Reducing non-collision injuries aboard buses: passenger balance whilst walking on the lower deck

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Abstract

Travelling by bus is a way millions of people choose for their everyday activities. However, the large acceleration levels, and therefore the associated increased number of falls and non-collision injuries, force current users to shift to other modes of transport, with cars still remaining the preferred choice.

This study investigates whether there is a possibility to improve the safety and comfort of buses, where all passengers can walk naturally inside a moving bus. Twenty nine regular bus users, between 20 and 80 years old, were invited to participate in a series of experiments. Their natural gait whilst walking on a flat surface was monitored in a static laboratory and was compared to their gait whilst walking on the lower deck of a moving bus. 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.

An ANOVA test was conducted on measures of changes in gait (double support time) as a measure of balance, taking into account passengers' age and gender as well as the acceleration of the bus. The results revealed that, although the dimensions of the lower deck of the bus are narrow, passengers are still able to move to the back of the stationary bus whilst sustaining their natural balance. However, their ability to control balance reduces with the increase of acceleration.

Keywords: non-collision injuries, bus acceleration, level walking, balance, accessibility

1 Introduction

There are more than 6,000 injuries on buses in the UK reported every year, with half of them suffered by 65 year olds and over (Kendrick et al., 2015). However, there seem to be 800 falls every day for people over 65 that are not officially reported and occur due to the developed accelerations (Age UK, 2009). Non-collision injuries on buses in London have increased by 82% between 2014 and 2015, and more female than male bus passengers are reporting balance loss incidents (Transport for London, 2015). Statistics from other countries in Europe and states in the USA are similar to those reported for the UK (O'Neill, 2016).

Passenger comfort is affected by technical, physiological or psychological factors (Oborne, 1978). Although comfort is subjective, it can be influenced by the design and ambience of the vehicle, e.g. position of handrails, noise and vibration, heating and ventilation, crowding (Bird and Quigley, 1999; Suzuki et al., 2006; Cox et al., 2006). The lack of perceived safety and comfort of buses, especially for older people, may act as a barrier to use. In England, bus journeys in the first quartile of the year 2016 reduced by 2.5% compared to those undertaken between 2014 and 2015 (Department for Transport, 2016). Similar trends are recorded for Europe (Eurostat, 2016).

One of the main documented reasons (3rd most important) for passenger dissatisfaction with the bus service and for making them turn away from using bus services is the lack of smoothness of the bus acceleration (London Travel Watch, 2010). Due to the high acceleration levels, 18% of bus passengers in England report to be dissatisfied with the smoothness of the service (Transport Focus, 2014), whereas many older people over 65 refrain from using the service as they think it is dangerous (Green et al., 2014). The danger they are referring to lies with the feeling of reduced stability they experience during their journeys. Generally, older people have weaker limbs and sway more than younger people (Hsue and Su, 2014), hence they present reduced balance in static environments (Era et al., 2006). One would expect this behaviour to be amplified when they negotiate dynamic environments, such as a moving bus, but this has not been investigated before the present study.

Buses are not used only by healthy individuals. More than 20% of bus journeys in England are made by people with a disability or long-term illness, and accessibility is an issue for them just as it is for those travelling with heavy luggage or small children. Passenger dissatisfaction related to the smoothness of the bus service for these people reaches up to 24% in some areas of England (Transport Focus, 2015). Hence, there is a general dissatisfaction with bus services around the world, and passenger falls or injuries require large national funds for treatment. Indicative, in 2010 £4.6 million was spent every day in the UK and US$ 82 million in the USA to cover fall-related costs (Age UK, 2010).

Buses interact with and depend on the movement of other vehicles on the road. Therefore, the accelerations recorded on them are much higher than those on other public transport modes and can often exceed the recommended threshold of 2.0 m/s^2 within which standing passengers can only maintain balance when holding a handrail (Browning, 1972; De Graaf and Van Weperen, 1997; Dorn, 1998). For example, the bus service in Amsterdam reaches accelerations of 2.2 m/s^2 compared to 1.5 m/s^2 on the metro system (De Graaf and Van Weperen, 1997), and buses in London reach accelerations of up to 2.5 m/s^2 (Sale, 2007), much higher than the 1.3 m/s^2 level of acceleration recorded on the London Underground network (Transport for London, 2009). Passengers' comfort is also affected by the rate of acceleration. Levis (1978) found that perceived comfort correlates more with jerk than acceleration. Acceleration rates below 0.9 m/s^3 offer a comfortable journey to passengers (Castellanos and Fruett, 2014), whereas an acceleration rate of 0.6 m/s^3 is considered ideal (Vuchic, 1900). In theses initial experiments, the impact of bus acceleration on passenger gait and balance is studied. Subsequent experiments can be focused on the effect of jerk on passenger movement.

