Maintaining balance on a moving bus: the importance of three-peak steps whilst walking on the lower-deck

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

The numerous falls reported on buses due to sudden accelerations indicate the importance of examining the effect of dynamic environments on people's gait and balance. Although such falls are more common for the elderly and increase the cost of medical care, they also reduce younger passengers' satisfaction for the service.

This study investigates the differences between natural gait and that resulting from the bus environment. 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. A medium level of acceleration (1.5 m/s^2) was examined, which falls in the range of accelerations experienced by passengers on the real bus service in London.

A new method of measuring and analysing gait in dynamic environments was established. *Chi-square* tests were conducted on measures of changes in gait (step type), which encloses important information about body balance, considering participants' age and gender and the bus acceleration. The statistical analysis has shown that as acceleration increases bus passengers use more three-peak steps, which denote that the entire foot is under pressure and in full contact with the ground, hence increasing balance.

This is the first study investigating people's gait inside moving vehicles, hence the gait of healthy people was examined so that the differences in walking patterns would be unaffected by health-related conditions, and to increase understanding of the real challenges passengers experience during bus journeys. The presented methods and outcomes can be used to improve research around eliminating risk of falling for people with mobility difficulties.

Keywords: dynamic environment, bus acceleration, level walking, gait analysis,

pressure mapping, three-peak steps

1 Introduction

Postural stability, also referred to as balance, is defined as the ability of an individual to maintain the centre of mass (CoM) within the base of support with minimal postural sway (Lord et al., 2007;Shumway-Cook et al., 1988). The base of support is the area of the body that is in contact with the support surface and depends on the task that is undertaken. For instance, the support base when standing relaxed is the area within the feet (Shumway-Cook and Woollacott, 2007).

Stability is equally affected by the environment within which the task is taking place (Shumway-Cook and Woollacott, 2007;Darowski, 2008), which provides complicated multi-sensory information that aid people to remain in control of their balance. However, processing sensory information from the environment as well as body functions become more difficult with normal ageing, and therefore poor balance is often observed in older individuals (O'Sullivan et al., 2013). As a result, elderly people are at an increased risk of falling. In the UK, one in three people over 65 (3.4 million people) suffers a fall (AgeUK, 2010) and are more likely to have fear of falling.

A fall is an event which results in a person coming to rest unintentionally on the ground or floor or other lower level World Health Organisation, 2015 and it depends on the person's characteristics, such as disability, or is affected by the environment altering a person's balance, such as the sudden acceleration of a bus. Stumbling or tripping are also an indication of altered balance. However, in these cases a fall can be avoided through recovery. In older people, 53% of trips result in falls due to the person's reduced body capabilities (Lord et al., 2007). Within the bus environment, such events are more common than actual falls but are of equal importance because the increase in fear of falling retains people from using buses or even going out of their house. This has implications for both physical and mental well-being and there is a substantial cost associated to it as a result of medical treatment and loss of earnings. In the UK and the USA in 2010, £4.6 million each day and US$30 billion were spent respectively to cover falls-related costs (AgeUK, 2010).

People, regardless of their gender or age, increase their walking speed after a perturbation of their gait (Krasovsky et al., 2014) and apply a higher force on their heel and toes (Burnfield et al., 2004; Chung and Wang, 2012). In the static environment, a correlation between increased body mass and higher pressure on the middle part of the foot is identified (Walsh et al., 2017), and older people present a higher minimum value at mid-stance than younger people (Yamada and Kondo, 1988). This, however, contradicts the findings of Toda et al. (2015), who identified no significant differences between the minimum value at mid-stance of young and older people. However, assessing level walking in a static environment provides limited information regarding an individual's walking style and their ability to respond to events that put them out of balance in the range of environments they have to navigate in daily living. When gait takes place in a moving vehicle, maintaining balance becomes more challenging, which decreases comfort whilst travelling. In a moving environment, older people have more difficulties in maintaining their balance and take extra steps in order to compensate for a missing double support phase, which provides the highest stability as both feet are on the ground (Krasovsky et al., 2014). Surprisingly, a higher likelihood for falling is observed for younger women, as older women walk with more caution from the beginning, whereas falling in men does not correlate with their age (Pavol et al., 1999).

A number of reviewed studies, discussed in Karekla (2016), mainly considered moving passengers in a stationary vehicle or non-moving passengers in a moving vehicle. This reveals a gap in the literature, in relation to passengers moving within moving vehicles, as studying the real-life situation has yet to be addressed. The acceleration and deceleration phase of a vehicle's movement, are considered as one of the most dangerous parts of a journey with the majority of non-collision injuries, especially for older people, recorded in these phases (London Travel Watch, 2010; Bird and Quigley, 1999). Hence, it is crucial to investigate people's gait when the bus is in motion and to examine the changes the bus environment brings to passengers' movement, in order to be able to offer more comfortable and safer journeys. Moving passengers cannot maintain their balance when acceleration is higher than 2.0 m/s^2. The current London bus service occasionally operates at accelerations higher than this limit (Karekla, 2016). Hence, investigating how this affects passenger walking would be essential to improve the provided service.

This study is aiming at identifying people's walking style in the real environment of a double-decker bus, a transport mode that many people use for their everyday movements, especially in cities with intense bus services, such as London, Hong Kong, or Singapore. Participant's natural gait will also be recorded in a laboratory and will highlight the effect of bus acceleration. The type of steps, age and gender of passengers will provide an insight regarding the balance mechanisms they adopt in order to remain upright. The present paper considers the case of walking along the lower floor of a double-deck bus.

1.1 Natural gait during level walking

The human gait is a bipedal cycle that describes the way body weight is shifted from one limb to the other in order to achieve a forward movement. It consists of repetitive events and can be described as the time interval between two consecutive occurrences of such events. For more information on level walking, its events (e.g. stance) and their length, two widely acclaimed textbooks are recommended for further reading (Whittle, 2014; Perry et al., 1992).

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.

The profile of the vertical GRF during level walking forms an M-shape curve with two distinct peaks of equal intensity, and reflect the support of the CoM (Toda et al., 2015); the first coincides with the initiation of the stance phase and the second with its termination. The events of a gait cycle in a static environment can be seen in Figure 1.

