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Enhancing pedestrian safety at track crossing: a motion analysis study

Ahmed Yacine Lardjane

IRT Railenium, Valenciennes, France. Yacine.Lardjane@railenium.eu
LAMIH, CNRS, UMR 8201, Université Polytechnique Hauts-de-France, Valenciennes, France. AhmedYacine.lardjane@uphf.fr

Mathias Blandeau

LAMIH, CNRS, UMR 8201, Université Polytechnique Hauts-de-France, Valenciennes, France. Mathias.blandeau@uphf.fr

Laura Wallard

LAMIH, CNRS, UMR 8201, Université Polytechnique Hauts-de-France, Valenciennes, France. Laura.wallard@uphf.fr

Christopher Paglia

IRT Railenium, Valenciennes, France. Christopher.Paglia@railenium.eu

Christophe Gillet

LAMIH, CNRS, UMR 8201, Université Polytechnique Hauts-de-France, Valenciennes, France. Christophe.gillet@uphf.fr

Sébastien Leteneur

LAMIH, CNRS, UMR 8201, Université Polytechnique Hauts-de-France, Valenciennes, France. Sebastien.leteneur@uphf.fr

Emilie Simoneau-Buessinger

LAMIH, CNRS, UMR 8201, Université Polytechnique Hauts-de-France, Valenciennes, France. Emilie.Simoneau@uphf.fr

This study introduces motion analysis as a novel approach for evaluating pedestrian safety at Pedestrian Track Crossings (PTC), addressing limitations of traditional assessment techniques. Using markerless 3D motion analysis, we examined movement patterns of 26 healthy participants (mean age: 22.8±2.8 years) in two locomotor tasks; i) normal walking under three conditions: standard slope, textured (tactile pavements) slope, and textured slope with safety marking. ii) emergency stopping where response times were quantified. The methodology enabled non-invasive, detailed tracking of gait parameters. Compared to walking on standard slope, results revealed significant changes in movement patterns with reduced mean walking speeds from 1.26±0.20 m/s on standard slope to 1.17±0.20 m/s on textured slope ($p<0.046$), and 1.21±0.19 m/s ($p<0.004$) on textured slope with markings. Emergency stopping response times decreased, with participants halting 270 ms faster on textured surfaces compared to standard slope. Notably, while 67% of participants reported no perceived change in their walking behaviour, quantitative analysis demonstrated significant modifications in gait parameters, highlighting the unconscious influence of environmental features on pedestrian behaviour. This research demonstrates the importance of quantitative motion analysis in safety equipment assessment, overcoming the subjective nature of questionnaires and limited scope of in-situ observational studies. The findings suggest including the tactile pavements in the future passive safety equipment and establish a methodological framework for future investigations using biomechanical analysis in railway crossing safety. This cross-disciplinary approach provides unprecedented insights into human-environment interactions, paving the way for more effective safety measure design and implementation.

Keywords: Safety, Pedestrians, Railway, Motion Analysis, Walking speed, Biomechanics, Ergonomics, Tactile.

1. Introduction

1.1. *History, methodologies, and analysis tools*

Railway crossing safety has challenged engineers and safety experts since trains first began operating in the 1830s. This fundamental safety challenge "protecting pedestrians from fast-moving trains" remains relevant today (Naweed and Larue 2021). Although technology has evolved dramatically since then, the safety of pedestrians remains challenging. Pedestrian Track Crossings (PTCs), also known as level crossing footpath, allow pedestrians to cross railway tracks where footbridges or underground passages are not present. In France, most PTCs are equipped with warning systems, such as flashing red pictograms, as part of an ongoing efforts by the French National Railway Company (SNCF) to improve pedestrian safety since several years (Aupetit et al. 2023).

While researchers often reference pedestrian street-crossing studies for their behavioural similarities, a comprehensive framework for analysing railway crossing behaviour remains underdeveloped (Freeman et al. 2013). Safety research in this field mainly employs two main approaches. Firstly, the individual approach focuses on user behaviour as an isolated component, emphasizing education and rule enforcement (Read et al. 2013). Secondly, the systemic approach offers a broader perspective, examining accidents as outcomes of multiple interacting factors within a complex system (Read et al. 2013). This approach has gained popularity. Recently, Vision Zero, a new traffic safety strategy initiated in Sweden, considers that both system designers and road users share responsibility (Lie and Tingvall 2024). This complexity of pedestrian crossing behaviour calls for a more holistic understanding of the system's intrinsic relationships. Various analytical tools have been developed to study those interactions at railway crossings, with the Pedestrian Unsafe Level Crossing (PULC) framework emerging to address these complexities. Based on AcciMap principles, PULC uses a prospective and predictive approach. Its innovation lies in its four-level structure, tailored to pedestrian behaviour, and its distinction between individual factors and social environment influences, offering greater analytical precision than previous models (Stefanova et al. 2018).

