Determining the Causes and Mechanisms of Falls in Children with Cerebral Palsy

Rebecca Louise Walker

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List of Abbreviations

CP	Cerebral palsy
TD	Typically developing
PPIE	Patient and public involvement and engagement
GMFCS	Gross motor function classification system
MOS	Margin of stability
FP	Foot placement
COM	Centre of mass
XCOM	Extrapolated centre of mass
COP	Centre of pressure
COG	Centre of gravity
BOS	Base of support
ROM	Range of motion
SWOC	Standardised walking obstacle course
NIH	National Institute of Health
NIHR	National Institute of Health Research
WHO	World Health Organisation
PF	Plantarflexion
DF	Dorsiflexion
AFO	Ankle-foot orthoses
3D	Three-dimensional

Abstract

Background: Falls are a common problem for children with cerebral palsy (CP). Falls lead to negative psychosocial consequences such as embarrassment and reduced activity participation, which negatively impacts daily wellbeing. However, causes of falls, particularly in the real-world are under investigated. To identify children with CP at high fall risk and develop effective interventions to reduce falls, we must first establish the mechanisms of falls that require prevention and thus must determine causes of falls in the real-world.

Research Question: What are the causes and mechanisms of falls in children with CP?

Study 1 (Chapter 2): A systematic review was undertaken that highlighted an understudied link between challenging environments and falls in children with CP. This work synthesised key gait characteristics that children with CP adopt when walking on surfaces other than level ground. However, a gap in knowledge was identified when trying to understand if gait characteristics were enough to prevent real-world falls and only three papers reported occurrence of falls in challenging environments. The understudied link evidenced within this review is likely due to a lack of investigation in challenging environments that reflects those in the real-world, as informed by children's lived experiences.

Study 2 (Chapter 3): Patient and public involvement and engagement (PPIE) with children with CP and their parents revealed more about causes of real-world falls to meaningfully contribute to the development of participatory informed methods. This work used child-centred consultations and creative activities to develop The Walk-Along Project; a method tailored for children with CP, for exploring lived experiences of falls using walk-along interviews. A critical reflection on the impacts, strengths and challenges of conducting PPIE with children with CP and their parents is reported.

Study 3 (Chapter 4): The Walk-Along Project was carried out with children with CP and their parents in their local walking places, to reveal novel insights into places that falls occur in the real-world. This study evidenced that the places children with CP find most

challenging and experience falls are uneven surfaces, e.g. grass potholes, and with distractions, e.g. dogs barking. Outcomes of this study highlighted the causes of real-world falls, which led directly into the design of a bespoke laboratory protocol for investigating the mechanisms of falls in replica real-world environments that had not been considered previously.

Study 4 (Chapter 5): This study captured incidents of instability using a bespoke laboratory protocol that offered novel insight into how children with CP negotiate replica real-world challenging environments. Outcomes from this study revealed several mechanisms of potential falls and demonstrated individualised fall risk factors. This included novel evidence that children with CP demonstrate suboptimal stepping strategies (e.g. a late change in foot placement) to avoid challenging features of the environment (e.g. potholes), that reduce stability, even when exhibiting compensatory mechanisms (e.g. reduced walking speed). Identification and understanding of these potential mechanisms of falls is vital for informing future fall prevention programmes.

Conclusion: This PhD generates novel insight about the causes and mechanisms of falls in children with CP. Mixed methods approaches used in this work went beyond typical stability assessments by understanding why and how falls occur in real-world environments. Early PPIE (Chapter 3), highlighted the importance of children with CP and their parents to produce more meaningful research outcomes. The Walk-Along Project (Chapter 4) was the first of its kind to conduct walk-along interviews with children with CP and their parents for exploring experiences of real-world falls. The bespoke walkway (Chapter 5) presents the first evidence of mechanisms of potential falls and high fall risk in replica real-world environments known to be most challenging. The outcomes of this PhD provide evidence that children with CP experience falls in uneven environments, with distractions, likely due to destabilizing interactions with an environmental feature e.g. trip over a pavement edge, or an avoidance of a feature e.g. step around a pothole. This novel knowledge paves the way for designing future diagnostic tools and fall prevention interventions, which previously were underinformed or not considered in treatment plans for children with CP.

Declaration and Copyright Statement

No portion of the work referred to in the thesis has been submitted in support of an application for another degree or qualification to this or any other university or other institute of learning.

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Chapter 1

General Introduction and Aims

1.1 Cerebral Palsy, stability and fall occurrence

Cerebral palsy (CP) is a complex neurological condition caused by damage to the immature brain (Krigger, 2006). It is one of the most common causes of childhood motor impairment, with research identifying 1.5 - 3 cases per 1000 births (Armand et al., 2016). Although non-progressive, meaning the brain injury does not worsen over time, growth can cause changes in musculoskeletal impairments with age, which can introduce motor disorders and impaired sensory systems (Kirtley, 2006; Rosenbaum et al., 2007). The majority of children with CP (75%) are ambulatory (Armand et al., 2016), meaning they can walk without walking aids. This includes children who have CP hemiplegia (unilateral impairments) and diplegia (bilateral impairments), who are between levels I to II of the Gross Motor Function Classification System (GMFCS, a classification of everyday motor ability, level I = most able) (Beckung and Hagberg, 2002; Damiano et al., 2006).

Children with CP often experience difficulty with balance and coordination; 35% report daily falls and an additional 30% report weekly or monthly falls (Boyer and Patterson, 2018). The World Health Organization recognises two main groups at risk of falls, these are adults over 60 years old and children in early developmental stages (World Health Organization, 2021). More detailed reports show that adults with CP fall more often than adults without CP (Ryan et al., 2020), however literature is lacking on similar comparisons for children with CP to typically developing (TD) children. The case for studying falls in children with CP lies in that following the age of 5 years, TD children demonstrate greater stability through plantigrade gait patterns allowing more controlled movement, whereas children with CP maintain a more unstable digitigrade gait and report regular falls (Massaad et al., 2004; Boyer and Patterson, 2018). With reduced stability, children with CP continue to fall throughout childhood and into adulthood, thus impacting overall well-being (Gibson et al., 2012; Towns et al., 2020).

1.2 Negative psychosocial consequences of falls

Health related quality of life is a measure that identifies perceptions of consequences of specific medical conditions and is reduced in two-thirds of children with CP (Vinson et al., 2010; Dobhal et al., 2014). Activity participation is a contributor to health related quality of life and is lower for children with CP than TD children (Voorman et al., 2006; Michelsen et al., 2009; Cleary et al., 2019). Child-centred research has identified themes of enjoyment related to activity for children with CP, but also reported barriers to participation (Lauruschkus et al., 2015). Gibson et al. (2012) identified fear of falling, resulting in a decreased value of walking for children with CP. Similarly, Towns et al. (2020) identified reduced balance confidence, but additionally evidenced feelings of frustration and embarrassment rather than fear, especially during adolescence (9-17 years old) when social pressures are high. Furthermore, falls are a leading cause of non-fatal childhood injuries such as contusions, lacerations, fractures and head injuries (Bulut et al., 2006) and to add to this, children with disabilities have higher risk of injury when falls are the leading cause (Zhu et al., 2012).