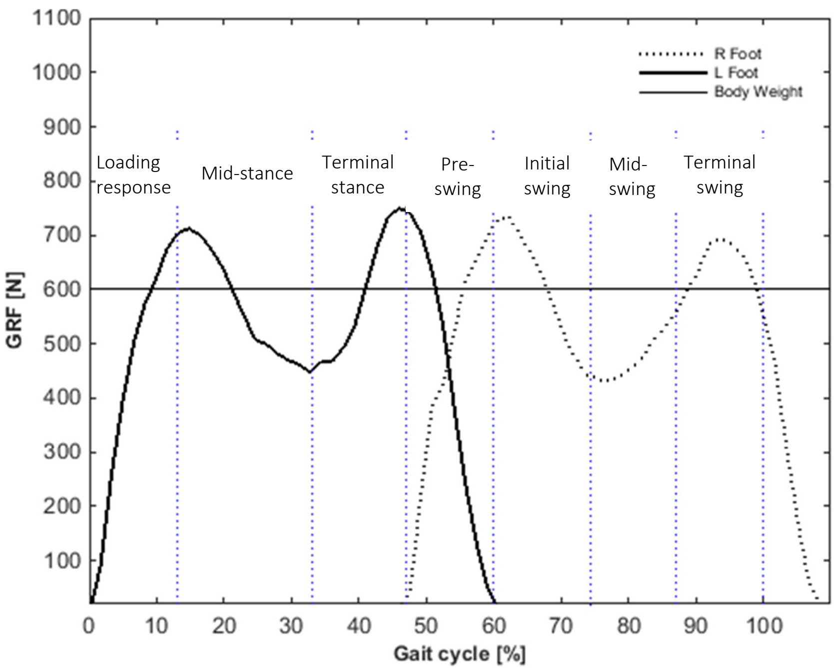

Figure 1: Ground reaction force profile and gait cycle events during level walking in a static environment. The data used to create this graph were taken from the study described in this paper.

The presence of one or both peaks in the GRF profile depends on the person's walking style and physical characteristics and the environment in negotiation. This was investigated with a series of experiments, the process of which and their results are discussed in the following sections.

2 Methods

2.1 Participants and Experimental process

People's walking in dynamic environments is still an unexplored area of research and hence, to be able to identify the true difficulties people experience during bus journeys, and to increase safety during the experiments, it was necessary to restrict recruitment to healthy individuals who had experienced accelerations on the London bus service before. As mentioned in the Introduction, there are no prior studies that could give insights into the size of the effect (differences in mean or variances between groups) that might be expected in the proposed research, so it was not possible to calculate the sample size using power analysis. Therefore, it was necessary to examine previous studies that related to the proposed work in some way and this process is described in detail in Karekla (2016). Furthermore, statistically, at least 28 participants are required to detect a large effect size (Cohen, 1992 as mentioned in Chapter 2 of Fields, 2009).

Thus, 29 regular and healthy bus users, between 20 and 80 years old, were recruited (UCL Ethics Approval: 4464/001). More information on the physical characteristics of each age group can be found in Table 1 below. Additional acceptance criteria concerned active lifestyle, and balance related impairments were verified through health screening Karekla, 2016.

Participants were equipped with an in-shoe plantar pressure system (F-Scan mobile system, Tekscan Inc., Boston, USA - error order: $\pm$ 3%) which provided information about their step type under different environmental circumstances. All participants were wearing sport shoes and the pressure sensors were trimmed to

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.

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. Their natural gait was recorded in the static environment of a laboratory (PAMELA, UCL), whilst undertaking ten steps on a flat surface at their preferred speed. The same task, walking on the straight part of the lower deck, was performed on a double-decker bus on a different day (Figure 2). Initially the bus was stationary (0 m/s^2) and participants' gait was compared to their natural gait, revealing whether the bus layout affects gait. Subsequently, the bus was moved at a 'medium' acceleration (1.5 m/s^2) to explore whether the bus movement alters natural gait. 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 is achieved. The bus was driving on a public road, but was not affected by the city traffic. Each task was repeated three times in each environment and participants could use the bus handrails whenever necessary. Grip force data were collected and will be reported in a future paper.

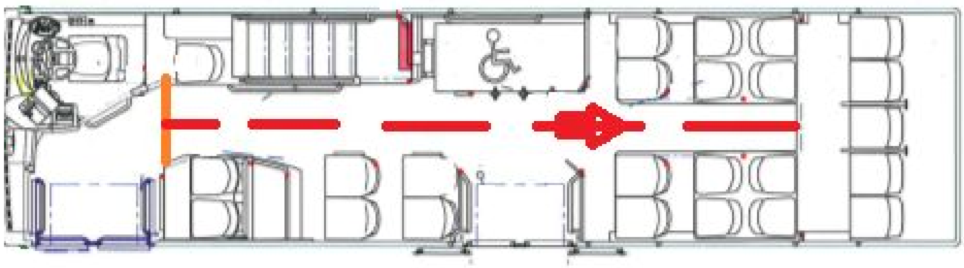

Figure 2: Experimental task of walking on the lower deck of the double-decker bus. The starting point (orange/solid line), walking path (red/dashed line) and direction of participant movement are marked in the picture.

2.2 Peak-detection algorithm development

Due to the originality of this topic - it is the first work studying gait of moving passengers in a moving vehicle - a male participant from the older age group was chosen to serve as the typical subject for the development of an algorithm that will then be applied to the data collected from the entire sample.

In a static environment, a person has control over the moment in time they will commence walking, the level of speed at which they will undertake a task, etc. Hence, following the biomechanical recommendations (Section 1.1), forces on the heel fall in the first half and forces on the toe fall in the last half of the stance period, whereas the middle stance (MS) force occurs at the local minimum between the two peaks. These periods were incorporated into the algorithm in order to extract the force values at each of the peaks.

After plotting the GRF data for all acceleration conditions, it was noticed that, as expected, the typical participant's gait consisted of two-peak steps in the static and stationary environment. However, once the bus was in motion, a third peak appeared extensively during mid-stance. Investigation of previously published work on gait analysis returned 80,000 irrelevant publications (key-phrase 'ground reaction force during mid-stance' used in PubMed, Science Direct and Google Scholar databases). Hence, it was necessary to define that third peak.

