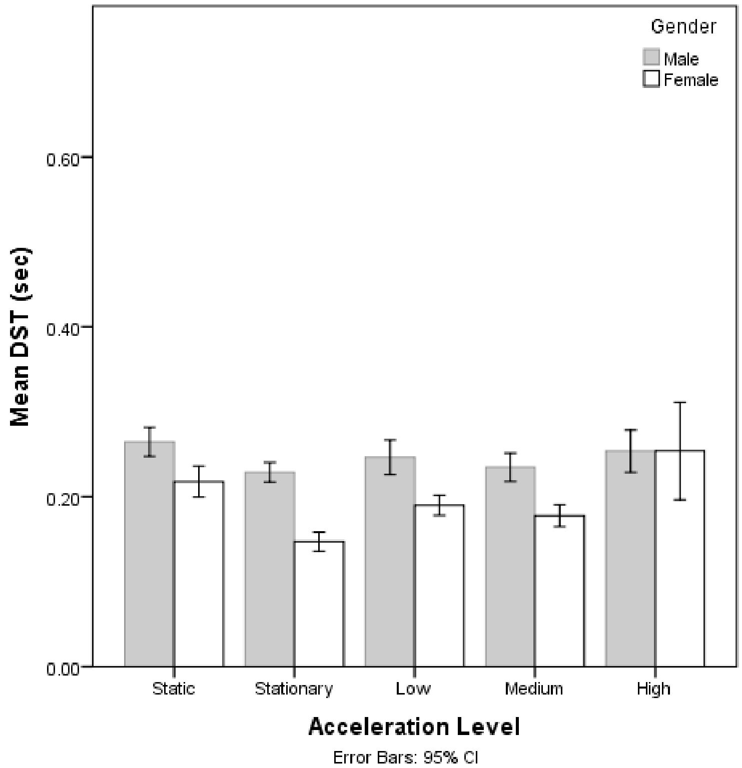

Figure 4: Mean DST and its variation for each gender during stair ascending at the five examined acceleration levels

female participants (0.20 sec), the difference of which was significant (p <0.05). Moreover, when each acceleration level was considered separately (Figure 4), it was shown that as the acceleration level was increasing men altered their DST only slightly, whereas the effect of acceleration on women had a greater effect.

Finally, the interaction between all three tested variables (Figure 5) has revealed that the increase of the examined acceleration had the greatest effect on young participants' mean DST, especially female ones. On the other hand, acceleration had little effect on the mean DST of middle-aged and older participants of both genders, especially on the stationary bus and during low and medium acceleration levels. At high acceleration though, almost all participants presented longer mean DST value than that calculated for medium acceleration. Compared to the natural mean DST value (static condition), young female, middle-aged female and older male participants presented longer mean DST than their natural, whereas shorter mean DST was observed for older female participants.