1.3 Dynamic stability

Fall prevention requires anticipatory mechanisms as well as reactive control to maintain the centre of mass (COM) within the base of support (BOS). During locomotion this can be described as maintaining dynamic stability (Patla, 2003). On any ground, maintaining dynamic stability requires continued control of the COM within the progression of the BOS, at each foot placement and throughout the stepping path (Patla, 2003). This becomes more difficult when walking on non-level ground. Falls may occur if the physical demands of particular environments are not met in order to negotiate them safely, for example, poor foot placement around a pothole or insufficient foot clearance over a raised surface (Patla et al., 1999). When the placement of the foot or control of COM is perturbed, this must be recovered to prevent a fall. This prevention depends on a multitude of internal contributors such as sensory systems (visual, proprioceptive, vestibular) and the ability of the musculoskeletal system to both anticipate and respond to fall incidents (Lockhart et al., 2005).

Measurement of dynamic stability requires a forward projection of the moving COM location relative to the advancing BOS. Margin of stability (MOS) is a common measure to assess dynamic stability that has been used when investigating gait of children with CP (Sharifmoradi et al., 2018; Tracy et al., 2019; Rethwilm et al., 2021). MOS uses the extrapolated centre of mass concept proposed by Hof (2008), which is based on the inverted pendulum model and considers centre of mass (COM) position, centre of pressure (COP) position and COM velocity, for measuring stability. MOS is the distance between the extrapolated COM and the edge of the base of support (BOS), where a negative value implies instability and positive value implies stability (Hof et al., 2005)(Figure 1.1).

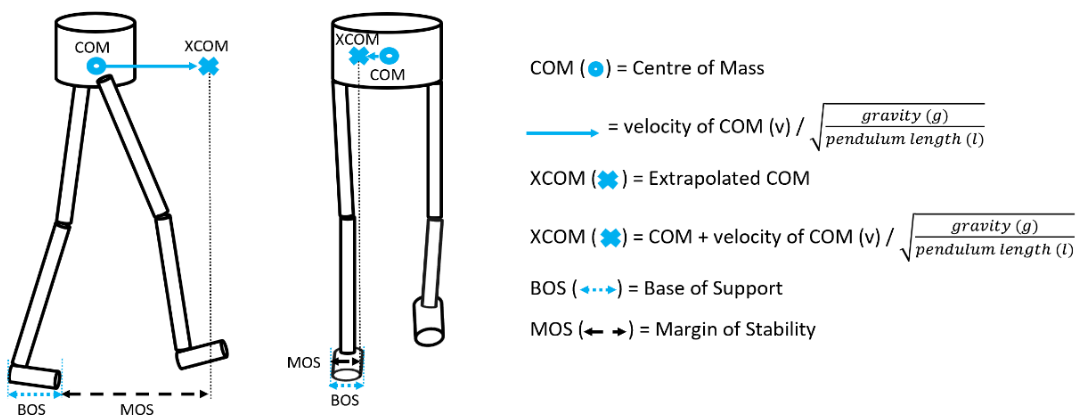


***Figure 1.1**. Margin of stability (MOS) in the anterior (left) and mediolateral (right) directions.*

1.4 Investigating the causes of real-world falls

The reasons that children with CP fall in real-world environments are not well understood. Treatment outcomes for children with CP are typically targeted at improving gait, which is expected to also result in increased stability and thus reduced falls (Narayanan, 2012). Boyer and Patterson (2018) found no difference in fall frequency between children with CP who exhibited gait characteristics typically associated with fall occurrence (intoeing, internal hip rotation, stiff knee gait) and children of the same GMFCS level without these characteristics. This suggests that current fall prevention may be both under informed and not targeting factors that characterise fallers. In other work, inability to sit for a long time and inability to balance on knees has been correlated with fall frequency (Alemdaroğlu et al., 2017). This study included a large range of children aged 3-18 years with and without walking aids (GMFCS I to V) and only assessed falls as they occurred in hospital and with fall history, therefore falls due to daily environments may have been missed or forgotten.

Understanding the reasons for falls in children with CP is an important step to reduce both negative physical and psychosocial consequences of falls. Further insight into causes and mechanisms of falls in children with CP may be revealed by including the thoughts and lived experiences of children with CP and their families when designing bespoke protocols tailored to places that children with CP fall most in the real-world. Additionally, methods for assessing dynamic stability, such as MOS, now offer the potential for quantifying fall risk in replica real-world environments that falls happen most. This would allow us to truly understand where and how falls happen in the real-world, whilst understanding the contributing factors to increased fall risk. This information could help identify individuals with CP at greater fall risk and inform the design of fall prevention programmes for those who need it most.

1.5 ICF Framework

The International Classification of Functioning, Disability and Health (ICF) was published by the World Health Organisation in 2001. The ICF provides a more detailed classification on a person's functioning and disability by considering personal factors, environmental factors and factors relating to health condition (World Health Organization, 2001). This aims to offer a holistic description of both the physiological functioning and social disability associated with a health diagnosis. Children with CP face both physical limitations that impact functionality and environmental barriers that can be contextualised by the ICF framework. Children with CP are heterogenous, showing different levels of ambulation and functional ability and varied gait patterns (Armand et al., 2016). Traditional assessments of functioning for children with CP use GMFCS and some classification of gait pattern e.g. crouch gait for children with diplegia. However, these methods are typically informed by physical limitations when walking on level ground and may not account for environmental barriers. Thus, the ICF offers a framework for deeper understanding of all barriers and limitations faced by children with CP day-to-day. Importantly, this has implications for clinical practice and research such as using interventions that are tailored for children with CP to account for both physical limitations and environmental barriers faced for improved functionality, disability, health and wellbeing.

Falls may be a key contributor to functioning, disability and health as outlined by the ICF framework, given that fall risk factors can be intrinsic (e.g. reduced functional ability, visual impairments), extrinsic (e.g. environmental challenges) and/or behavioural (e.g. fear of falling, hesitancy, footwear) (Montero-Odasso et al., 2022). For children with CP, falls may be due to a variable number of interacting factors including environmental surroundings and different levels of functionality. Moreover, previous work using the Gait Outcomes Assessment List with caregivers of children with CP suggests that factors such as not falling, improved gait characteristics and environmental features of the environment are among the most important and difficult goals for day-to-day living (Thomason et al., 2018; Boyer et al., 2022). Falls are also suggested to contribute to reduced physical and social activity participation based on experiences discussed with children with CP and their parents (Gibson et al., 2012; Towns et al., 2020). Thus, falls may be a key contributor to physical functioning and social disability experienced by children with CP.