In a dynamic environment, if a person can withstand the external forces applied to them they can act as they would in a static environment, and thus the biomechanical interpretation of the gait cycle can be applied. However, if the person's body capabilities are lower than the capabilities required to act naturally, then the external forces can either make the person start walking in an accelerated way before they are even ready to do so (Figure 3, a - heel peak achieved quickly), or the forces can deter them from walking and the person remains with their heel on the ground for prolonged periods until they feel comfortable to finish the step (Figure 3, b - heel is in contact with the ground for more than half of the gait cycle).

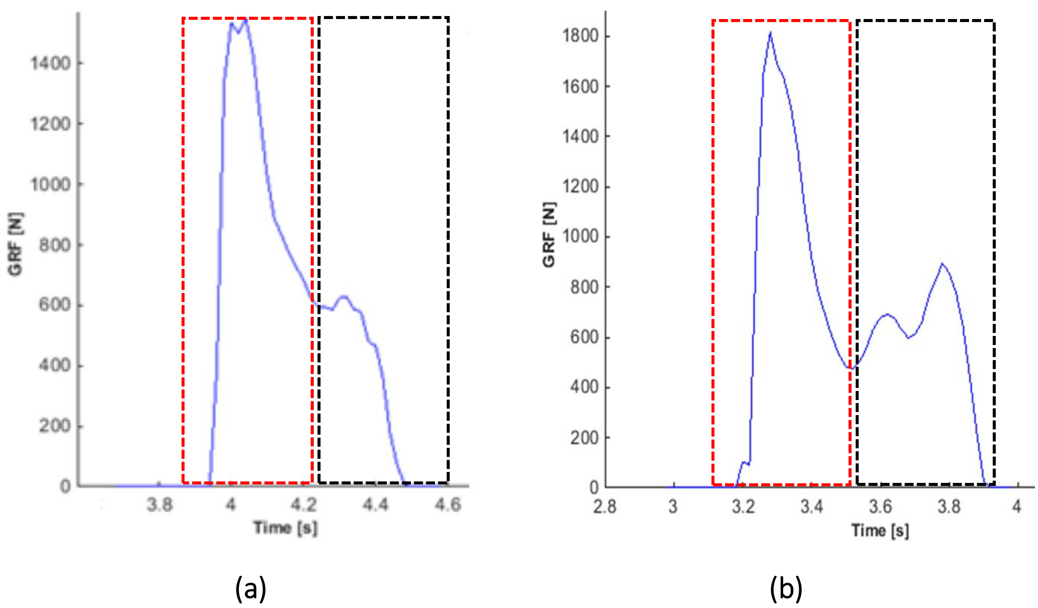

Figure 3: Division of stance period of (a) a two-peak step and (b) a three-peak step during medium acceleration, following definitions of biomechanical studies. Note that forces applied on the heel are included in the left box and forces applied on the toes in the right box, with the extra middle foot peak shown in (b) falling incorrectly into the right box.

Focusing on Figure 3 (b), an additional 'third peak' is identified in the middle of the stance period, which coincides with forces applied on the middle part of the foot. In order to apply the same analysis throughout and to treat data of different acceleration conditions in the same way, a new approach had to be designed for the algorithm to automatically detect the occurrence of each peak relative to the gait cycle. One option would be to give an index number to each peak; 'one' for that on the heel, 'two' for that on the middle part of the foot and 'three' for that on the toes. However, this method could not be applied to the discussed data as one-peak steps were also recorded, the time occurrence of which was important for labelling them correctly.

As mentioned above, the typical subject's gait consisted of two-peak steps both in the static and in the stationary environment. Hence, the description here of the two-peaks is focused on the data collected in the static environment, which also indicates the subject's natural gait. Ground reaction forces, recorded during the ten-steps task (static), were plotted against time and pressure maps corresponding to each peak indicated the plantar areas under pressure. The vertical dashed line in Figures 4, 5 and 6 shows the point in time captured by the pressure map.

During the first peak, the participant applies force on the heel (Figure 4, a) which coincides with the heel strike (HS) force described in biomechanical studies. This force is a result of the weight of the person passing through this point of the plantar. As the participant moves towards the end of the step, their weight shifts to the front of the plantar which coincides with the second peak shown in Figure 4, b. The force during this peak corresponds to the toe-off (TO) force in biomechanics. Hence, in environments with no external force (static and stationary), the walking pattern of both feet is characterised by two distinct peaks. When external forces are present (bus in motion), a walking pattern with more than two peaks is observed (Figure 5 and Figure 6).

Looking at the right foot during the first peak (Figure 5, a), the heel is under full pressure as the person's weight is applied entirely to this area. At the second peak (Figure 5, b), the heel continues to be loaded but shares the body weight with