After applying this model following Branford recommendations (Branford et al. 2009) to over 43 studies in a previous work, we found that most accidents occur due to a misunderstanding of the signals or a poor perception and also due to insufficient attention from travellers (Aupetit et al. 2023).

1.2. *Safety solutions at railway crossings*

Research shows that active warning systems, such as flashing lights and automatic barriers, are highly effective for reducing risks at railway crossings. However, they come with significant implementation challenges, including high installation and maintenance costs due to the need for reliable technology that maintains safety standards even in failure modes. In rural areas, limited access to electrical infrastructure further raises implementation costs (Read et al. 2021). Recent research has shifted towards developing safety systems that integrate ergonomic principles rather than purely technical solution, recognizing the importance of human factors in crossing safety. Of particular interest are crossing designs based on Rasmussen's Ecological Interface Design (EID) principles, which represent a significant advancement in human-centred safety approaches and can be applied to the railway environments (Read et al. 2021).

The EID stipulates that safety systems should support all cognitive processing levels (Read et al.

2021). This includes Skill-based processing, which involves automatic sensorimotor responses operating without conscious control; rule-based processing, where learned patterns and stored rules based on experience are applied; and knowledge-based processing, which requires conscious analysis for unfamiliar or complex situations. An effective design should allow direct perception and action when appropriate, supports all levels, including the Skill and Rule-based processing, which depends on immediate perception. Therefore, this processing is directly linked to biomechanical field. Human movement is indeed guided by sensorimotor mental representations that integrate both environmental and body sensory information (Gallimard et al. 2023). Thus, biomechanical analysis offers valuable insights for understanding and improving Skill-based processing, suggesting that effective safety designs must consider both cognitive and biomechanical pedestrian's behaviours.

1.3. *Current research, methodologies and their limitations*

Recent advances in pedestrian safety have centred on the development of Intelligent Vehicle Systems with pedestrian detection and tracking capabilities. These systems aim to prevent collision by delivering warnings when pedestrians are detected (Straughn et al. 2009). While substantial research has focused on the technical aspects of these warning systems, such as detection algorithms and computer vision technologies, human factors have received comparatively little attention. This gap in understanding how humans interact with and respond to different systems, including various sensory modalities (audio, tactile, visual), represents a critical area needing further investigations (Straughn et al. 2009). For street crossing, many studies have been suggesting that tactile warnings might be more effective in preventing collisions, by improving driver's reaction time and stopping distance, since this sensory modality is relatively unengaged during driving (Laakmann et al. 2023; Alyamani et al. 2024). However, in the context of railways, a train may require up to one kilometre to come to a complete stop (SNCF 2014). Therefore, a sequential understanding of the pedestrian behaviour both before and during the crossing is essential (Luu et al. 2022). This approach provides insights into how pedestrians perceive the crossing environment, and how this perception influences their crossing behaviour (Kalantarov et al. 2018). Adding tactile warnings on the ground has been suggested to improve stopping facing an expected event while walking and might enhance the pedestrian safety (Koo and Kwon 2023). Pedestrian behaviour is typically studied using questionnaires or interviews, where participants are asked to imagine different scenarios and respond about their preferences, attitudes, and behaviours in relation to those situations (Kalantarov et al. 2018). Another approach involves field observations, such as video recordings (Fugger et al. 2000). However, field observations can be complex and require interpretation by researchers (Kalantarov et al. 2018). Furthermore, they lack control over personal factors such as age, or health status, which have been shown to significantly influence gait patterns (Avineri et al. 2012), but also over Environmental factors such as the slopes or textures on the ground, which can impact the gait of the pedestrians (Strutzenberger et al. 2022; Aghabayk et al. 2021). Although many studies investigated the spatiotemporal aspects of crossing, and mainly reported the walking speed (Fugger et al. 2000; Dommes 2019; Goldhammer et al. 2014), they could lack of accurate instruments, making it difficult to detect subtle variations in gait parameters, such as reaction time, stride length, stride width and variability, or lack of ecological validity, which is essential for understanding sensorimotor performance, all linked to the Skill-based processing.

The aim of this study was to examine the impact of adding tactile textures and visual markings on the ground of a downward slope on pedestrians' gait patterns and alertness. Through this, we aimed to quantify the effectiveness of the environment in influencing pedestrian behaviour prior to tracks crossing. For security reasons we simulated a slope leading to tracks crossing in a motion analysis laboratory.