In alignment with the ICF framework, generating a greater understanding of the multifaceted causes of falls and how to reduce them may offer novel approaches for addressing the functioning, disability and health of children with CP. This PhD looks to explore the multifaceted causes and mechanisms of falls in children with CP. This work cannot look at all the potential mechanisms of falls, with all sub-types and classifications of CP given the diverse and heterogenous nature of the group and the variety of personal, environmental and health factors at play. However, the majority of children with CP are ambulatory, and ambulatory children with CP have shown the highest frequency of falls in the real-world (Boyer and Patterson, 2018). Thus, this work aims to determine the causes and mechanisms of falls in ambulatory children with CP.

Aims and Objectives

The primary aim of this thesis was to determine the causes and mechanisms of falls in children with CP. This primary aim was achieved through a series of study specific aims to more closely identify how and why falls occur in real-world environments:

(1) Study 1 (Chapter 2) aimed to synthesise existing knowledge on whether challenging environments contribute to fall occurrence in children with CP and identify whether gait characteristics contribute to or compensate for instability and fall risk in challenging walking environments, using a systematic literature review.

(2) Study 2 (Chapter 3) aimed to use PPIE with children with CP and their parents/guardians to design and refine innovative methods of 'walk-along' interviews that are specific to and informed by daily experiences of children with CP.

(3) Study 3 (Chapter 4) aimed to use the specific 'walk-along' interview protocol tailored for children with CP, to understand where and why falls occur day-to-day for children with CP by determining the real-world environments children with CP find challenging.

(4) Study 4 (Chapter 5) aimed to use findings from studies 2 and 3 to identify potential mechanisms of falls and fall avoidance by understanding how challenging environments and sensory perturbations effect fall risk, in a laboratory-based study.

Chapter 2

Study 1. Systematic Literature Review

The contents of this chapter have been published in Gait and Posture in the following formats:

- Accepted Journal Article:
    - Walker, R.L., O'Brien, T.D., Barton, G.J., Carter, B., Wright, D.M. and Foster, R.J., (2025) Are challenging walking environments linked to falls or risk of falling in children with cerebral palsy? A systematic review. *Gait & Posture*, 117, pp.306-316. https://doi.org/10.1016/j.gaitpost.2025.01.008. *Accepted 12.01.2025*
- Special Issue Abstract:
    - Walker, R., O'Brien, T.D., Barton, G.J., Carter, B., Wright, D.M. and Foster, R.J., (2021). Do challenging walking environments contribute to increased fall risk in children with cerebral palsy? A narrative review. *Gait & Posture*, *90*, pp.304-305. https://doi.org/10.1016/j.gaitpost.2021.09.157

The contents of this chapter have been disseminated as presentations at the following academic meetings:

- European Society for Movement Analysis in Adults and Children (ESMAC) Annual Meeting 2021, Online
- British Association of Sport and Exercise Sciences Biomechanics Interest Group Meeting (BASES BIG) 2022, Online

Abstract

<u>Background:</u> Children with cerebral palsy (CP) regularly fall over and this has negative effects on their physical and psychosocial wellbeing (e.g., reduced activity participation). However, the reasons for falls are not well understood. The way in which children negotiate challenging walking environments (e.g., uneven surfaces), may reveal more about how falls occur as these environments require gait modifications to maintain stability. Stability in challenging walking environments has been explored for children with CP; however, it remains unclear how these lead to falls. <u>Research question:</u> Do challenging walking environments that mimic those faced in the real-world, contribute to increased fall occurrence and fall risk in children with CP? <u>Methods:</u> Five databases were searched, and 1386 records screened to include ambulatory children with CP, aged 5-18 years old, investigating dynamic walking in challenging environments, with outcomes of fall occurrence or fall risk. The full protocol for this review was registered on PROSPERO (CRD42021290456). <u>Results:</u> Sixteen studies met the inclusion criteria. One study reported occurrence of stumbles, two reported no falls. Fifteen studies identified gait alterations used by children with CP in challenging environments. Twenty-four gait characteristics were identified to be indicative of cautious walking strategies and seven gait characteristics identified to increase fall risk, suggesting a potential link. However, limited evidence exists as to whether this reflects falls faced in the real-world. <u>Discussion:</u> Based on the studies included in this review, investigations into stability over challenging walking environments for children with CP are lacking any measures of fall occurrence, even though near-falls were evidenced in some challenging environments. Investigations into the mechanisms that may contribute to high fall risk, or fall avoidance when negotiating obstacles, uneven surfaces, steep declines and stairs may reveal further information about the causes of real-world falls, and in doing so inform an avenue for future fall prevention techniques. Finally, understanding the multifaceted causes of falls in real-world challenging environments from the perspectives of children with CP is key for future research.

2.1 Introduction

Research on the epidemiology of falls in TD children in the real-world is well documented (Bulut et al., 2002, 2006; Young et al., 2013), but understanding of the mechanisms that contribute to real-world falls in children with CP is limited. Children with CP have demonstrated greater instability compared to TD children during walking (Bruijn et al., 2013), suggested to be due to associated gait characteristics including smaller knee flexion-extension range of motion (ROM) (Chakraborty et al., 2020) or in-toeing of the foot (Boyer and Patterson, 2018). However, evidence to link these gait characteristics to real-world fall frequency is limited (Boyer and Patterson, 2018), as described in Chapter 1.

Children with CP show gait alterations over level ground compared to TD children to maintain stability, for example, increasing step width, which increases BOS and therefore improves dynamic stability (Sharifmoradi et al., 2018; Tracy et al., 2019; Rethwilm et al., 2021). These adjustments could be identified as a cautious approach to walking, whereby changes to gait are proactive and pre-planned by children, or a compensation to a challenging task, where by changes to gait are reactive to instability that occurs with each step. Regardless, it is not fully understood whether cautious strategies or compensatory mechanisms increase or decrease real-world falls in children with CP.

A lack of understanding about where and how falls occur in children with CP is likely in part due to investigations of stability taking place over level surfaces in most experimental studies and clinical gait analysis. Assessments of dynamic stability for children with CP have used various outcome measures, for example, COM-COP separation (Hsue et al., 2009a; Wallard et al., 2014), foot placement estimator (Bruijn et al., 2013), maximum Floquet multiplier (Kurz et al., 2012), COM accelerometery (Hsue et al., 2009b; Iosa et al., 2012, 2013; Saether et al., 2013), margin of stability (MOS) (Sharifmoradi et al., 2018; Tracy et al., 2019; Rethwilm et al., 2021)). These assessments are typically conducted over level ground in laboratory environments, however in the real-world, children will often encounter and must negotiate challenging natural and built environments such as uneven surfaces (e.g. on the walk to school). Walking in a laboratory over level ground does not consider these real-world challenging environments that might increase fall risk and thus cannot truly reflect how kinematics are adjusted during more advanced balance challenges that are encountered day-to-day (Malone et al., 2015, 2016).

Challenging environments are defined here as places that require additional adjustments to gait characteristics for maintaining stability, and successful negotiation (preventing a fall) due to difficulty imposed by the surrounding natural or built environment compared to level walking. Examples include encountering unseen obstacles (e.g. branches, kerbs), uneven surfaces (e.g. cobble stones, uneven grass) or places with restricted foot placement or foot contact with the ground (e.g. narrow paths, stairs), which require adjustments to gait characteristics such as greater step width to increase stability or higher foot clearance to prevent tripping (Malone et al., 2016).