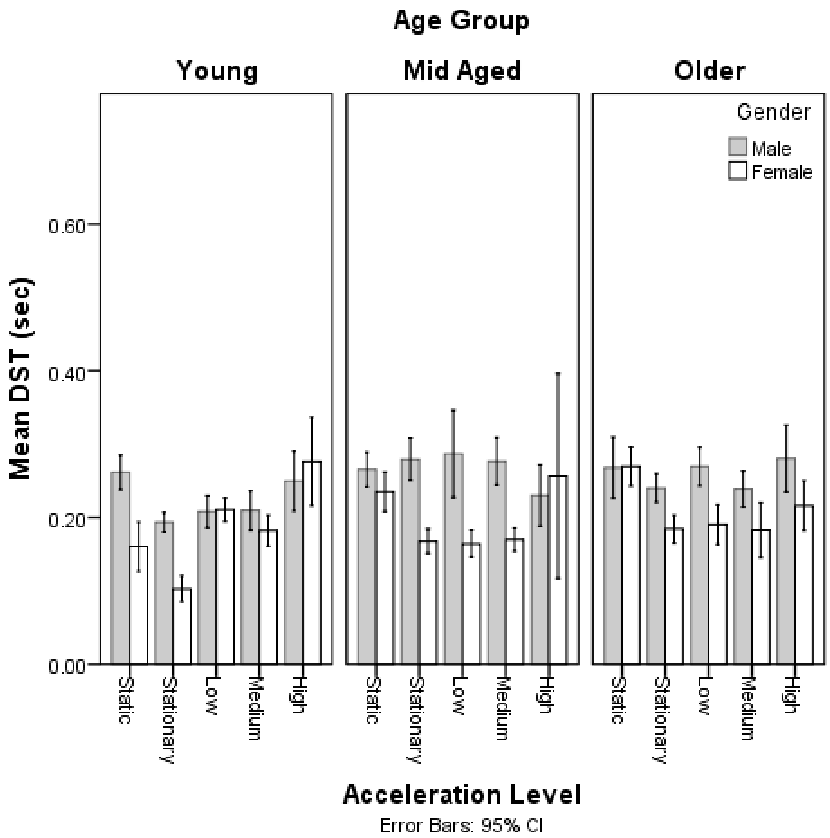

Figure 5: Mean DST and its variation for each gender and age group during stair ascending at the five examined acceleration levels

Even though the mean value of the DST parameter is capable of providing information about people's response to an environment, its variation can unveil the difficulty of a person to control their balance in that environment (Section 2 and Karekla and Tyler, 2018). Therefore, in order to understand the stability challenges participants experienced at each examined acceleration level during stair ascending on the bus, the standard deviations (SD) of the obtained DST values were plotted in respect to the SD of the DST values recorded in the static environment (Figure 6). An SD multiple equal to 1.0 states that the variability of the DST values in the said condition was the same as for the DST values recorded in the static environment. Hence, participants were able to sustain their natural stability. Consequently, SD multiples below 1.0 denote that the variability of the examined DST values is lower than that observed in natural gait, and hence participants completed stair ascending with caution whilst presenting increased ability in controlling balance. On the contrary, SD multiples above 1.0 state that the recorded DST values were not as consistent as in the static environment, and thus participants experienced more difficulty in controlling balance and avoiding a fall.

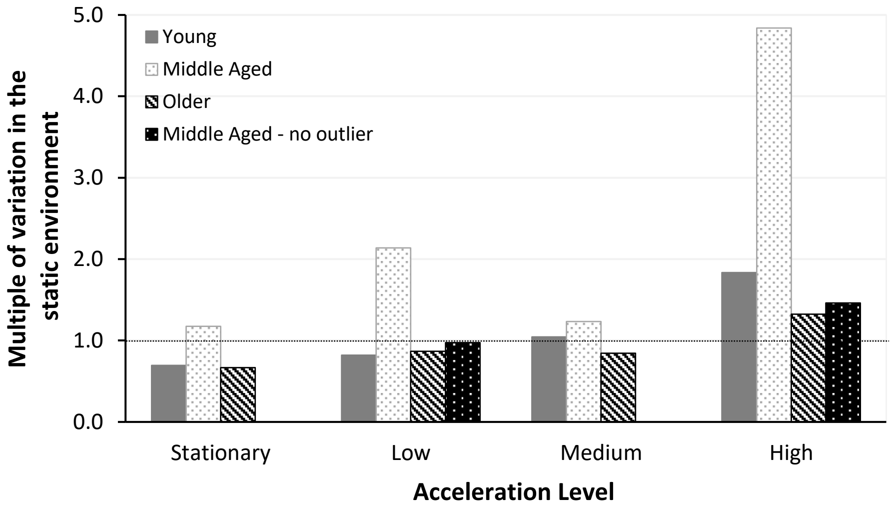

Figure 6: Variation of DST values compared to the static environment during stair ascending at the five examined acceleration levels. Value 1.0 of the vertical axis indicates the variation recorded in the static environment (natural walking).

Following the above logic, one can see that, on the stationary bus, young and older participants completed the ascending task with caution, while middle-aged participants almost sustained their natural gait. Thus, it is reasonable that the majority of participants (93%) did not report loss of balance at this acceleration level (Karekla, 2016). Young and older participants remained vigilant at low and medium acceleration levels. However, middle-aged participants, especially male (large SD bar in Figure 5), were less able to control their balance during low acceleration. Nonetheless, their behaviour during medium acceleration was similar to that recorded on the stationary bus. Surprisingly though, only 13% of middle-aged reported balance loss during low and medium acceleration levels when they were asked (Karekla, 2016). Stair ascending during high acceleration was revealed to be the most challenging task for all participants. As can be seen in Figure 6, young participants of both genders as well as middle-aged female participants were unable to control their balance in this acceleration condition (variation of DST values much higher than 1.0). Unexpectedly, older participants seemed to be the only ones facing the least problems. Although the observed DST values of older participants in high acceleration were higher than 1.0, their gait was the closest to natural gait compared to participants of the other two age groups.