2. Methods

2.1.*Participants*

Overall, twenty-six healthy participants (mean age: 22.8±2.8 years) were included in this study. The inclusion criteria for participants were as follows: healthy, free from any neurological or musculoskeletal disorders that could potentially affect their balance or gait. Prior to initiating the experimental procedures, each participant provided informed consent, in line with the Declaration of Helsinki. The study was approved by the CERSTAPS and registered under the number IRB00012476-2024-15-01-289. Participants performed two locomotor tasks: continuous walking and emergency stop, separately. Both were performed on a seven meter long and one-meter-wide walking corridor (cf. Fig1) with a slope of 8.5° equipped with Kistler 9286B force plate (500 Hz). For the first locomotor task, eighteen participants performed the continuous walking task under three randomized conditions (standard slope, textured, textured with added markings). The instructions were given verbally “walk at your preferred speed and stop at the end of the downward slope”. Three trials were recorded in each condition, and at the end of each one the participant replied to a survey. For the second locomotor task, eight additional participants were recruited, the 26 participants were asked to “walk 3 to 8 times and stop immediately whenever you hear a train’s horn”. To guarantee a surprising effect, the participants were told “This sound might be played after the third trial”; in fact, a Python code was used to play the horn loudly by speakers, always at the first trial, once the forces exceeded 20 N on the force plate. To avoid the effect of anticipation, each participant did only one trial, either under the condition standard slope or the textured with markings. Motion data was captured using 10 Miqus video cameras (30 Hz), mounted on the laboratory’s walls, ensuring a full view of the entire walkway. All devices were synchronized by Qualisys software. Textures were 3.06 meters long, 0.91 meters wide and 22 millimetres high; they were made by a professional French signalization company and respect the norms LOGC940024A. They were placed 1.9 m from the beginning of the slope, the height of the slope at that point was 0.60 meter and yellow markings were added at the end of the textures.

Fig 1: The slope equipped with textures and markings

2.2.1.*Survey*

Participants were invited to answer the questions (Table 1) of each section after each condition, the survey covered demographics, transportation habits, also slope condition, texture and markings as environmental factors. Answers were both in a form of Likert scale and open answers.

Table 1. Exemple of survey questions

1	What is your age?
2	What is your gender?
3	How often do you use public transportation?
4	How often do you take the train?
5	Was your walking speed influenced by any environmental elements? If yes, by what?
6	During this trial, did the slope influence your walking speed?
7	Did the ground texture and markings influence your walking speed?
8	Does the influence make walking slower or faster?

Table 1. (continuous)

9	In your opinion, what changed?

2.2. Data analysis

For gait analysis, the markerless software Theia3D (v2022.2.0.2777) was used to estimate 3D gait kinematics, then the software Visual3D (v2023.12.1) was used to calculate the following gait parameters from the moment the subject enters the textures zone to the end of the slope: walking speed; based on participant's Centre of Mass (CoM), stride length; distance between two successive steps of the same foot's heels, and stride width; the lateral distance between the heels of both feet. Gait events were determined following Zeni method (Zeni et al. 2008). For emergency stopping condition, we measured the simple reaction time, which can indicate the alertness of the pedestrians (Appelle and Oswald 1974). The reaction time was calculated using MATLAB (R2023a), from the moment when vertical ground reaction forces exceeded 20N, triggering the horn, until the CoM reached values under 0.05 m/s in the anteroposterior direction, indicating the end of the gait (Kwon et al. 2023).

2.3. Statistical analysis

The software Jamovi (2.3.26) was used to perform statistical analysis, a Shapiro Wilk test was applied to verify normality, then a repeated measure Anova was applied on spatiotemporal gait parameters obtained during the continuous walking task and a T-test for the reaction times of the emergency stop. The significance threshold was set at $p < 0.05$.

3. Results

3.1. *Survey results*

The results of the survey revealed that all participants are regular train users, with usage frequencies varying from at least twice a year to more than once a week. When it comes to the effect of environmental factors, most of the participants (66.9%) reported that their walking speed was not impacted by any elements of the environments under the textured slope condition. In line with that, 62.6% of the participants reported that their walking speed was not affected by any elements of the environment under the texture and marking condition.

3.2.1. *Continuous walking*

Statistical analysis revealed that walking speed (Fig 2) was higher in the standard slope condition (1.26 ± 0.20 m/s) compared to the textured slope condition (1.17 ± 0.20 m/, $p < 0.046$) and to the textured with markings condition (1.21 ± 0.19 m/s, $p < 0.004$). However no statistically significant effect was observed between textured slope and textured with markings ($p < 0.564$).

Regarding stride length and width, there were no significant differences between the three slope conditions ($p > 0.05$).

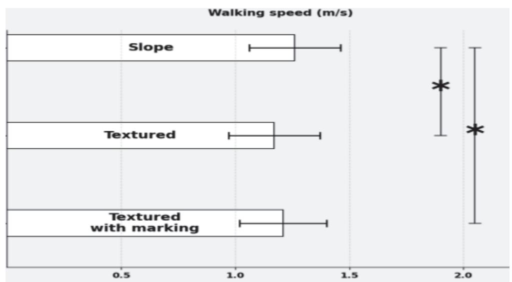

Fig 2: Mean walking speed (m/s). * Indicates statistically significant differences.