Falls, particularly in the anterior direction, may be more likely in the presence of a challenging environment that causes a perturbation (Tracy et al., 2019). Reasons for falls out of control of the individual, such as the environment, can also be described as extrinsic factors to increased fall risk. Impairments associated with CP may additionally make the required adjustment to avoid a fall within these environments difficult (Armand et al., 2016), these are intrinsic factors that may influence falls. It is plausible that changes to gait characteristics (spatiotemporal parameters, trunk and lower limb kinematics and various measures of stability) in challenging environments may be good indicators of fall risk in children with CP.

Challenging environments have been used to assess some gait characteristics, including dynamic stability of children with CP previously (Law and Webb, 2005; Böhm et al., 2014; Stott et al., 2014; Malone et al., 2015, 2016; Topçuoğlu et al., 2018; Ma et al., 2019; Romkes et al., 2020). However, direct links to everyday fall risk and fall rates remain unclear. Moreover, the necessity for further investigation specifically into fall risk and the impact of challenging environments on gait in children with CP has been highlighted in a recent review (Chakraborty et al., 2020). To current knowledge, there does not exist a synthesis of current evidence on whether investigations of children with CP walking over challenging environments in laboratory settings can offer a potential link between challenging environments and fall risk or fall occurrence in children with

CP. This information is vital for planning of future work that could potentially advance this understanding to be applicable to lived experiences in the real-world.

2.1.1 Aim

This systematic review aimed to (1) synthesise existing knowledge on whether challenging environments contribute to fall occurrence in children with CP and (2) establish whether any specific gait characteristics demonstrated by children (spatial-temporal parameters, kinematics, stability measures) compensate for or contribute to instability and increased fall risk, specifically when children with CP negotiate challenging environments.

2.2 Methods

This systematic review protocol was carried out following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA), guidelines (Moher et al., 2009). The protocol for this review was registered with PROSPERO (CRD42021290456).

2.2.1 Search strategy

Five electronic databases (Web of Science, PubMed, Scopus, CINAHL and MEDLINE) were searched using specific search terms defined by the study's Population, Exposure, Comparator, Outcomes, Study Design (PECOS) framework (Table 2.1). Searches were carried out on the 6th December 2021, then re-run on the 5th May 2022, 11th October 2022, 3rd May 2023 and 13th September 2024 to check for any new publications. Search strings and key words were carefully selected to ensure a comprehensive search by discussion of the study PECOS and inclusion firstly of any word relating to ambulatory children with CP (e.g. hemiplegi*), then any word relating to real-world challenging environments (e.g. incline, uneven) and finally any word relating to falls or stability (e.g. trip, balance). These terms were tailored for each database (Appendix 1). Reference lists of eligible articles were additionally searched. Searches had no restriction on country or year of publication but were restricted to full text articles written in the English language.

Table 2.1. *PECOS for systematic review study design*

PECOS	Description
Participant	Ambulatory children with cerebral palsy (5 to 18 years old) with a gross motor function classification system level I to level III and the ability to walk without walking aids.
Exposure	Challenging walking environments: defined as real-world or laboratory settings in which additional gait difficulties are induced by surrounding external features within that environment (e.g. uneven surfaces, obstacles), that have been designed to replicate daily challenges to gait that occur in the natural or built environment.
Comparison	Typically developing children to children with cerebral palsy Level walking compared to challenging environments.
Outcome	Fall occurrence and fall risk.
Study Design	Peer-reviewed original articles. Observational or intervention studies.

2.2.2 Screening and selection process

Duplicates were removed in EndNoteTM X9 (The EndNote Team, 2013). Remaining articles were imported into Rayyan© (Ouzzani et al., 2016), a freely usable systematic review software for screening research articles, where two researchers (RW, RF) independently reviewed titles and abstracts, according to inclusion and exclusion criteria (Table 2.2).

Table 2.2. *Inclusion and exclusion criteria*

Inclusion Criteria	Exclusion Criteria
• English, full text, all years, all countries • Peer-reviewed original research articles • Involvement of ambulatory children or adolescents with CP • Observational studies assessing gait between children with CP and TD children and baseline data from intervention studies (if applicable) • Studies involving dynamic walking • Studies involving walking in challenging environments designed to replicate daily walking experiences other than typical level overground walking (e.g. obstacles, uneven ground, incline walking) • Outcome measures of fall rates or fall risk as measured by associated gait characteristics (e.g. dynamic stability)	• Reviews (literature or systematic), books, theses, congress proceedings, letters to editors, qualitative studies • Studies including adults over 18 years of age and children under the age of 5 years • Studies not including children or adolescents with CP, or that focus only on children with CP with Gross Motor Function Classification System (GMFCS) level IV-V or who are non-ambulant (cannot walk without walking aids) • Assessment of TD children alone or level overground walking alone (without comparison to patient population or exposure of interest) • Any challenge to gait other than natural or built environmental features and topography, for example activities during walking that are initiated by children not due to environmental constraints (e.g. dual-tasking, running, turning) or any standing or sitting postural tasks

Full text articles were screened with inclusion and exclusion criteria. Final articles were included for data extraction, synthesis and quality assessment and grouped according to challenging environment.

2.2.3 Quality assessment

The National Institute of Health (NIH) quality assessment tool (NIH, 2013) was used to assess quality and internal validity of included studies and determine any risk of bias. This was assessed according to study type (e.g. observational or intervention). The NIH quality assessment tool allows assessment of study design, methods and implementation using 14 individual questions in which a response of “yes”, “no” or “could not determine” was awarded by two independent reviewers. Two reviewers (RW, RF) each reached a decision on quality rating of each included study (good, fair or poor) using NIH guidance. Any disagreements were discussed and resolved by both reviewers after each separately completing another quality assessment and determining an agreed score.

2.2.4 Data extraction

Two reviewers (RW, RF) carried out data extraction using a shared data extraction table in Microsoft Excel (Microsoft 365, Microsoft Corporation Washington, USA) which was discussed with all members of the review team (TOB, GB, BC).

Data extraction included: study title, authors, year, study type (observational or intervention), definition of falls or near-falls, number of participants, participant demographics (age, clinical diagnosis, GMFCS level), study methodology (involvement of challenging walking environments, assessment tool) and study outcomes.

Study outcomes included: number of falls or near-falls, and measures indicative of fall risk: spatial-temporal parameters (walking speed, step length, step width, cadence, single and double support time), margin of stability, COM movement, feelings of stability and kinematics (joint angles, ROM, foot clearance). Measures of central tendency (median, mean, standard deviation and range) were extracted.