Looking at the data of the middle-aged group more closely, in an attempt to explain the large variation of their gait in low and high accelerations compared to their natural gait, it was found that a 47 year old male and a 46 year older female performed unnaturally prolonged DST periods. After removing the outlying values of these individuals, the new DST variation was then calculated for the middle-aged group (black dotted bars in Figure 6). Therefore, excluding the extreme values, middle-aged participants were able to control their balance during low acceleration (DST variation almost 1.0), just like young and older participants. However, the new results show that at high acceleration they continue to have problems with remaining upright. It is worth mentioning that a 76 year old (older age group) and a 31 year old (young age group) were unable to complete stair ascending during high acceleration. Hence, the variation for these two age groups presented in Figure 6 would have been higher.

Despite that, it is essential to understand that the said individuals are regular bus users and the examined accelerations are experienced on the real service in London (Section 2). Hence, the inability of these individuals to control their balance during low and high acceleration, or to complete the task during high acceleration, shows that they are confronted with such challenges during their everyday bus journeys. Had they not been physically healthy, they would not have avoided a fall or even an injury. Hence, their response to these acceleration levels should not be ignored, but it should be rather considered when defining the level of acceleration performed on public transport system, especially buses.

3.2 Stair descending during bus deceleration

Similar to stair ascending, the data collected from participants during the stair descending task were used to perform a three-way independent ANOVA test. For consistency, the term ‘acceleration level’ will also be used in this section. However, what is actually being discussed is the deceleration phase of the bus movement which corresponds to the deceleration levels mentioned in Section 2.

The ANOVA test showed that age, gender and acceleration level can be held accountable for the significant changes observed in double support time ($p <.05$). Furthermore, the combined effect of age and gender (that was not proven significant when ascending a stair), age and acceleration, gender and acceleration as well as age, gender and acceleration on double support time are also significant ($p <.05$).

Considering all participants at each acceleration level, it was shown that as acceleration increases the mean DST value also increases, especially when the bus is moving (Figure 7). In fact, in the static and stationary environment, participants kept both of their feet on the floor for an average of 0.21 and 0.20 sec respectively. At low bus acceleration, the mean DST value was calculated to be 0.24 sec, whereas at medium and high accelerations, higher mean values were obtained (0.27 and 0.33 sec respectively).

Applying *Gabriel's* pairwise comparisons, it was verified that the 0.01 sec difference between the mean DST in the static and stationary environments is not

Table 3: Analysis of variance (ANOVA) for double support time (DST) whilst stair descending during bus deceleration

Source	*Type III Sum of Squares*	*df*	*Mean Square*	*F*	*Sig.*
Corrected Model	9.847 [a]	29	.340	6.509	.000
Intercept	100.987	1	100.987	1935.798	.000
Age Group	.374	2	.187	3.583	.028
Gender	.667	1	.667	12.794	.000
Accel. Level	3.253	4	.813	15.587	.000
Age Group * Gender	.808	2	.404	7.744	.000
Age Group * Accel. Level	1.007	8	.126	2.412	.014
Gender * Accel. Level	1.610	4	.402	7.713	.000
Age Group * Gender * Accel. Level	2.421	8	.303	5.800	.000
Error	97.554	1870	.052		
Total	213.488	1900			
Corrected Total	107.401	1899			

[a] R Squared = .060 (Adjusted R Squared = .049)