3.2.2. *Emergency stopping*

While the mean stopping reaction time for participants under the standard slope condition was 1.68 ± 0.48 s, it was significantly lower in the textured condition (1.41 ± 0.32 s, $p = 0.046$).

4. Discussion

This study investigated the impact of texture and visual markings added on the ground of a downward slope on pedestrian biomechanical behaviour. It was assumed that such environments could influence the pedestrian prior to tracks crossing, with a particular focus on walking speed and emergency stopping capabilities. The main results showed that textures significantly decreased both walking speed and emergency reaction time. Walking speed has been extensively studied in pedestrian crossing research (Onelcin and Alver 2017). Our results revealed means walking speeds of 1.26 ± 0.20 m/s, on a standard slope, 1.17 ± 0.20 m/s on a textured slope and 1.21 ± 0.19 m/s on the textured with markings slope. Our results are in line with previous research investigating effect of environments and reporting average speed of 1.36 ± 0.25 m/s in young adult (Aghabayk et al. 2021) on slopes. A reduced gait velocity at crossing has been linked to more effective stopping and to better visual scene stability before reaching danger zones (Menz al. 2003). This behaviour might improve information gathering and hazard detection by pedestrians (Luu et al. 2022) and thus limit accidents. Our results are in line with previous studies that also showed that proprioceptive and visual information were crucial for adjusting walking speed (Frost et al. 2015). It has been suggested that visual information plays a key role in slowing down the forward motion of the COM and guiding the final foot placement, while mechanoreceptors in the plantar surface provide feedback about foot contact to initiate braking forces (Frost et al. 2015). In the present study, contrary to what was expected, the addition of visual markings on the textured slope did not further reduce walking speed comparing it to textured condition. Similarly, the textured slope, markings did not influence either the stride length or its width. Since there was no reduction or increase in stride length and in stride width, it meant that participant simply slowed down gait velocity, suggesting an adaptation to environmental cues.

In addition, our study also demonstrated improved reaction times in emergency stopping scenarios when tactile feedback was present in the textured condition. This improvement in emergency response capabilities suggests an improvement in pedestrian alertness. These results align with previous research showing that enhanced tactile feedback can positively influence biomechanical parameters and muscular activity during gait termination (Robb et al. 2021). Specifically, the research revealed that walking on textured surfaces lead to earlier muscle activation times in the thigh muscles, including the rectus femoris, vastus medialis, and biceps femoris, suggesting improved responsiveness to unexpected perturbations. This could induce a higher pedestrian alertness and enhance pedestrian's safety during critical situations. (Appelle and Oswald 1974; Nie et al. 2021). A noteworthy finding emerged from comparing subjective reports with objective measurements. While our quantitative analysis demonstrated significant changes in walking speed and reaction time, 66.9% of the participants reported that their walking speed was unaffected by environmental elements, suggesting an unconscious adaptation to the environment. This striking discrepancy between perceived and actual behaviour highlights the importance of using objective motion analysis as a non-invasive ecological tool for assessing pedestrian safety measures. The availability of validated markerless open-source tools (Lardjane et al. 2024), provides new opportunities to understand how safety equipment impacts unconscious behavioural processes, offering insights that might be missed through traditional subjective assessments or observational studies. The integration of both conscious and unconscious behavioural adaptations appears crucial for a comprehensive safety design. While participants may not have been aware of their speed modifications, these automatic adjustments could prove vital in emergency situations where rapid response times are essential (Nie et al. 2021). Especially when the equipment requires no active engagement from pedestrians while might still influencing their behaviour. Future research in this field should expand to include more comprehensive biomechanical data, incorporating detailed kinematics and kinetics analysis. Additionally, analytical methods such as entropy (Thiry et al. 2022) could provide deeper insights into the complexity and variability of body movements during crossing scenarios. As human locomotion is inherently variable and complex, rather than robotic (Winter 1987), these additional measures could offer a more complete understanding of how safety features influence natural movement patterns. While our study focused on young healthy participants to control age and mobility-related variables, future research should include a more diverse population to enhance the generalizability of findings.

5. Conclusion

The implementation of safety measures at railway crossings requires evidence-based evaluation methods. This study demonstrates how markerless 3D motion analysis can quantify the effectiveness of overground tactile equipment on pedestrians, revealing significant improvements in walking speed control and reaction times that occur below conscious awareness. These findings not only support the inclusion of tactile pavements as passive safety features but also establish motion analysis as a crucial tool for future safety design and assessment in railway environments.

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