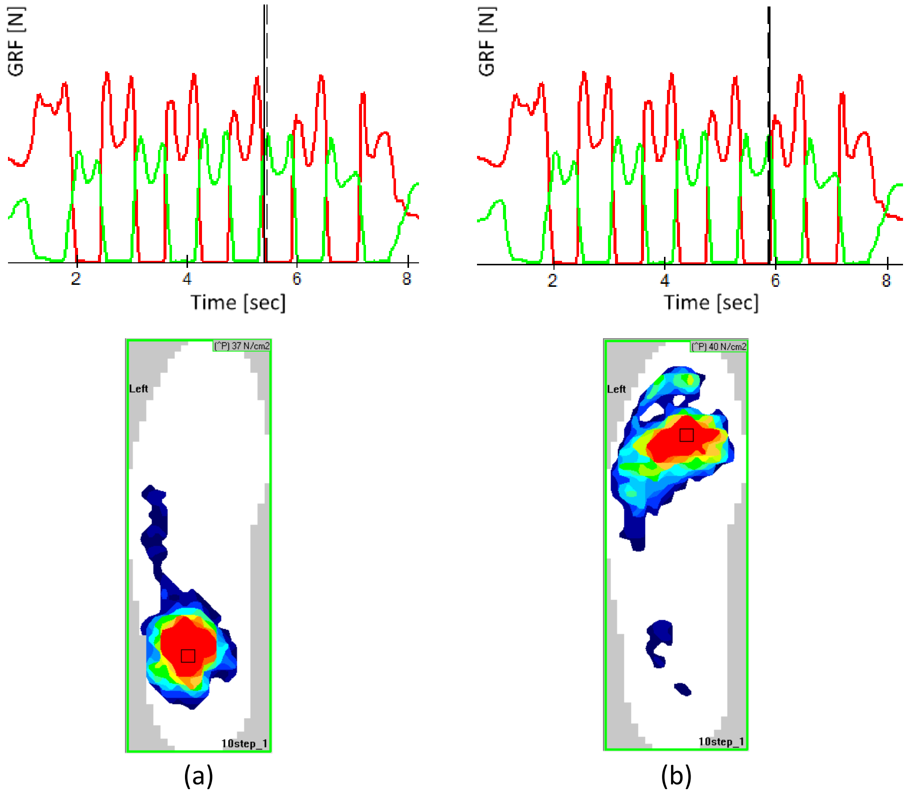

Figure 4: Definition of two-peak steps. GRF profiles and pressure maps are given for the left foot of the typical subject whilst walking on the flat in the static environment. Similar curves were obtained for the stationary environment and for the right foot. Note that the colour scale corresponds to the intensity of the applied force in the pressure maps, increasing between blue, green, yellow and red areas.

the middle of the plantar. As the step is about to finish (Figure 5, c), the body weight is being transferred towards the front part of the plantar.

Focusing on the left foot of the typical subject (Figure 6, the heel is under full pressure, forming the first peak of the step profile (Figure 6, a). However, during the second peak (Figure 6, b), the heel continues to be loaded indicating that the subject is not comfortable to move forward. At the third peak (Figure 6, c), the subject transfers their weight to the front part of the plantar and finishes the step.

The first and third peak in both examples (Figure 5 and 6, a and c) occur at the beginning and end of the gait cycle as those in natural gait (Figure 4). Paying attention to the time occurrence of the second peak relative to the duration of stance, it can be seen that the middle of the foot is under pressure at around 50%

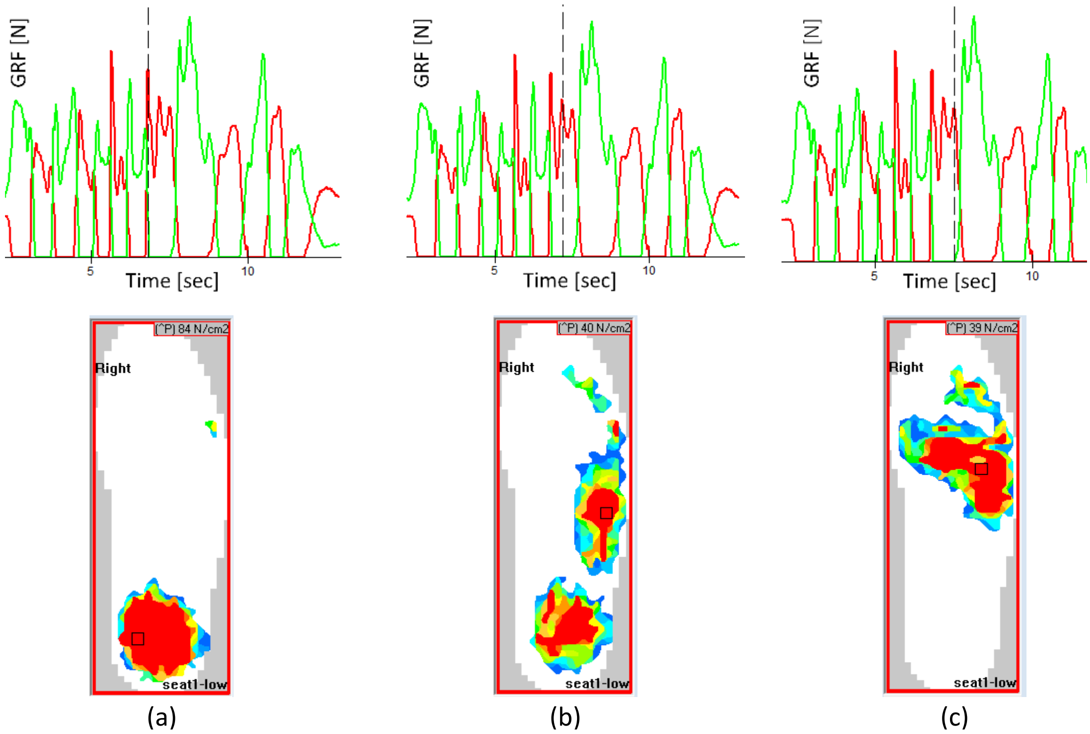

Figure 5: Definition of three-peak steps. GRF profiles and pressure maps are given for the right foot of the typical subject whilst walking on the flat during bus acceleration.