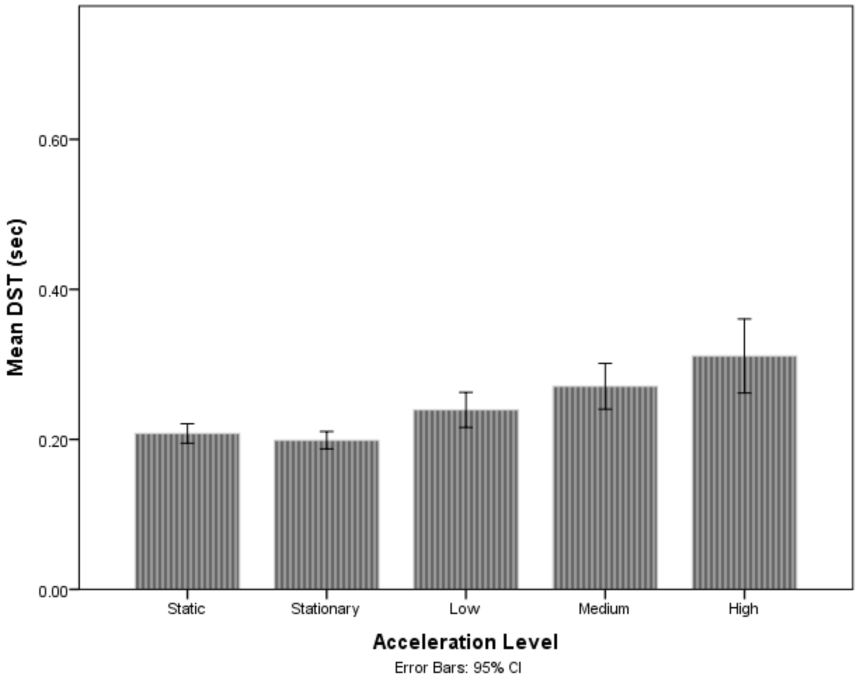

Figure 7: Mean DST and its variation during stair descending at the five examined acceleration levels

significant (p >.05). The same is confirmed when the mean DST of each of the static and stationary environments is compared against the mean DST calculated for low acceleration (p >.05). However, the difference between the mean DST during medium acceleration and that in the static environment (natural gait) is significant (p <.05). Equally, the difference between the mean DST during medium acceleration and that calculated on the stationary bus is also significant (p <.001). The mean DST calculated during low and high accelerations does not differ significantly compared to that during medium acceleration (p >.05). Consequently, the difference between the mean DST during high acceleration and that in the static and stationary environments as well as during low acceleration is significant (p <.001).

Focusing the analysis on participants' age, the mean value of DST for young participants was 0.22 sec, whereas for both middle-aged and older participants was 0.25 sec, when all acceleration cases were considered together. The employed pairwise comparisons (*Gabriel's post hoc test*) showed that the difference between the mean DST of young and middle-aged participants is not significant (p >.05), however the mean DST of young and older participants is significantly different (p <.05). As expected, the difference between the mean DST value of middle-aged and older participants is not significant at a 0.05 level (p >.05).

The effect of bus acceleration on the mean DST time of each age group had a higher effect in the stair descending task (Figure 8) than in the stair ascending task (Figure 3 in Section 3.1). Both young and older participants reduced their natural mean DST when they were undertaking the task on the stationary bus. Once on the bus, both age groups were increasing their mean DST as acceleration was increasing, with the exemption of low and medium acceleration which had no effect on the DST of young participants (0.23 sec in both cases). Therefore, the highest mean DST value for these two age groups was recorded during high acceleration (0.30 sec for young and 0.25 sec for older participants). Regarding middle-aged participants, they were increasing their natural mean DST as acceleration was increasing. However, unlike the young and older age groups, middle-aged were observed to decrease their