This paper investigates people's ability to control balance inside the dynamic environment of a moving double-decker bus, a mode of transport widely used by many people in international urban centres, with the aim to define an acceptable level of bus acceleration below which most passengers can move freely during their journeys. This is achieved by monitoring people's natural gait in a static environment and comparing it to their gait, and therefore ability to remain upright whilst moving inside a moving bus. The observed differences in walking style will indicate the impact of the environment, e.g. bus design or movement, on passengers' balance. Taking into account that balance deteriorates with age and that women sway more than men (Hsue and Su, 2014), passengers' age and gender will also be considered when comparing their walking style.

2 Methods

A series of randomly repeated experiments under controlled conditions was organised in the static environment of a university laboratory (PAMELA, UCL) and on a real double-decker bus, owned by UCL. After obtaining ethical approval (4464/001), 29 regular bus users, between 20 and 80 years old, were recruited to undertake these experiments on two different days (16 males, 13 females, 47.2 (±16.1) years, 172.9 (±10.4) cm, 73.0 (±14.3) kg). More information on the physical characteristics of each age group can be found in Table 1 below.

In the static environment, participants were asked to take ten steps on a flat

Table 1: 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.

surface at their preferred speed, whilst their natural gait was being recorded by an in-shoe plantar pressure system (F-Scan mobile system, Tekscan Inc., Boston, USA - error order: ± 3%). All participants were wearing sport shoes and the pressure sensors were trimmed to their shoe size. The sensors were calibrated based on the participants' weight over the plantar area at which this was applied during a single stance calibration test. On a different day, and equipped with the same gait monitoring device, they were asked to walk on the straight part of the lower deck of the double-decker bus, moving from the front door towards the back of the bus, simulating the situation of a boarding passenger who is searching for a seat on the lower deck (Figure 1). Initially the bus was stationary and participants' gait was compared to their natural gait (that recorded in the static environment), revealing whether the bus layout affects gait. Subsequently, on the same day, the same task was repeated when the bus was moved 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 explore whether the bus movement alters natural gait. The bus was driving on the straight parts of a public road, the surface of which presented a similar good condition to the roads where the London bus service operates, and was not affected by the city traffic. The examined level

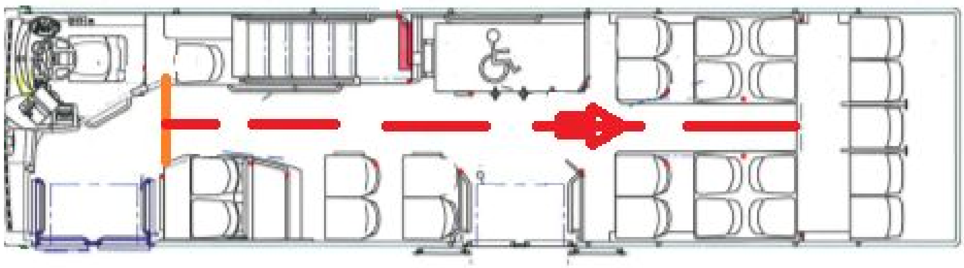

Figure 1: Experimental task of walking on the lower deck of the double-decker bus. The starting point (orange/solid line), walking path (red/dashed line) and direction of participant movement are marked in the picture.

of acceleration was set in the range of accelerations passengers experience on the current bus service in London (Karekla, 2016) and was monitored by a wireless accelerometer (MT SDK 3.8.1., Xsens Technologies, Netherlands - error order: 0.05 m/s^2). Each task was repeated three times in each environment and participants could use the bus handrails whenever necessary. The two monitoring devices were synchronised and their use did not affect participants' gait.