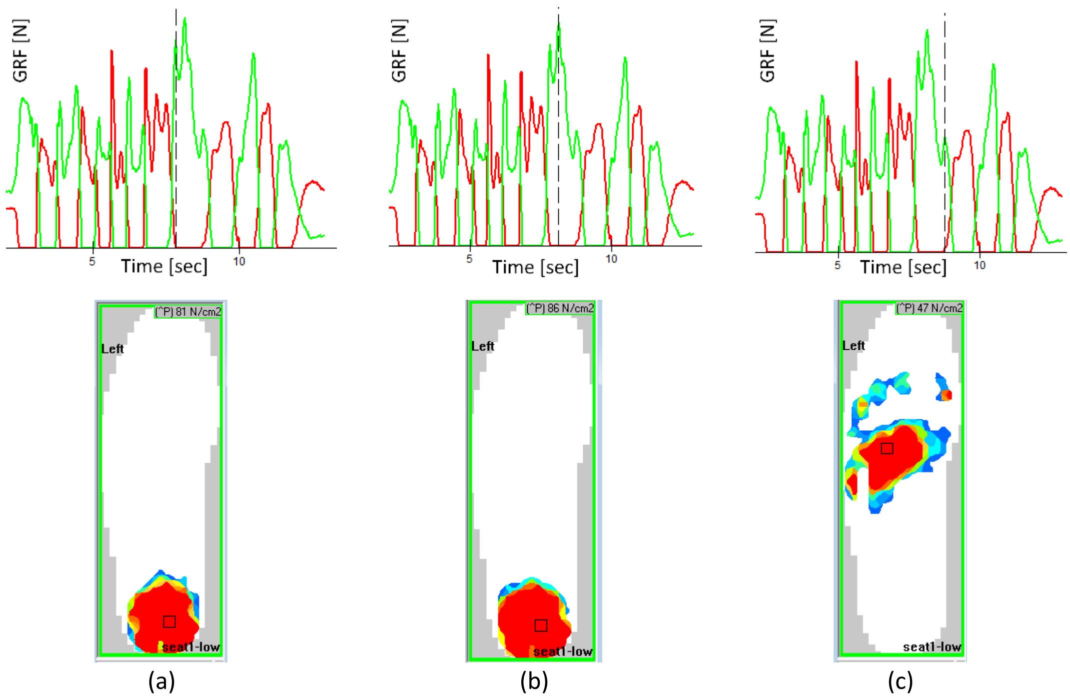

Figure 6: Definition of three-peak steps. GRF profiles and pressure maps are given for the left foot of the typical subject whilst walking on the flat during bus acceleration.

of the stance period.

Therefore, the following logic was pursued: if a peak is detected between 0 and 35% of the stance phase, then it corresponds to a force applied in the heel area of the plantar (GRF HA). If, on the other hand, a peak is detected between 35 and 70% of the stance phase, it is a force applied to the middle area of the plantar (GRF MA) and finally, when the peak falls between 70 and 100% of stance, the force is applied to the toe area of the plantar (GRF TA). In the case that more than one peak is detected in each of these bands, the one with the highest intensity is selected. A longer part of the stance period was allocated for the detection of GRF HA and MA peaks (35%) due to the fact that, in a dynamic environment and as verified from the F-scan recordings, participants were hesitating to initiate a step whereas finishing a step required less time. These are illustrated in Figure 7. The peak-detection algorithm was developed in MATLAB 2014 and the code for the right foot is presented below. The code for the left foot was written in the exact same way, replacing _R with _L in each line.

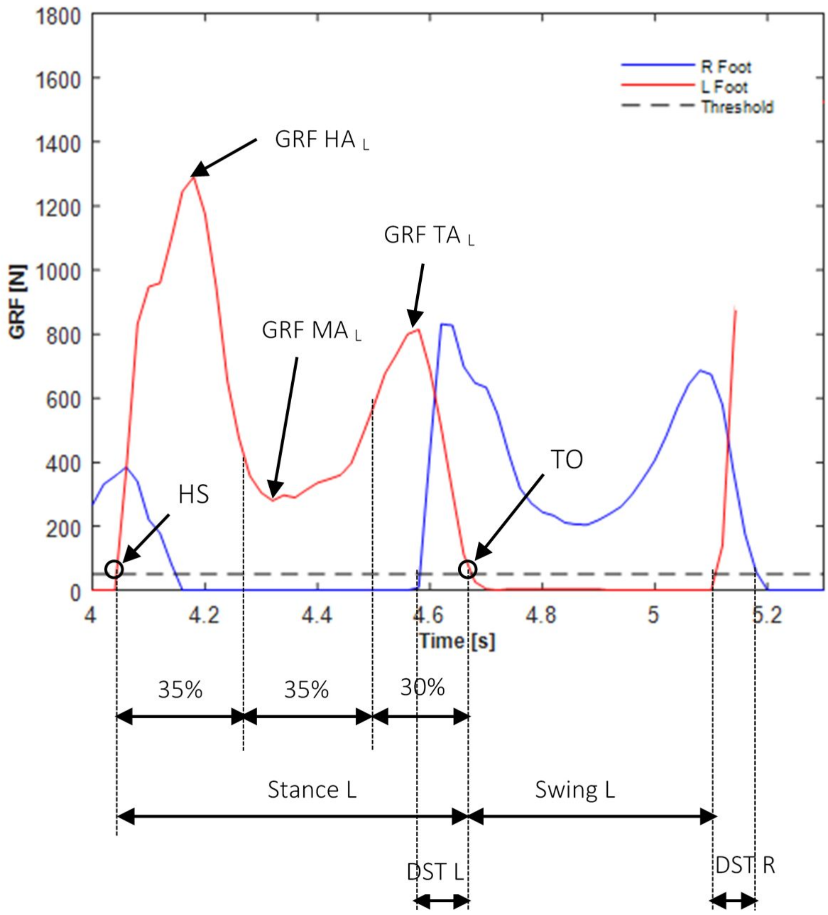

Figure 7: Gait events as they were calculated by the developed algorithm.