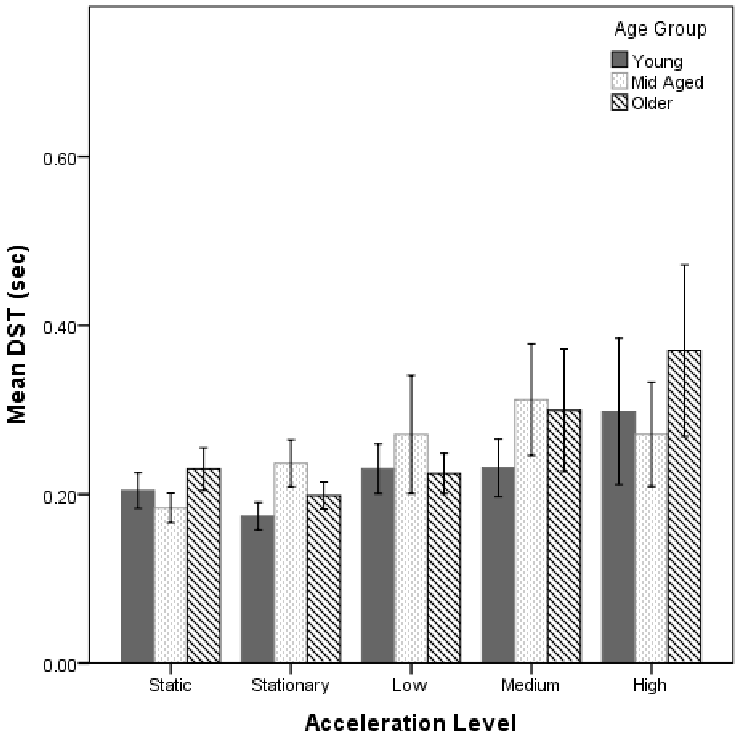

Figure 8: Mean DST and its variation for each age group during stair descending at the five examined acceleration levels

DST during high acceleration, and to sustain a mean DST similar to that observed during low acceleration (0.27 sec).

As in stair ascending, a longer mean DST was recorded for male participants (0.27 sec). The 0.04 sec difference between the mean DST values of the two genders was significant ($p < .001$). Naturally (static environment), both males and females present equal mean DST (0.20 sec). However, when the acceleration condition becomes more demanding, the two genders present opposite responses (Figure 9); on the stationary bus, males increase their mean DST, whereas females reduce it. As bus acceleration is increasing, female participants increase their mean DST, showing that they require more time on both feet to sustain their balance. Although male participants also increase their mean DST up to medium acceleration level, during high acceleration they appear to spend less time on both feet (decreased mean DST).

Examining the interaction between age, gender and acceleration level (Figure

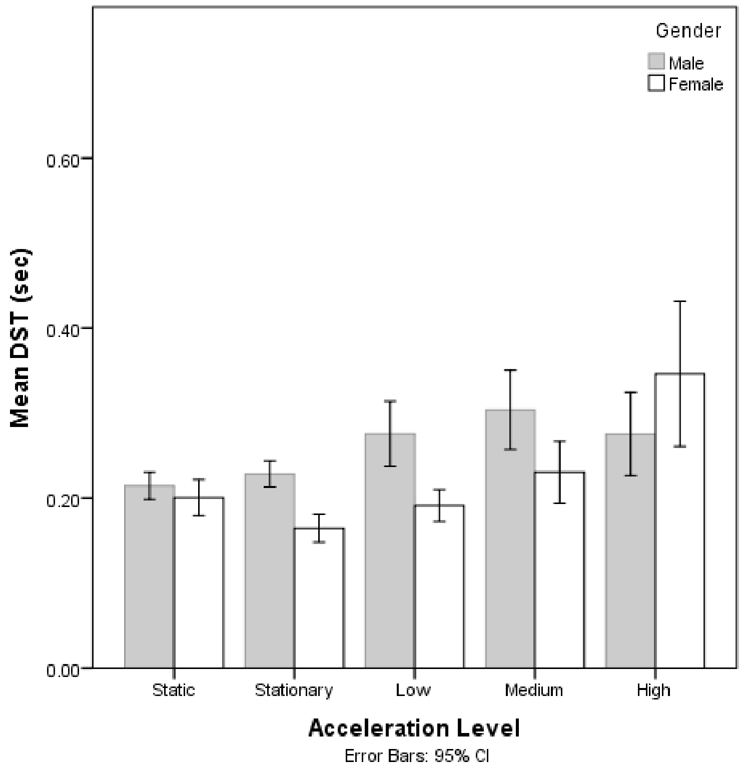

Figure 9: Mean DST and its variation for each gender during stair descending at the five examined acceleration levels

10), it is shown that acceleration has a large effect on the mean DST of all examined sub-groups. For young participants, the effect of acceleration is larger on the mean DST of women during high accelerations. Similarly, for older participants, the largest effect is observed on the mean DST of females during high acceleration, as well as on that of males during medium and high acceleration. Large differences of the mean DST value are also observed for middle-aged male participants on the bus and for middle-aged female participants during medium and high accelerations.