For the analysis of the data, participants were divided into three age groups following Steenbekker and Van Beijsterveldt's analysis on balance (Steenbekkers and Van Beijsterveldt (1998)): young (20-39 years); middle-aged (40-59 years) and older (over 60 years). Furthermore, changes of temporal and spatial gait parameters, such as walking speed, stance, double support time (DST) and step width, have been shown to be an indication of instability and to provide accurate predictions between fallers and non-fallers. From biomechanical principles, an increase in the value of such parameters leads to greater stability and may be regarded as compensation for instability (Gabell and Nayak, 1984; Kalron and Achiron, 2014). At the same time, an increase in the variability of gait parameters, e.g. DST, indicates poor ability to control balance and increased risk of falls (Gabell and Nayak, 1984;Kloos et al., 2012). This paper focuses on DST, a temporal gait parameter, and analyses the changes and variation of it identified in gait patterns between different environments, which provide information about people's balance. This is important where the reason for instability is the result of having to respond to dynamic changes in the environment, rather than some inherent lack of capability in the participant.

3 Results

A three-way independent ANOVA test was conducted and revealed that age, $F(2, 3181) = 52.56, p < .001$, gender, $F(1, 3181) = 18.50, p < .001$, and acceleration level, $F(4, 3181) = 54.20, p < .001$, have a significant effect on double support time. Furthermore, the combined effect of age and acceleration, $F(8, 3181) = 4.24, p < .001$, gender and acceleration, $F(4, 3181) = 3.142, p < .05$, as well as age, gender and acceleration, $F(8, 3181) = 7.87, p < .001$, on double support time was also proven significant.

When all participants were considered at each acceleration level, the mean DST value in the static environment was 0.23 sec. On the stationary bus a value of 0.24 sec was found, while at low acceleration (0.18 sec) and at medium and high accelerations (0.15 sec) lower values were found (Figure 2). *Gabriel post hoc* tests revealed that the difference in the mean value of DST between the static and stationary environments is not significant ($p >$0.05), however the reduction in mean DST during low, medium and high accelerations is significantly different from the mean DST of both the static and stationary environments ($p <$0.001). When comparing the cases during which the bus was moving, the mean DST at low acceleration is significantly longer than that during medium and high accelerations ($p <$0.001), whereas no significant difference is identified between medium and high accelerations ($p >$0.05).

When considered together in all cases, the mean value of DST for young participants was 0.16 sec, whereas that for middle-aged and older was greater at 0.21 sec and 0.22 sec respectively. *Gabriel post hoc* comparisons between young and middle-

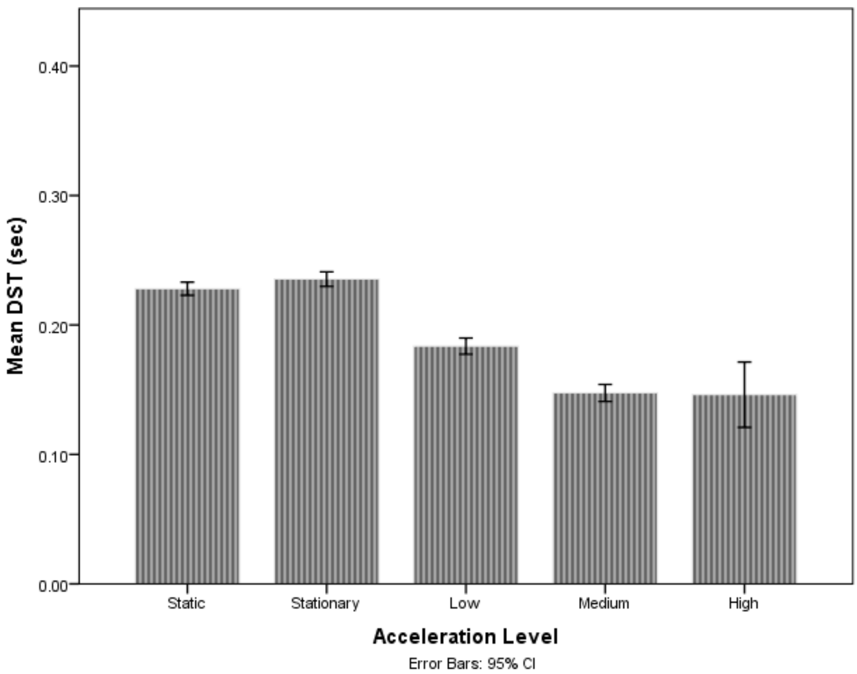

Figure 2: Mean DST and its variation whilst walking on the flat at the five examined acceleration levels

aged as well as between young and older participants revealed that the difference of the mean values in both cases is statistically significant (p <0.001). However, no significant difference in the mean value of DST between middle-aged and older participants was shown (p >0.05).