[HS: Heel Strike, GRF HA: Ground Reaction Force in Heel Area, GRF MA: Ground Reaction Force in Middle Area, GRF TA: Ground Reaction Force in Toe Area, TO: Toe Off, DST L and R: Double Support Time of Left and Right foot respectively]

```
--------------------------------------------------------------------------------
% Detect Peak Characteristics of Right Foot (Time of Occurance)
           for i = 1:length(c_sleg_num_R)
                 [maxtab_R, mintab_R]= peakdet(Rfoot_force(c_t_hs_R(i):c_t_to_R(i)), 50, Time(c_t_hs_R(i):c_t_to_R(i)));

                    t_GRF = maxtab_R(:,1);
                    temp_GRF_HS_R = [];
                    temp_t_GRF_HS_R = [];
                    temp_GRF_MS_R = [];
                    temp_t_GRF_MS_R = [];
                    temp_GRF_TO_R = [];
                    temp_t_GRF_TO_R = [];

                    for j = 1:length(t_GRF);
                        if ((t_GRF(j)-(c_t_hs_R(i)/samp_freq)) <= (0.35*gait_parameters_b(i,2)));
                            temp_GRF_HS_R = [temp_GRF_HS_R; maxtab_R(j,2)];
                            temp_t_GRF_HS_R = [temp_t_GRF_HS_R; maxtab_R(j,1)];
```

```
                elseif ((t_GRF(j)-(c_t_hs_R(i)/samp_freq)) > (0.35*gait_parameters_b(i,2))) && ((t_GRF(j)-(c_t_hs_R(i)/samp_

                    temp_GRF_MS_R = [temp_GRF_MS_R; maxtab_R(j,2)];

                    temp_t_GRF_MS_R = [temp_t_GRF_MS_R; maxtab_R(j,1)];

                else ((t_GRF(j)-(c_t_hs_R(i)/samp_freq)) > (0.70* gait_parameters_b(i,2)));

                    temp_GRF_TO_R = [temp_GRF_TO_R; maxtab_R(j,2)];

                    temp_t_GRF_TO_R = [temp_t_GRF_TO_R; maxtab_R(j,1)];

                end

            end

        end

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2.3 Data Analysis

The finalised peak-detection algorithm was applied to the collected data. A total of seven different step types were identified; their definition can be found in Karekla and Tyler (2015). Over 85% of three-peak steps were correctly labelled with this method. The remaining 15% were part of two-peak steps, the unidentified peaks of which were lying at the border of the three bands, and hence were manually corrected. Knowing that the base of support is the area of the body that is in contact with the support surface (Shumway-Cook and Woollacott, 2007), the percentage of the plantar that is in contact with the ground, and therefore the number of peaks identified in each step, encloses information regarding a person's balance in response to the environment in negotiation. A single-peak step type (e.g. heel peak) offers less balance than a two- (e.g normal) or a three-peak step, as a very small area of the plantar becomes the support base.

This paper focuses on step type (set as the dependent variable of the chi-squared tests), a gait parameter that indicates a person's balance, analyses the number of peaks identified in gait patterns and discusses the differences in walking patterns of individuals in a static environment, on a stationary bus and on a moving bus. This is important where the reason for instability is the result of the person having to respond to dynamic changes in the environment, rather than to some inherent lack of capability in the participant. The participant's age and gender, as well as bus acceleration were also taken into account in order to identify the significant factors that affect people's gait in this context. These consisted the independent variables of the chi-squared tests. 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).

3 Results and Discussion

The bus acceleration does not affect a person's gait only when the foot is on the ground, but also when it is in the air. In these experiments, participants' walking pattern differed between runs, and hence the data derived from each participant could not be averaged. Obtaining the average between runs revealed no significant differences in participants' gait between environments, which is an unrealistic outcome. This is a limitation found in studies dealing with people in real environments. Furthermore, a within-subject analysis confirmed that participants' performance was not affected by the experimental trial, and treating runs as unrelated cases would not produce biased outcomes (Karekla, 2016).

Chi-squared tests were performed using SPSS v.22 to determine the association between each categorical variable (age, gender and acceleration level) and step type. A statistically significant association was accepted at a 0.05 level of confidence and the results have shown that age, gender and acceleration level are factors that significantly affect people's step type when walking on a flat surface ($p < .001$, Table 2).

Table 2: Chi-square tests for step types observed whilst walking on the flat

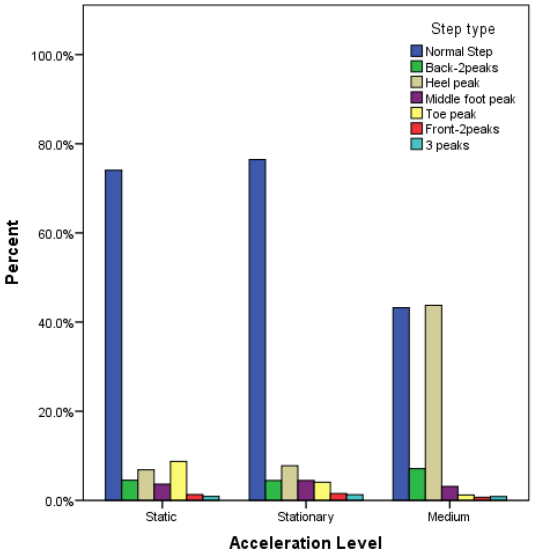
	Age			Gender			Acceleration Level		
	Value	df	Asymp. Sig. (2-sided)	Value	df	Asymp. Sig. (2-sided)	Value	df	Asymp. Sig. (2-sided)
Pearson Chi-Square	104.61[a]	12	.000	34.72[a]	6	.000	589.83[a]	24	.000
Likelihood Ratio	108.15	12	.000	36.13	6	.000	611.20	24	.000
N of Valid Cases	3182			3182			3182		

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

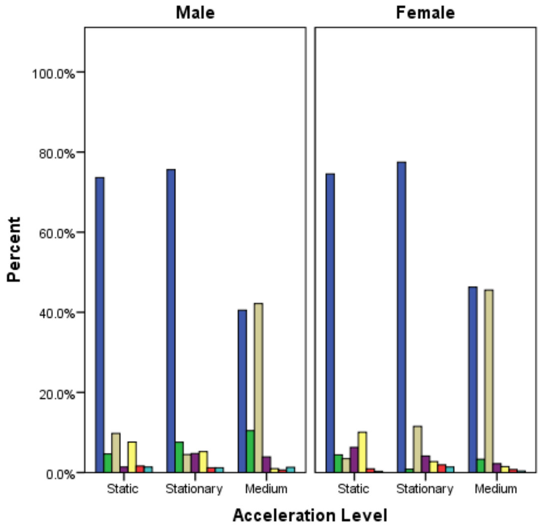
The amount of steps observed for each step type was plotted as the percentage of the overall steps identified at each acceleration level (Figure 8). In the static environment (laboratory), 74.1% of the steps were normal, whilst the other step types were used for less than 10% of the steps, with heel (6.9%) and toe (8.7%) peak steps used more frequently that other step types (Figure 8a). Three-peak steps were used 0.9% of the time in the static environment. This shows that naturally participants used two-peak steps (normal step type), but as the environment in negotiation does not challenge their ability to balance, they instinctively used step types of reduced stability (one-peak steps such as heel-, toe- and middle foot- peak steps).

In the constrained environment of the stationary bus, the number of normal steps increased by 2.4%, whereas toe peak steps reduced by almost 5% and three-peak steps increased 0.4%, compared to the gait pattern observed in the static environment (natural gait). The gait pattern observed in the stationary environment, indicates that overall participants needed to use step types that increased stability more frequently than in the static environment (increase of two- and three-peak steps), whereas step types that are less stabilising (one-peak steps) were used less frequently. Therefore, comparing participants' step type in the stationary and static environments, it can be said that the stationary environment of the bus challenges passengers' ability to balance, and forces them to incorporate balance mechanisms that somewhat alter their natural gait.

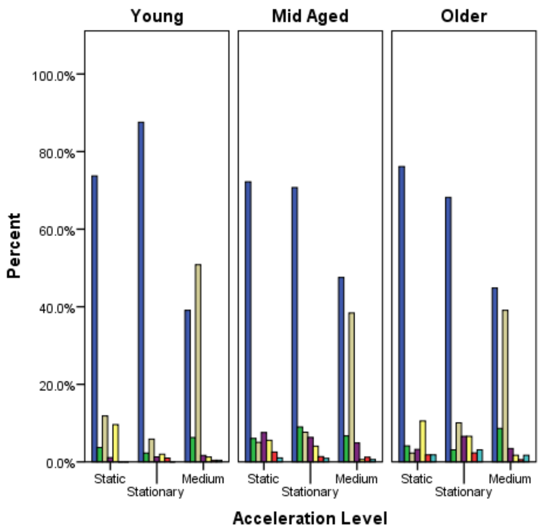
When the bus was in motion (Figure 8a, medium acceleration level)and participants were dealing with the constrained bus environment, as well as with the inertia generated by the acceleration, normal steps reduced by 31% compared to the static environment and by 33.3% compared to the stationary environment. They were substituted by heel peak steps, which were increase by around 36% compared to the static and stationary environment. Considering that a passenger is walking to the back of the bus whilst the bus is accelerating, the inertia acting on the