In order to further understand each group's behaviour towards controlling balance compared to their natural ability, as described in subsection 3.1, the variation of DST values was calculated for each acceleration level. As can be seen in Figure 11, young and older participants were vigilant on the stationary bus, as the variation of their DST values was lower than the one recorded in the static environment

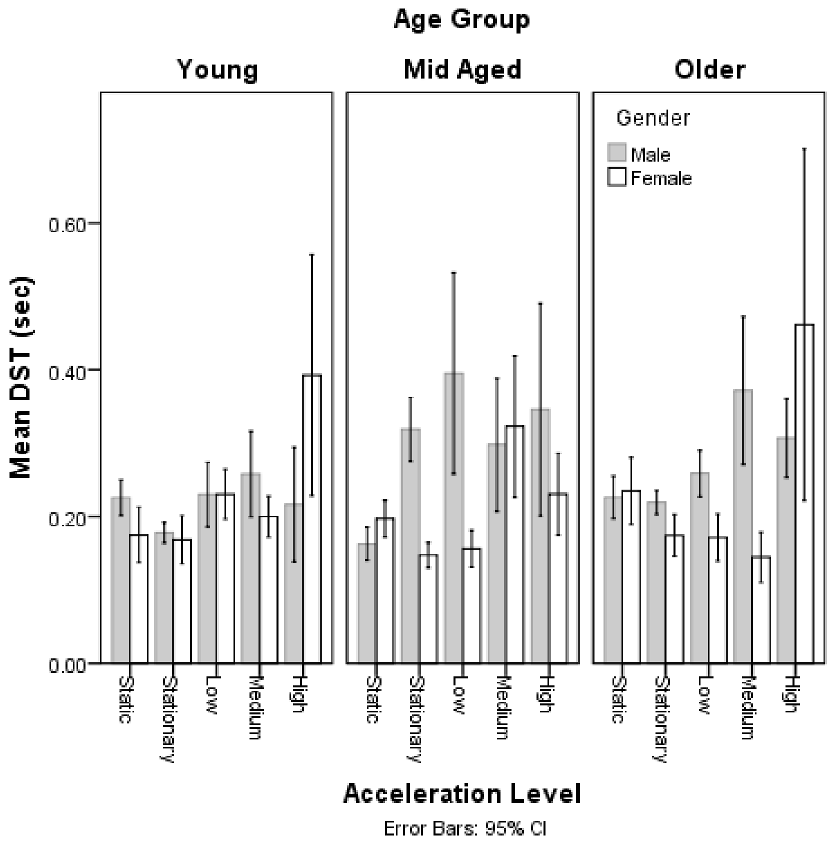

Figure 10: Mean DST and its variation for each gender and age group during stair descending at the five examined acceleration levels

(SD <1.0). Whereas older participants completed stair descending with caution also during low acceleration, young participants appeared to have difficulty in controlling their balance in this environment (SD >1.0). As acceleration was increasing, both the young and the older participants presented reduced ability to control their balance, with older participants, especially male, having more balance problems during medium acceleration than young ones. While participants of all age groups presented difficulty in controlling their balance during high acceleration, middle-aged participants were unable to sustain their balance in all environments (SD >1.0), especially during low acceleration. This came as a surprise, as middle-aged participants reported no difficulty in completing stair descending on the stationary bus and during low acceleration, but more than half of them reported balance loss during medium and high accelerations (Karekla, 2016).

Comparing the speed at which all participants completed stair descending when the bus was moving, an explanation for the abnormal response of middle-aged participants can be given. Irrespectively of the movement of the bus, young participants were overall significantly faster (1.17 ± 0.5 m/s) than middle-aged (0.93 ± 0.4 m/s) and older (0.90 ± 0.4 m/s) participants ($p = .000$). However, no difference in walking speed was observed between middle-aged and older participants ($p = .586$). Therefore, one would expect middle-aged participants to present similar balancing behaviour to those of the older age group. Looking at each acceleration level separately, it appears that middle-aged participants have the illusion that their body capabilities are much stronger than they actually are. As the bus acceleration level increases, young and older participants reduce their walking speed gradually from low to medium to high acceleration in order to compensate for their lost balance and remain upright (-0.03 and -0.07 m/s between low and medium accelerations and -0.01 and -0.04 m/s between medium and high acceleration for the young and older age group respectively). Middle-aged participants, however, present a greater reduction in their speed between low and medium acceleration (-0.09 m/s) and instead of reducing their speed further when bus acceleration reaches the high level, they become faster (+0.03 m/s) which increases their instability.

