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

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ABSTRACT

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

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

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

1. Introduction

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

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

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

Level walking is an activity that requires a level of stability, as a controlled fall is generated whilst the body weight is transferred from one limb to the other. The recurrent events of level walking in a static environment have been the focus of many biomechanical studies (Karekla, 2016) and the effect of the surrounding environment, especially when this is dynamic, have also been described elsewhere, using the example of a moving bus (Karekla and Tyler, 2018b). In this environment it was shown that people's walking style consists of seven types of steps, the most important one of which is the three-peak steps, which is considered as an unintended balance mechanism. Increasing the contact area between the plantar and the ground increases the support base and provides additional stability.

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

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

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

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

The balance mechanisms people adopt during stair walking in dynamic environments are expected to be more distinct than in level walking. Using the peak-detection algorithm described in Karekla and Tyler (2018b), this paper aims to identify people's walking style when they are negotiating stairs, in a static and a dynamic environment. The dynamic environment chosen for this work is a double-decker bus, a transport mode that many people in cities use for their everyday movements, especially in cities with intense bus services, such as London, Hong Kong, or Singapore. Despite the availability of buses, people – especially older – are unsatisfied with the level of service provided and report many incidents of loss of balance. This work is discussing the way the bus environment, in terms of its layout , affects the natural way people walk on staircases when no external forces hinder their movement. The walking style observed when the bus is in motion will also be presented and the differences between age groups and genders will be discussed.

1.1. Natural gait during stair walking

The gait cycle during stair walking is similar to that of level walking, in the sense that it involves recurring movements of the two limbs. Just like in level walking, the force that a person applies to the ground during walking generates an equal and opposite force