(a) Overall



(b) Gender



(c) Age Group

Figure 8: Step type distribution at each acceleration level whilst walking on the flat. The legend enclosed in (a) also applies to (b) and (c).

person is causing the CoM to accelerate, putting them in a destabilising position. Although the CoM displacement will have to be measured for the reasoning to be proven, the increased use of heel peak steps, observed during medium acceleration (1.5 m/s^2), generates the question whether participants adopted this walking style in an attempt to keep their CoM in a location further back, in order to counteract the forces applied onto their body due to acceleration. This is the first study to look at step type and its correlation with acceleration, age and gender, and therefore, comparisons to the literature are difficult to be made.

Looking at the influence of gender in the step type observed at all acceleration conditions (Figure 8b), males used 6% more normal and middle foot peak steps, 20% more three-peak steps and 47% more back two-peak steps than females, whereas both genders used the same amount of front two-peak and heel peak steps (50%). Focusing on each acceleration level, both males and females used more normal steps when walking inside the stationary bus (+2% and +3% respectively compared to the static environment). Both genders reduced the frequency of normal steps by around 35% on the stationary bus. The amount of one-peak steps (combining the amount of heel, toe and middle foot peak steps) men used, was increasing as the difficulty of the tested environment was increasing. In particular, men used 2% more one-peak steps in the stationary environment compared to their natural gait (static) and around 33% more one-peak steps during medium acceleration compared to both the static and stationary environment. Female participants presented a similar walking pattern, however the number of one-peak steps they used on the stationary bus decreased by 1.4% compared to the static environment. A 30% increase in one-peak steps was observed during medium acceleration compared to both the static and stationary environments. Two-peak steps besides normal steps (combining the amount of back and front two-peak steps), were used more by men (+3%) and less by women (-3%) on the stationary bus compared to the static environment, whereas both men and women increased the frequency of two-peak steps by 2% during medium acceleration compared to the amount used on the stationary bus. An almost equal amount of three-peak steps were used by men throughout the experiment, whereas women used more three-peak steps (+1%) on the stationary bus than in the static environment and on the moving bus. Therefore, the bus acceleration forces both men and women to alter their gait and to use less normal steps that are the main characteristic of natural gait. As the environment becomes more challenging (moving from static, to stationary to medium acceleration), men seem to be using more stabilising steps (two- and three-peak steps) and less steps that offer reduced stability (one-peak steps) than females. This contradicts the existing literature that argues that women sway more than men and therefore have reduced balance Hsue and Su, Lord et al., 2014, 1996. A factor that could be affecting this result, might be body mass. It has been shown that increased weight reduces balance (Gaur and Parekh, 2015), and as the males of the studied sample are 32% heavier than females (Karekla, 2016), it is a possible explanation for their reduced stability, although its influence should be investigated further.

In terms of age, and focusing on all acceleration conditions, young participants used normal steps more frequently (65%) than middle-aged (57%) and older (62%) participants (Figure 8c). They also used more heel peak steps (45%) than middle-aged and older participants (29% and 26% respectively), whereas they used the least amount of all other examined step types, especially three-peak steps (11%), compared to the other two age groups. Older participants used the most toe-peak steps (44%) and three-peak steps (68%), whereas middle-aged participants used back two-peak (40%), front two-peak (40%) and middle foot peak (49%) steps more frequently than the other age groups. When the experiment was moved onto the bus, young participants increased the number of normal steps they were using in their natural gait (static environment) by 14%. This shows that, even though young participants were the most physically able of the sample, the bus environment even without movement, forced them to alter their gait and seek for more stability. Surprisingly, during medium acceleration young participants reduced the amount of normal steps by 35% compared to their natural gait and by 49% compared to the stationary bus. These were substituted by one-peak and other two-peak steps. Combining the amount of heel, toe and middle foot peak steps, young participants used less of them on the stationary bus (-13%) and more when the bus was moving (+45%) compared to their natural gait. The same trend was observed for two-peak steps other than normal steps, such as back and front two-peak steps, (-0.4% on the stationary bus and +3.5% during medium acceleration compared to their walking pattern in the static environment). Focusing on three-peak steps, young participants used these only during medium acceleration (0.42%), which shows that the bus acceleration created the most demanding environment for them to complete the task and they needed to incorporate a more stabilising type of step into their gait to avoid a fall. The small amount of three-peak steps though also reveals that, due to their strong body capabilities, they could sustain their upright position using a smaller area of their plantar (one- and two- peak steps) more frequently that the whole of their plantar (three-peak steps).

Unlike young participants, middle-aged and older participants reduced the amount of normal steps in the stationary environment compared to their gait in the static environment (-1.5% and -8% respectively). These were substituted by more two-peak steps (combination of back and front two-peak steps) for the middle-aged group (+2%) and by more one-peak steps (combination of heel, toe and middle foot peak steps) and three-peak steps for the older age group (+7% and +1.3%