2.2.5 Data Synthesis

Narrative synthesis was chosen for this review. Studies needed to be arranged into homogenous groups depending on the challenging environment investigated, thus narrative synthesis allowed textual comparison within and between challenging environments. The data extraction table was used to assess study characteristics and group studies according to type of challenging environment (e.g. uneven surfaces), since gait characteristics associated with fall risk (e.g. foot clearance) could not be compared between different environments. Fall occurrence was synthesized using descriptive measures of central tendency of number of falls or near-falls recorded in each study. Fall risk was grouped according to associated gait characteristics (e.g. kinematics), then synthesized according to descriptive measures of central tendency (means, standard deviations, range, and median scores).

During narrative synthesis, data from children with CP were compared to TD children when negotiating the same challenging environment, but comparison across different tasks was not possible for fall risk. Data were summarised firstly by study characteristics, then by fall occurrence, then by fall risk characteristics for each environment. Findings were visualised in the data extraction table, then data synthesis was checked by all members of the review team.

2.3 Results

2.3.1 Study characteristics

A total of 1386 studies were screened following removal of duplicates (Figure 2.1). Full text screening was completed on 34 studies, 1 could not be retrieved and 17 were excluded, leaving 16 studies included in the review following all searches. A summary of included studies is shown in Appendix 2, all were published between 2002 and 2024.

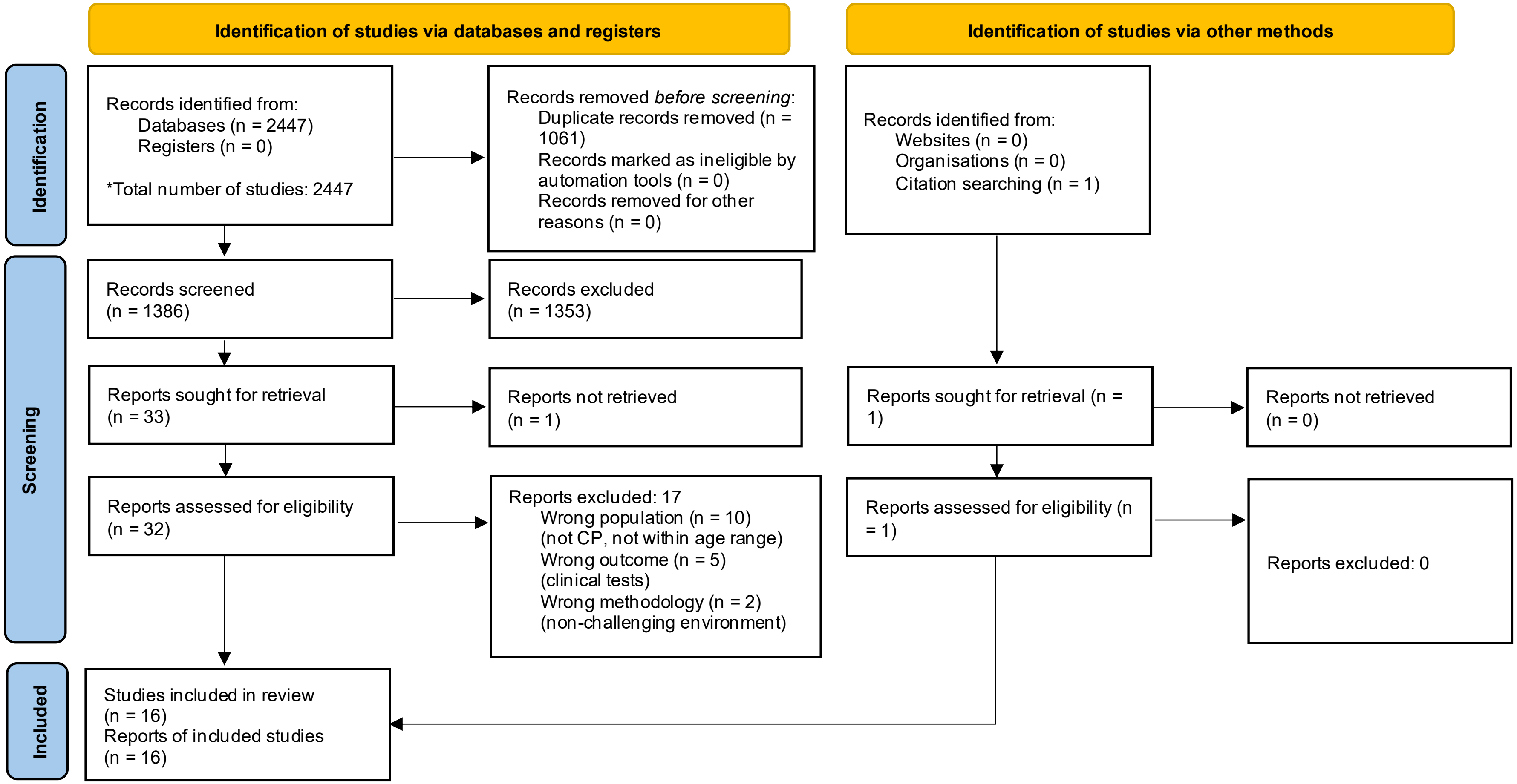


Figure 2.1. *PRISMA flow diagram* (Page et al., 2021)
**Total number of studies (before duplicate removal): 2447 (Web of Science: 960, PubMed: 442, Scopus: 913, MEDLINE: 92, CINAHL: 40)*

Five challenging environments were investigated across all studies, these were: uneven surfaces (n=4) (Böhm et al., 2014; Malone et al., 2015; Romkes et al., 2020; Coman et al., 2022); incline/decline walking (n=7) (Stott et al., 2014; Hösl et al., 2016; Mélo et al., 2017; Topçuoğlu et al., 2018; Ma et al., 2019; Choi et al., 2022; Camuncoli et al., 2024); obstacle crossing (n=4) (Law and Webb, 2005; Malone et al., 2016; Bailes et al., 2017; Coman et al., 2022); treadmill perturbations (n=1) (Flux et al., 2021) and stairs (n=1) (Sienko Thomas et al., 2002). One study investigated two challenging environments (uneven surfaces and obstacle crossing) before and after a 4-week exercise intervention (Coman et al., 2022). Thirteen out of 16 studies were cross-sectional or case-control designs (Law and Webb, 2005; Böhm et al., 2014; Stott et al., 2014; Malone et al., 2015, 2016; Hösl et al., 2016; Mélo et al., 2017; Topçuoğlu et al., 2018; Ma et al., 2019; Romkes et al., 2020; Flux et al., 2021; Camuncoli et al., 2024), three studies were interventions from which baseline data were extracted (Sienko Thomas et al., 2002; Bailes et al., 2017; Coman et al., 2022).

All studies included children with CP between the ages of 5 and 18 years who could walk independently (GMFCS I and II), except one study with children with spastic diplegia that did not specify GMFCS (Law and Webb, 2005). Four studies included only children with hemiplegia (Sienko Thomas et al., 2002; Romkes et al., 2020; Choi et al., 2022; Camuncoli et al., 2024), six studies included only children with diplegia (Law and Webb, 2005; Böhm et al., 2014; Stott et al., 2014; Hösl et al., 2016; Mélo et al., 2017; Topçuoğlu et al., 2018). Sample sizes of children with CP across studies ranged from 10 (Stott et al., 2014; Mélo et al., 2017; Ma et al., 2019) to 46 (Coman et al., 2022), all including similar numbers of TD children, apart from Bailes et al. (2017), Coman et al. (2022), Choi et al. (2022) and Camuncoli et al. (2024), who only included children with CP.