The significant interaction between age and acceleration level (Figure 3) revealed that each age group was affected differently by the level of bus acceleration. In particular, it was shown that the mean DST of young participants was reducing as acceleration level was increasing. The same was recorded on the bus for middle-aged participants. Older participants, on the other hand, were reducing double support time as acceleration was increasing between the stationary environment and medium acceleration level, but a much higher mean DST value was recorded during high acceleration.

Regarding participants' gender, the mean value of DST for men was 0.20 sec and for women 0.18 sec, when all cases of acceleration level were considered, and

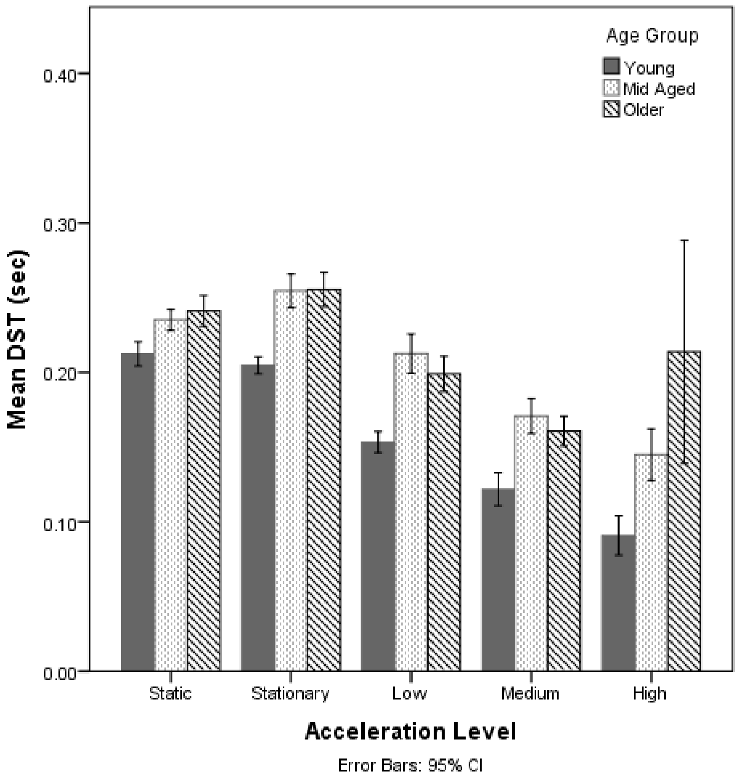

Figure 3: Mean DST and its variation for each age group during level walking at the five examined acceleration levels

the difference of 0.02 sec is statistically significant (p <0.001).

The interaction between gender and acceleration level (Figure 4) also revealed decreased mean DST values for both men and women as acceleration was increasing between the stationary environment and medium acceleration level. However female participants, just like older participants, presented increased DST values when the bus was moving at high acceleration. Thus, it can be said that older female participants, due to their reduced body capabilities (Karekla, 2016;Karekla and Tyler, 2015), require more time with both feet on the ground in order to compensate for their lost balance during stance. It is important to mention that the results presented for the female (Figure 4) and the older female participants (Figure 5) include an outlier, which is discussed at the end of this section.

The variation of the particular parameter also underlines important information about the effect of acceleration on passenger's stability. As mentioned in Section