respectively). The wobbly bus, even without acceleration, created an environment for the middle-aged and the older age group that needed to be handled differently than the static environment. Middle-aged participants, as they are stronger than older participants, were able to move forward and to complete the task by shifting their CoM to the front or to the back. As they are not as strong as the younger age group though (Karekla and Tyler, 2015), it would be interesting to investigate the use of handrails whilst they were doing this. Older participants on the other hand, increased the amount of three-peak steps in an attempt to increase their stability. It could be that they performed this technique as a compensation mechanism for the increased number of less stable steps they were taking (one-peak steps). When they were undertaking the task during medium acceleration, like young participants, middle-aged and older participants also decreased the amount of normal steps further (-25% for middle-aged and -31% for older participants compared to the static environment). In exchange, middle-aged participants used mainly more one-peak steps (+26% compared to both the static and stationary environments), whereas older participants used a higher number one-peak (+28% compared to natural gait) and two-peak steps other than normal steps (+3.2% compared to natural gait and +3.8% compared to the stationary bus). Interestingly, older participants reduced the amount of three-peak steps (-1.6% compared to the stationary bus) and relied on the security of less stable foot steps. This could be due to the fact that older participants, unlike middle-aged participants, assessed the difficulty of the task in the stationary environment and could foresee the challenge they will be faced with in the moving bus, hence they adopted a more cautious gait by excessively increasing the number of three-peak steps on the stationary bus. The cautious gait mechanism that older people adopt has also been observed by other researchers, in the form of reduced walking speed (Pirker and Katzenschlager, 2017).

To summarise, one-peak steps, that provide less stability compared to two-peak and three-peak steps, were mostly used by the strongest of the sample (young participants of both genders) when the bus was moving. Two-peak steps on the moving bus were used less frequently by young participants, as their body capabilities allowed them to use a combination of step types whilst maintaining their body balance, and more frequently by male and older participants. Whilst using the least amount of two-peak steps, male and older participants used the most three-peak steps when the bus was moving in order to increase their stability. Older participants, being the least strong of the sample, required extra stability to avoid a fall which they found by applying their body weight on the entire plantar. On the other hand, male participants, being naturally stronger than females, were extremely challenged on the moving bus that needed to increase their balance to sustain their upright posture. Female participants however, appeared to be able to manage their reduced stability in the challenging environment of the moving bus better than male participants and it would not be extreme to argue that possibly they were being more careful than men whilst undertaking the task in the less demanding environments (static and stationary), that when they walked on the moving bus, they did not need to perform excessive gait alterations to avoid a fall.

Lower and higher acceleration levels were also tested as part of a more detailed work that was done (Karekla, 2016). Although the step types used by the sample in these two environments are not presented or discussed in this paper, it is important to mention the overall trend obtained to strengthen the point made here. It was found 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 increase their contact with the ground, which is interpreted as a way people respond to disruptive external forces, such as the acceleration change, which reduce their balance. Such responses though are imperceptible to the naked eye and can only be detected through experiments such as these.

4 Conclusions

A new method of measuring and analysing gait in dynamic environments was established and presented in this paper. Three-peak steps were identified for healthy bus users between 20 and 80 years old, revealing that the environment of the bus, as well as its motion, affect people's natural gait and forces them to unintentionally seek for extra support by distributing body pressure to more plantar areas.

The aim of this study was not to suggest possible solutions for increasing people's balance during bus journeys. Its scope was to investigate the way healthy people negotiate an environment that confronts them with challenges due to unforeseen perturbations, which in turn will enhance understanding regarding the challenges people with mobility difficulties might be facing in similar environments. Although the experiments described here were focused on level walking, it would be interesting to investigate the extent at which stairs and their design intervene with people's natural walking style, and this is considered in Karekla and Tyler (Under revision). The outcomes would increase our understanding regarding gait in dynamic environments, especially for vulnerable groups such as older passengers. The results of this study would be very useful to transport operators in general, as by reducing the maximum level of acceleration passenger satisfaction would increase and more people will be using public transport systems for their everyday commutes. A London bus operator has seen a potential benefit (operational and environmental) in this study and is currently applying changes to their fleet by reprogramming the bus engines and we are currently involved in assessing the outcomes of this programme. Furthermore, the described method can be applied by orthopaedics and prosthesis specialists with the potential to improve research around foot prosthetics, in order for their users to be able to negotiate such environments and successfully adjust their walking to the present external forces, avoiding trips or falls.

To increase the benefits of the present work, the proposed method should be applied on the gait pattern of more people and to a bigger range of ages. As societies are ageing, people above 80 years old should also be active members of a society, and using public transport modes is one indication of this. For a fully universal algorithm, the gait of passengers of other public transport modes should also be incorporated, considering other vehicle movements such as turns and deceleration. GRF measured with F-Scan can be compared to GRF measured with force plates or other wearable devices that measure GRF. In addition, to increase the accuracy of the developed algorithm the horizontal and lateral component of the force generated by the bus should be examined, as it will also play a part in the way people distribute their weight onto their plantar. An acceleration level lower than 1.5 m/s^2 might be considered as not effective by bus operators. Hence, its impact on bus travel times, as well as its effect on the environment should be investigated as part of a future work. People's gait and the alterations they perform to it when they are challenged with the lateral component of the external force is also an interesting area for future research.

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Author Declaration

We wish to confirm that there are no known conflicts of interest associated with this publication and that this research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

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.