Within studies of uneven surfaces utilized polyurethane plastic squares moulded to create an uneven walkway of 6 m (Romkes et al., 2020) or 7 m length (Böhm et al., 2014), or bags of 0.5 cm pebbles placed at various positions over a 1.5 m x 0.4 m area (Malone et al., 2015; Coman et al., 2022). Incline walking was measured on a treadmill at 5° (Choi et al., 2022), 7° (Hösl et al., 2016) or 10° (Ma et al., 2019; Choi et al., 2022) slope, and on fixed ramps of 7° (Stott et al., 2014; Mélo et al., 2017) or 5° and 10° (Topçuoğlu et al., 2018) slopes.

Five studies measured both incline and decline walking, on either 5°, 7° or 10° slopes (Stott et al., 2014; Mélo et al., 2017; Topçuoğlu et al., 2018; Choi et al., 2022; Camuncoli et al., 2024). Four studies conducted incline or decline walking barefoot (Stott et al., 2014; Hösl et al., 2016; Mélo et al., 2017; Ma et al., 2019), one study conducted incline and decline walking outside with shoes (Stott et al., 2014) and two studies conducted incline and decline walking inside with shoes on a fixed ramp (Topçuoğlu et al., 2018) or a treadmill (Choi et al., 2022). One study conducted incline and decline walking in an interactive environment on an instrumented treadmill with different types of ankle-foot orthoses (AFOs) (Camuncoli et al., 2024).

Obstacle crossing was assessed by stepping over a fixed hurdle height of either 10 cm (Malone et al., 2016) or 23 cm (Coman et al., 2022) or over obstacles of various heights (0%, 10% and 20% leg length) (Law and Webb, 2005), and all hurdles were made using cylindrical sticks placed on two vertical stands. One study observed obstacle crossing performance using the standardized walking obstacle course (SWOC) (Bailes et al., 2017), a test designed to measure stability and speed of gait over a number of different surfaces and challenges (three directional turns, stepping over a crutch placed on the floor, walking over various surfaces and sit-to-stand activities) (Held et al., 2006).

One study investigated treadmill perturbations within a virtual reality environment by applying posterior split belt treadmill accelerations at three different walking speeds (0.5, 0.8 and 1 m/s) (Flux et al., 2021). One study assessed stair negotiation, which analysed stepping up and down four steps (rise: 15.2 cm, run: 24.1 cm) both with and without AFOs (Sienko Thomas et al., 2002).

2.3.2 Fall occurrence

Three studies identified presence or absence of a fall or near-fall within a challenging environment (Malone et al., 2016; Bailes et al., 2017; Flux et al., 2021). One recorded stumbles as part of the SWOC test and found that children with CP stumble 0.27 times per attempt at the SWOC (Bailes et al., 2017), and two (obstacle crossing (Malone et al., 2016) and treadmill perturbations (Flux et al., 2021)) stated that no falls occurred during the challenging task or that the task was completed successfully. All studies that included a fall occurrence measurement (Malone et al., 2016; Bailes et al., 2017; Flux et al., 2021), did not state whether the challenging environment of interest increased fall occurrence or fall risk.

One study (Bailes et al., 2017) defined a stumble as having contact with obstacles on the SWOC but no other studies out of 16 provided a definition for a fall or near-fall. Thirteen studies did not measure fall occurrence (Sienko Thomas et al., 2002; Law and Webb, 2005; Böhm et al., 2014; Stott et al., 2014; Malone et al., 2015; Hösl et al., 2016; Mélo et al., 2017; Topçuoğlu et al., 2018; Ma et al., 2019; Romkes et al., 2020; Choi et al., 2022; Coman et al., 2022; Camuncoli et al., 2024), four of which did not include 'falls' or a derivative of near-falls (e.g. 'stumble') within text (Hösl et al., 2016; Mélo et al., 2017; Coman et al., 2022; Camuncoli et al., 2024).

2.3.3 Fall risk

Fourteen studies assessed gait characteristics using three-dimensional (3D) motion capture (Sienko Thomas et al., 2002; Law and Webb, 2005; Böhm et al., 2014; Malone et al., 2015, 2016; Hösl et al., 2016; Mélo et al., 2017; Topçuoğlu et al., 2018; Ma et al., 2019; Romkes et al., 2020; Flux et al., 2021; Choi et al., 2022; Coman et al., 2022; Camuncoli et al., 2024), one study used two-dimensional (2D) motion capture (Stott et al., 2014). One study assessed obstacle crossing observationally using measures determined by the SWOC test (e.g. time to complete SWOC, number of steps taken, number of stumbles and steps on and off SWOC path) (Bailes et al., 2017). In all studies except one (Stott et al., 2014), children with CP were assessed by walking over challenging environments in laboratory settings. All 15 studies that used 2D or 3D motion capture (Sienko Thomas et al., 2002; Law and Webb, 2005; Böhm et al., 2014; Stott et al., 2014; Malone et al., 2015, 2016; Hösl et al., 2016; Mélo et al., 2017; Topçuoğlu et al., 2018; Ma et al., 2019; Romkes et al., 2020; Flux et al., 2021; Choi et al., 2022; Coman et al., 2022; Camuncoli et al., 2024) identified gait alterations in children with CP when walking over a challenging environment compared to level walking.

All extracted gait characteristics (n=52) for each challenging environment can be seen in Table 2.3, with contributing studies, quality assessment score and comparison to TD children and level ground. This table shows which studies have reported similar gait characteristics in children with CP when walking over challenging environments, in comparison to level ground or TD children. All challenging environments except treadmill perturbations (Flux et al., 2021) and decline walking (Stott et al., 2014; Mélo et al., 2017; Topçuoğlu et al., 2018; Choi et al., 2022; Camuncoli et al., 2024) reported a reduction in walking speed. All challenging environments showed increased step width in children with CP compared to TD children. The narrative synthesis of findings identified several gait characteristics in Table 2.3, that were suggested by authors of included studies to either be indicative of cautious walking strategies or compensatory to maintain stability, or potentially increase fall risk over each challenging environment (Figures 2.2a and 2.2b). Figure 2.2a shows gait characteristics suggested to be cautious or compensatory across multiple environments e.g. increased foot clearance over obstacles, which will reduce the likelihood of the foot coming into contact with an obstacle during swing phase. The largest number of cautious strategies were during decline walking. Figure 2.2b shows characteristics that were suggested to potentially increase fall risk across multiple environments e.g. reduced ankle dorsi-flexion on uneven surfaces might increase the risk of a trip from the toes making contact with the surface during swing phase. Fall risk characteristics (Figure 2.2b) were less common than those suggested to be cautious (Figure 2.2a) and were only suggested during obstacle crossing, walking on uneven surfaces and during incline or decline walking, none of which shared the same fall risk characteristics.