The high variability of DST values in middle-aged participants' gait, compared to participants of the other two age groups, raised questions regarding potential outliers that were probably providing a false image of the group's capability to maintain balance. Combining the information given in Figure 10 and 11, two male participants (47 and 57 years old) in the stationary environment, a 42 year old male participant during low deceleration and two 57 years old male and female participants during medium deceleration, were sustaining longer DST times than other participants of this age group. Hence, the outlying DST values in each case

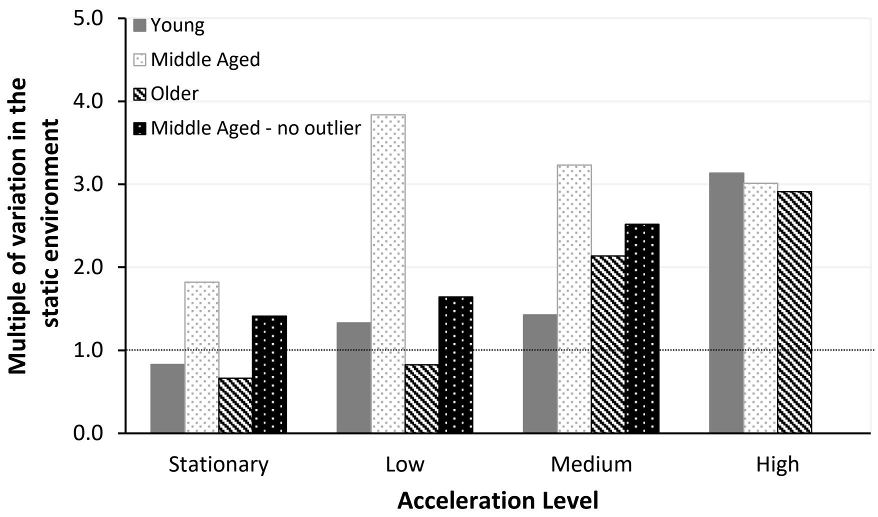

Figure 11: Variation of DST values compared to the static environment during stair descending at the five examined acceleration levels. Value 1.0 of the vertical axis indicates the variation recorded in the static environment (natural walking).

were removed and a new SD value was calculated (black dotted bars, Figure 11). Even without the outliers, the variation of DST in middle-aged participants' gait is still higher than that recorded in the static environment and than that of the other two age groups. Thus, it can be concluded that stair descending during bus deceleration was more demanding and caused bigger balance problems for middle-aged participants, than for young and older participants.

4 Discussion

This paper analyses passenger balance in two cases along real bus journeys: when a passenger is walking up the stairs whilst the bus is accelerating away from a bus stop or traffic lights (stair ascending during bus acceleration) and when a passenger is walking down the stairs whilst the bus is decelerating into a bus stop or due to the traffic ahead (stair descending during bus deceleration).

Examining the gait of 29 regular bus users, it was observed that when it comes to stair negotiation, passengers commence their journeys by altering their natural gait due to the bus interior. The bus staircase is narrower and steeper than a staircase built under the Public Buildings Regulations. The latter ensures health and safety, whereas a constrained environment, such as that of the bus staircase, is limiting the movement of the extremities and reduces balance (Tung et al., 2011). Moreover, the higher the stair riser the bigger the displacement of the centre of mass (Chou et al., 2001), the more muscle activity required (Lord et al., 2007) and the slower the movement of the person (Graat et al., 1999). The latter has also been evident in this work; taking into account the way passengers negotiate the lower deck of the bus (Karekla and Tyler, 2018) and combining it with the way passengers negotiate bus staircases (results presented in this paper), it is observed that, regardless of the acceleration condition, participants complete the staircase tasks at a slower pace compared to level walking.

The movement of the bus imposes additional deviations from the natural gait. As bus acceleration increases, passengers become slower at both ascending and descending the stairs and as a result DST time increases. This occurs due to the inertia, generated by the movement of the bus, which, in both cases - stair ascending during acceleration and stair descending during deceleration, acts in the opposite direction of the movement of the passenger, therefore pulling them towards the rear of the bus. In stair ascending, a misplaced foot or an inertial force higher than the person's body capabilities can counterbalance, would result in a fall at the bottom of the staircase. In stair descending a fall would find the person landing on a higher stair, and in the worst case that the inertial force is very high, the person could end up sliding down the stairs. Hence, in order to avoid the unfortunate situation of a fall, passengers compensate for their instability by altering their natural gait. The force passengers apply on the handrails during these tasks can reveal additional balance mechanisms that are being incorporated into walking and are currently being investigated by the authors.