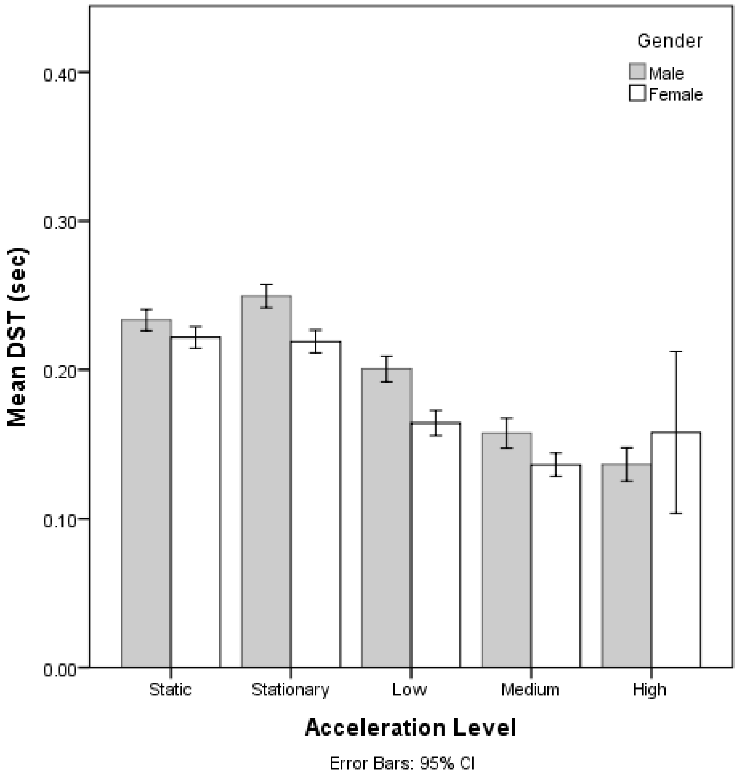

Figure 4: Mean DST and its variation for each gender during level walking at the five examined acceleration levels

2, an increase in the variability of DST indicates inability to control balance and might result in falls (Gabell and Nayak, 1984;Kloos et al., 2012). As is shown in Figure 5, older women present the largest variability for DST values compared to the rest of the sample. In order to assess the magnitude of this variability for the general sample, the standard deviations (SD) recorded for the various age groups during each acceleration level were plotted in respect to the SD recorded in the static environments, as this presents participants' natural gait (Figure 6). Hence, an SD multiple that is equal to 1.0 in Figure 6, denotes that the variability of DST in the examined environment is equal to the one that was calculated in the static environment. SD multiples below 1.0 denote ability in controlling balance, whereas SD multiples above 1.0 denote difficulty in controlling balance.

Young participants seem to have been able to control their balance on the stationary bus and during low acceleration (DST variation below 1.0), however remaining

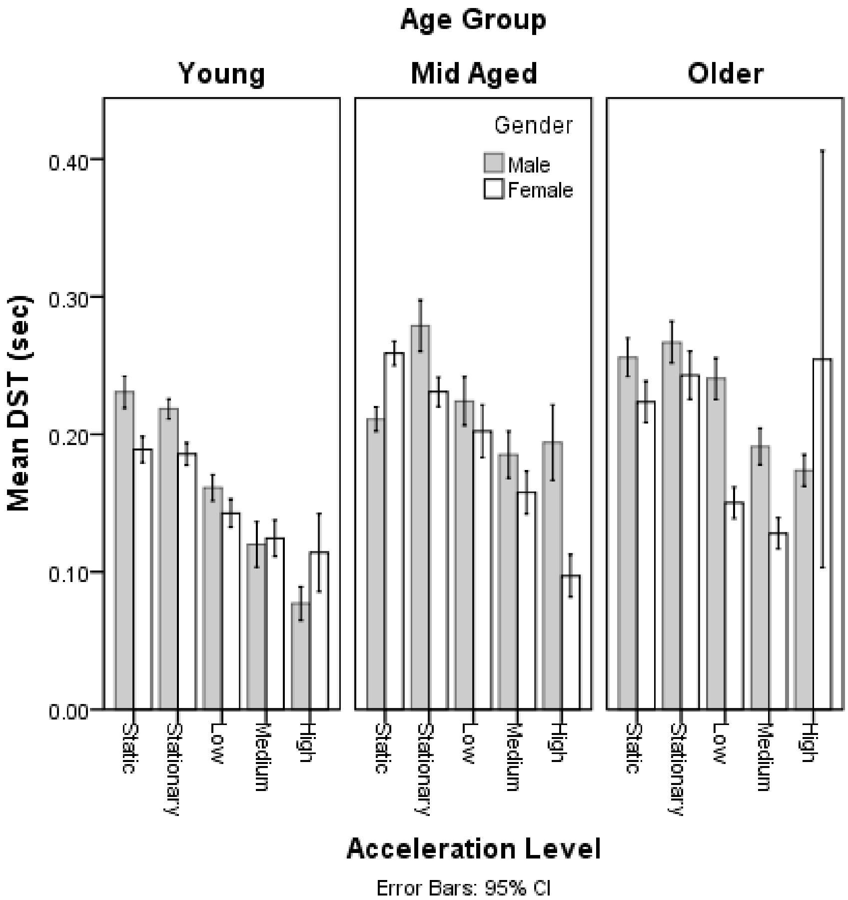

Figure 5: Mean DST and its variation for each gender and age group whilst walking on the flat at the five examined acceleration levels