2.3.4 Quality scores

Final quality scores are shown in Table 2.3. Eight studies were rated as ‘Good’ (Sienko Thomas et al., 2002; Böhm et al., 2014; Malone et al., 2015, 2016; Bailes et al., 2017; Topçuoğlu et al., 2018; Choi et al., 2022), six studies as ‘Fair’ (Stott et al., 2014; Hösl et al., 2016; Ma et al., 2019; Romkes et al., 2020; Flux et al., 2021; Coman et al., 2022) and two studies rated as ‘Poor’ (Law and Webb, 2005; Mélo et al., 2017). Studies were typically rated as fair because they did not include a sample size justification (Stott et al., 2014; Hösl et al., 2016; Ma et al., 2019; Romkes et al., 2020; Flux et al., 2021) or did not meet the sample size required to reach statistical power based on earlier calculations (Coman et al., 2022). Additionally, several studies did not report details on how participants were recruited (Stott et al., 2014; Hösl et al., 2016; Ma et al., 2019;

Romkes et al., 2020; Flux et al., 2021). Two studies were rated as ‘Poor’, due to lack of reporting of the method of determining exposure (cerebral palsy diagnosis) (Law and Webb, 2005; Mélo et al., 2017) and for one there was no clear reporting of inclusion and exclusion criteria and no sample size justification (Law and Webb, 2005).

***Table 2.3**. Outcomes of included studies relating to fall risk, measured by associated gait characteristics (kinematics, spatiotemporal parameters). In order of total number of articles offering the same finding, grouped into quality rating.*

	Reported gait characteristics			
		Contributing articles		
Challenging environment	**Finding**	**NIH Quality Assessment Score**		
		Good	**Fair**	**Poor**
Uneven surface	↓ Walking speed [a b]	(Malone et al., 2015)[ab], (Böhm et al., 2014)[ab]	(Romkes et al., 2020)[ab], (Coman et al., 2022)[b]	
	↓ Step length [a] No change in step length [b] ↑ Hip flexion [b]	(Malone et al., 2015), (Böhm et al., 2014)	(Romkes et al., 2020)	
	↑ Knee flexion [a b]	(Malone et al., 2015)[ab], (Böhm et al., 2014)[ab]	(Romkes et al., 2020)[b]	
	↓ Cadence [b] ↑ Step width [a b *] ↑ Foot clearance [a b] Smaller ↑ ankle dorsiflexion (on uneven surface) [a]	(Böhm et al., 2014)	(Romkes et al., 2020)	
	↑ Anterior pelvic tilt [b]	(Malone et al., 2015), (Böhm et al., 2014)		
	↓ Internal foot rotation [b]	(Böhm et al., 2014)		
	↑ Double support time [b] ↑ Elbow flexion [b] ↑ Medial COM [a]		(Romkes et al., 2020)	
	↑ Sagittal pelvis ROM [b] ↑ Sagittal trunk ROM [b] Similar frontal trunk ROM [b] Similar transverse trunk ROM [b]		(Coman et al., 2022)	
	Similar dorsiflexion ROM [b] ↑ Hip abduction [a] ↑ Frontal pelvis ROM [a] ↓ Frontal pelvis ROM [b] ↑ Transverse pelvis ROM [b] ↑ Sagittal trunk ROM [a] ↓ Frontal trunk ROM [b] ↑ Transverse trunk ROM [a]	(Malone et al., 2015)		

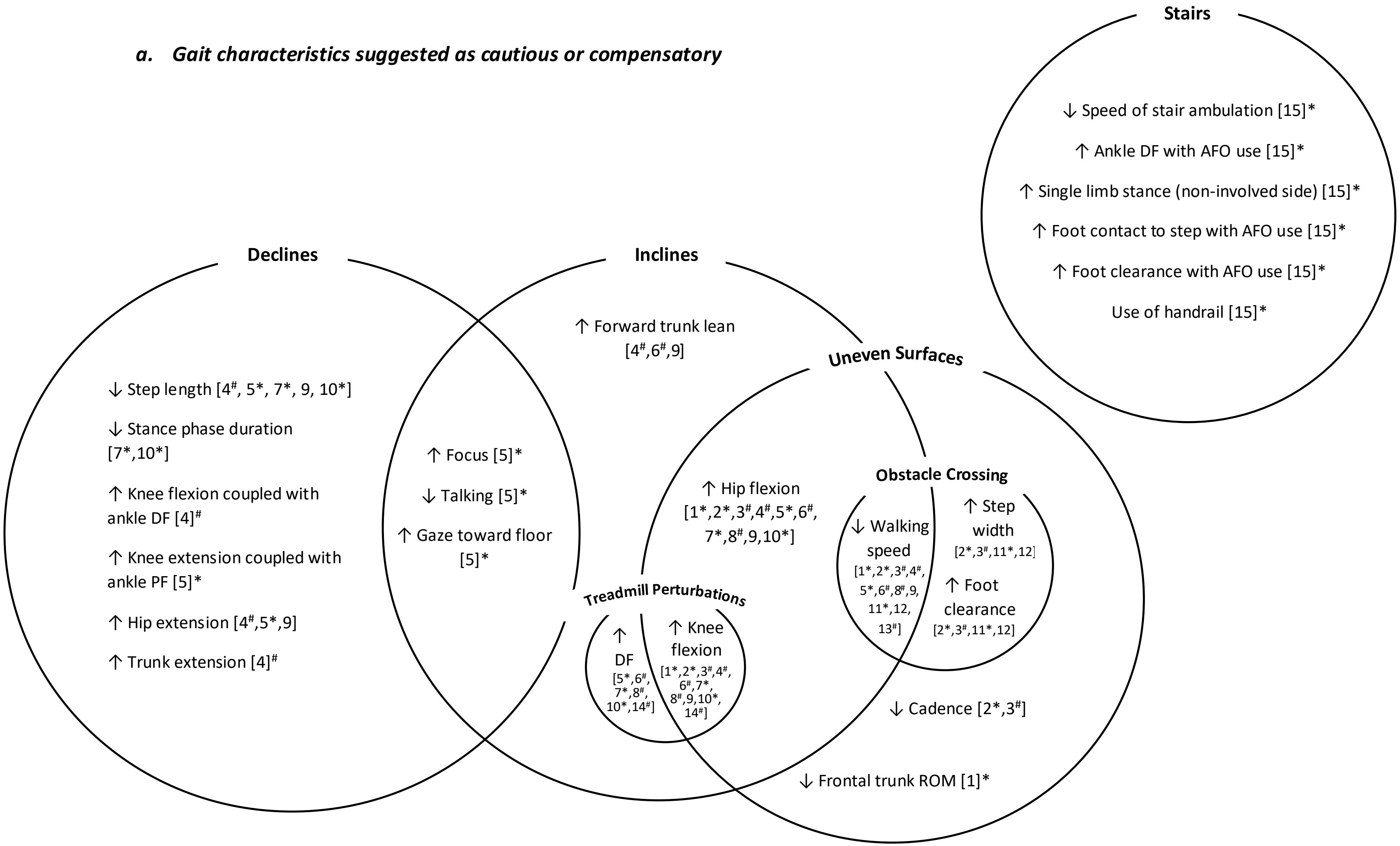
	↓ Sagittal COM to COP inclination angle [a] ↓ Separation of COM-COP [a] ↓ Max velocity of COM [a b]			
Gradient Walking	↓ Walking speed [a b] ↓ Stride length (level and inclines) [a]	(Topçuoğlu et al., 2018)[a]	(Stott et al., 2014)[a], (Ma et al., 2019)[ab], (Hösl et al., 2016)[a]	(Mélo et al., 2017)[a]
Inclines	↑ Hip flexion [b]	(Topçuoğlu et al., 2018), (Choi et al., 2022), (Camuncoli et al., 2024)	(Stott et al., 2014), (Ma et al., 2019), (Hösl et al., 2016)	(Mélo et al., 2017)
	↑ Knee flexion at IC [a b]	(Choi et al., 2022)[b], (Camuncoli et al., 2024)[b]	(Stott et al., 2014)[ab], (Ma et al., 2019)[b], (Hösl et al., 2016)[ab]	(Mélo et al., 2017)[b]
	↑ Forward trunk lean [a b]	(Camuncoli et al., 2024)[b]	(Stott et al., 2014)[ab], (Ma et al., 2019)[b]	(Mélo et al., 2017)[a]
	↑ Dorsiflexion (stance) [b]	(Topçuoğlu et al., 2018), (Choi et al., 2022), (Camuncoli et al., 2024)	(Ma et al., 2019), (Hösl et al., 2016)	
	↑ Anterior pelvic tilt [a b]	(Camuncoli et al., 2024)	(Ma et al., 2019)[ab],	(Mélo et al., 2017)[a]
	↓ Cadence [a b]	(Topçuoğlu et al., 2018)[ab]		(Mélo et al., 2017)[b]
	Similar stride length [b]		(Stott et al., 2014)	
	↑ Step length (affected side only) [b]	(Choi et al., 2022), (Camuncoli et al., 2024)		
	↓ Foot clearance [a] ↑ Stride width [a]			(Mélo et al., 2017)
	↑ Stance phase duration [a b] ↑ Dorsiflexion (swing) [a b] ↓ Plantarflexion (swing) [a b] ↓ Knee flexion (swing) [a b] ↓ Hip abduction (swing) [b] ↓ Frontal pelvis ROM [b] ↓ Transverse trunk ROM [a b] ↓ Sagittal COM-COP separation		(Ma et al., 2019)	
	↓ Dorsiflexion (swing) [b] ↑ Foot contact (with treadmill belt) [b]		(Hösl et al., 2016)	
	↑ Forefoot contacts (larger inclines) [a] ↑ Sagittal pelvis ROM [a] ↑ Sagittal trunk ROM [a] ↑ Frontal trunk ROM [a b]	(Topçuoğlu et al., 2018)		
	↓ Stride length [a b]	(Topçuoğlu et al., 2018)[ab],	(Stott et al., 2014)[ab]	(Mélo et al., 2017)[a]