It is considered that women are less confident in negotiating stairs. They are 1.4 times more likely to report difficulty in stair negotiation than men (Startzell et al., 2000), they walk with more caution (Hsue and Su, 2014) and keep both feet on the ground for longer periods (Figure 6 (a), page 39 in Karekla, 2016. Resulting from an extensive literature review carried out on gait differences between age groups and genders). However, the results presented in this paper are contradicting the literature. Although males of this study reported difficulty fewer times than females whilst negotiating the bus staircase (Karekla, 2016), they presented longer DST times than female participants in both tasks and all acceleration levels except high acceleration. This shows that the staircase design and the level of bus acceleration challenged male participants' balance more than females' balance, as males needed to spend more time on both feet to compensate for their instability. This raises the question whether physical capabilities are irrelevant when negotiating a dynamic environment. At high acceleration, females presented longer and more variable DST times than males and can be considered as a threshold, where the forces applied on passengers' body due to the bus acceleration are so high that women, who have weaker limbs than men, are no longer able to control their balance and need to regain stability before moving on to the next step.

With regards to age, young participants kept both feet on the ground for significantly shorter periods compared to middle-aged and older participants when negotiating the bus staircase. They are better at controlling their balance on the stairs, especially during descending (Ewen et al., 2009) and this can be attributed to their better natural balance and stronger limbs. In addition, being the tallest of the examined sample (Table 20, Section 6.1, Chapter Six in Karekla, 2016) possibly enabled them to develop larger foot clearance between their swinging foot and the edge of the stair compared to older participants, which allows faster transitions from one stair to another (De Asha and Buckley, 2015).

Even though middle-aged participants generally rated walking on the stairs, and particularly stair ascending, easier than older participants (Karekla, 2016), the analysis of their gait has shown that they actually sustained similar double support times to the older age group, although more variable due to the outliers. Older participants were negotiating the stairs with more caution throughout the experimental process, however their ability to control balance reduced dramatically when acceleration levels were higher than 1.5 m/s^2, especially during stair descent.

Whether ascending or descending a staircase is physically more demanding than level walking, is not relevant when it comes to enjoying a safe bus journey. Participants have expressed their preference of sitting upstairs (Table 22 in Karekla, 2016) and thus being able to safely walk up or down the bus staircase, whilst the vehicle is in motion, is essential. For a fully accessible bus journey, during which the likelihood for injuries is minimal for passengers of any age group and gender, bus acceleration should not be higher than 1.0 m/s^2. Acceleration levels above 1.5 m/s^2 should be avoided, as middle-aged and older passengers will not be able to sustain their balance and this might result in falls.

5 Conclusions

Passenger gait on a staircase was successfully investigated for the first time in the real environment of a moving bus and a threshold value for bus acceleration, which ensures an accessible service for all, was defined. This was achieved by comparing the natural walking behaviour of 29 regular bus users on a static staircase in a laboratory against their behaviour whilst walking on the staircase of a double-decker bus. The analysis was focused on double support time, a temporal gait parameter that is normally used to provide information about people's balance.

The design of the bus staircase has a significant impact on passengers' balance, who are struggling to maintain their balance even when the bus is stationary, especially during stair descending. When the bus is in motion and as acceleration is increasing, passengers spend more time on both feet as a mechanism to compensate for their lost balance. Passengers' age and gender are also significant factors in their ability to control balance on the stairs. Especially middle-aged men appear to have more difficulties in maintaining balance compared to young and older people of both genders. Therefore, to reduce injuries on the bus service, double-decker buses should operate at accelerations lower than 1.0 m/s^2. At this level of acceleration, the majority of passengers will be able to ascend and descend the bus staircase naturally, whereas passengers of the middle-aged group will still be somewhat challenged.

To enhance understanding around passenger movement in dynamic environments, the role that the upper body plays in maintaining balance should also be studied. Moreover, it is not clear whether acceleration or acceleration rate is the most influential factor in dynamic environments and its investigation will contribute greatly to the scientific field. Road turns, carried objects (e.g. buggies or shopping bags) and the effect of shoe types in the way people negotiate the bus environment during their journeys will also contribute in reducing injuries aboard buses worldwide. Finally, understanding how people perceive their capabilities and comparing this to the actual capabilities they present during tasks would inform the abnormal behaviour middle-aged participants in this study presented.

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