balanced became more difficult as the examined acceleration level increased (DST variation increasingly above 1.0), with the largest variation recorded during high acceleration. Middle-aged participants presented difficulty in controlling their balance during all examined conditions (DST variation above 1.0 in all cases). Referring back to Figure 5, and focusing on the SD bars, it can be seen that middle-aged male participants had more difficulty to be in control of their balance than middle-aged females, especially on the stationary bus and during high acceleration. Older participants seem to have been able to control their balance in all environments except during high acceleration. The recorded variation of DST values in high acceleration is extremely high (6.5 times higher than the DST variation recorded in the static environment), which requires further investigation.

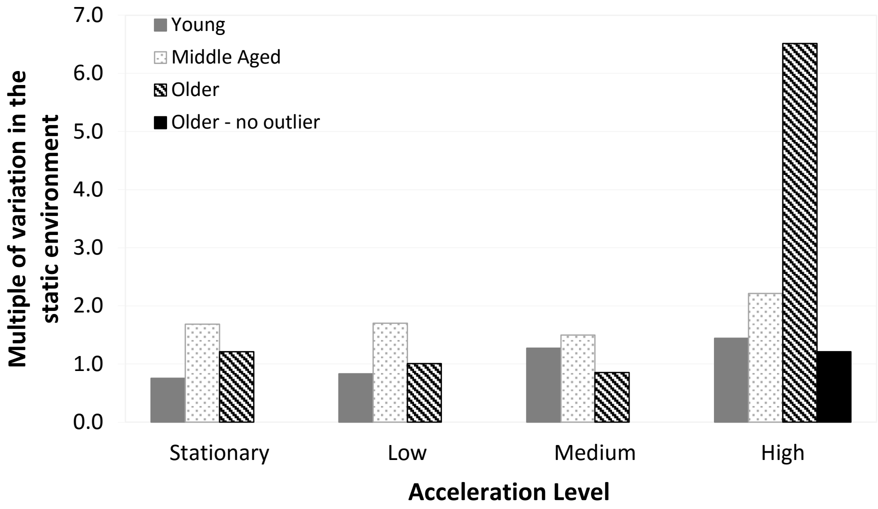

Figure 6: Variation of DST values compared to the static environment whilst walking on the flat at the five examined acceleration levels. Value 1.0 of the vertical axis indicates the variation recorded in the static environment (natural walking).

Searching for outliers in the older group during high acceleration, and recognising that these might be female participants (Figure 5), it was found that the extreme DST variation of the older group was caused by the walking technique of a 76 year old female, the oldest of the sample. The high acceleration of the bus was forcing her to sustain a double support phase (i.e. to keep both feet on the ground) for prolonged periods as she was not confident to continue walking. It is worth noting that the said participant was not able to complete both of these tasks on the stairs during high acceleration. The outlying values in the high acceleration condition were removed and a new SD was calculated (Figure 6, black bar). Excluding the outlying values, older participants did not face severe problems controlling their balance during high acceleration. However, the behaviour recorded for the 76 year old participant can be encountered in real life and should not be ignored when designing accessible public transport systems. In addition, a larger sample of participants, as well as a wider age range of older individuals needs to be examined to determine whether the behaviour of the 76 year old female is representative or not.

4 Discussion

The derived results have showed that, in the case of the bus used in these experiments, the design of the lower deck of the bus (stationary environment) has no measurable effect on passengers' natural gait (static environment). Although the width of the lower deck of the bus is much narrower (varies between 0.40 and 0.83 m) than the unlimited space participants had in the static environment, this did not seem to affect their double support times as they sustained similar DSTs in both environments. However, the movement of the bus (during low, medium and high acceleration levels), forces passengers to adopt a walking style that is far from their natural style and to spend less time with both feet on the ground. Mean DST generally reduces as acceleration increases because, as the passengers are moving to the back of the bus, the inertia due to the accelerating movement of the bus is acting in the same direction, and as a result it causes the centre of mass to accelerate. The increased walking speed of the participants also exhibits this (Karekla, 2016). Hence, passengers find themselves in a destabilising position, and depending on their physical body capabilities, they are either able to control their balance or not.

Young and female participants kept both feet on the ground for significantly shorter periods than middle-aged, older and male participants, whereas double support time of middle-aged and older participants was almost equal. The natural body strength and good balance of young participants (Karekla, 2016) allowed them to complete the task without requiring additional time for double support. On the other hand, female participants did not show better natural strength and stability compared to males, and hence it is questionable why they were able to complete the task with shorter periods of stability compared to men. One factor, amongst others, affecting this outcome could be body mass. It has been shown that increased weight reduces mobility and therefore balance (Gaur and Parekh, 2015), and hence, as male participants of the studied sample were heavier than the female participants (Karekla, 2016), this might have urged them to spend more time on both feet.

Although passenger natural walking style is altered when the bus is moving at low and medium acceleration, young and older participants were able to control their balance and avoid a fall. On the contrary, middle-aged participants, and especially males, presented increased difficulty in controlling their balance during low and medium acceleration. This is surprising as, when they were asked to assess the task in these conditions (Karekla, 2016) they found both levels of acceleration acceptable and reported no incidents of reduced stability. It could be that females, who tended to take many shorter steps than males from the beginning (Karekla, 2016), seemed able to cope with acceleration changes without altering their steps, whereas males, who naturally take larger steps, had fewer opportunities to adjust to the acceleration during their normal gait and had to adjust their steps subconsciously to respond to the change of acceleration. Hence, an important outcome of this study is that questionnaire surveys are useful tools for assessing a problem, but should be used in conjunction with well monitored experimental work in order to derive in depth analysis of what causes the problem.

The high variability recorded in DST values during high acceleration, indicates that all participants experienced increased difficulty in controlling their balance during this condition. Especially for older female participants, high acceleration was the most difficult condition. In fact, it was so difficult that older females of the general population would have been unable to avoid a fall, unless they are seated.

Therefore, it can be concluded that an accessible bus service, that accommodates the needs of all passengers, should not operate at acceleration levels that reach 2.0

m/s^2 and higher. This agrees with the threshold values reported in the literature (Section 1). Walking on the lower deck of the bus with no difficulties can be feasible for most passengers at acceleration levels of 1.5 m/s^2, although only 30% of the older passengers will find it comfortable (Karekla, 2016). However, a truly accessible bus service, where all passengers are able to move comfortably on the lower deck whilst sustaining their natural walking style can be created when bus acceleration remains below 1.0 m/s^2.

We believe that reducing the bus acceleration level would not have an impact on bus travel times, as only the accelerations above the proposed thresholds (1.0 m/s^2 or 1.5 m/s^2) will be reduced. However, a detailed investigation of its effect on journey time is required. It is also important to point out that, the reduction of bus acceleration will greatly affect passenger comfort as it will provide more pleasant bus journeys but most importantly, it will reduce the number of injuries and their cost for national care services.

5 Conclusions

Passenger gait 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 examining the natural walking behaviour of 29 regular bus users who walked on a flat surface in a laboratory and comparing it to their behaviour whilst walking on the lower deck of a double-decker bus. The analysis was focused on double support time, a temporal gait parameter that provides information about people's balance. The main outcomes of this work highlight that the design of the lower deck of the bus, although narrow, has no significant impact on passengers' balance, who can maintain their natural ability to remain upright when the bus is stationary. However, the acceleration of the bus, as well as the age and gender of the passenger, significantly affected their ability to control balance. Specifically, the higher the level of acceleration the less time passengers spend on both feet, which reduces their balance, and the more unable they become to control their stability. Surprisingly, this is more apparent in middle-aged men. Therefore, buses, whether single or double-decker, should operate at accelerations lower than 1.0 m/s^2 for all passengers to be able to walk freely and avoid falls inside the bus.

Although the experiments described here were focused on level walking, it would be interesting to investigate the extent at which stairs and their design influence passengers' balance. Furthermore, bus acceleration rate was not a control factor in these experiments and further investigation is required to identify whether acceleration or jerk levels have a greater impact on bus passengers. As part of the future work, it would also be interesting to examine the effect on gait and balance of bus deceleration, road turns and the case when passengers turn to sit.

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