		(Choi et al., 2022)[b]		
	↑ Hip extension at IC [a b]	(Topçuoğlu et al., 2018)[b]	(Stott et al., 2014)[ab]	(Mélo et al., 2017)[b]
Declines	↑ Plantarflexion at IC [a b]	(Topçuoğlu et al., 2018)[b], (Choi et al., 2022)[b]		(Mélo et al., 2017)[a]
	↑ Walking speed [b] ↑ Dorsiflexion at IC [a] ↑ Knee flexion at IC [a] ↑ Trunk extension at IC [a] Similar sagittal trunk, knee, hip, ankle angles at midstance [a]		(Stott et al., 2014)	
	Similar walking speed [b] ↑ Cadence [a b] ↑ Forefoot contacts with secondary heel touch (larger inclines) [b] ↓ Sagittal ankle ROM [b] ↑ Sagittal knee ROM [b] ↓ Knee flexion at IC [b] ↓ Sagittal hip ROM [b] ↓ Frontal trunk ROM [b]	(Topçuoğlu et al., 2018)		
	↓ Stance phase duration [b]	(Choi et al., 2022), (Camuncoli et al., 2024)		
Inclines and declines	Similar knee flexion (swing) [a]			(Mélo et al., 2017)
	↓ Feelings of safety (10° ramp) [a b] ↑ Focus ↓ Talking ↑ Gaze at ground (10° ramp) [a b]	(Topçuoğlu et al., 2018)		
Obstacle	↓ Walking speed [a b]	(Malone et al., 2016)[a]	(Coman et al., 2022)[b]	(Law and Webb, 2005)[ab]
	↑ Step width [a] ↓ Step length (trail limb) [a] ↑ Foot clearance over obstacle [a]	(Malone et al., 2016)		(Law and Webb, 2005)
	↓ Foot clearance over higher obstacle (compared to low) [a] ↑ Variability of foot clearance [a]			(Law and Webb, 2005)
	↓ Stance phase time [b] ↑ Trunk ROM (sagittal, transverse, frontal) [b]		(Coman et al., 2022)	
	Similar step length [a] Similar single support time [a] ↓ Dorsiflexion (swing) [a] Similar ↑ knee flexion over obstacle [a] Similar ↑ hip flexion over obstacle [a] ↑ Hip flexion (trail limb) over obstacle [a] ↑ Hip abduction (swing) [a] ↑ Sagittal pelvis ROM [a] ↑ Frontal pelvis ROM [a] ↑ Sagittal trunk ROM (trail limb crossing) [a] ↑ Frontal trunk ROM (lead limb crossing) [a] ↑ Transverse trunk ROM [a]	(Malone et al., 2016)		

	Similar sagittal COM-COP inclination angle [a] Similar frontal COM-COP inclination angle [a] ↓ COM velocity (lead limb toe-off) [a]			
Treadmill perturbation	Similar gait pattern [b] ↓ Stance phase duration [b] Same number of recovery strides [a] ↑ Dorsiflexion for CP and TD [b] ↑ Knee flexion for CP and TD [b]		(Flux et al., 2021)	
Stairs	↓ Speed of stair ambulation [a] Similar single support % (ascent) (involved limb) [a] ↓ Single support % (descent) (involved limb) [a] ↑ Single support % (ascent and descent) (non-involved) [a] Plantarflexion at IC (ascent and descent) (barefoot)[a] ↓ Dorsiflexion (ascent) (barefoot) [a] ↓ Knee flexion (swing) (ascent) [a] ↑ Dorsiflexion at IC with AFO (ascent and descent) ↑ Foot clearance with AFO ↓ Sagittal ankle ROM (descent) (barefoot) [a] ↑ Knee flexion (descent) (barefoot) [a] ↑ Foot contact and stair ambulation with AFO	(Sienko Thomas et al., 2002)		

[a] = compared to TD children, [b] = compared to level ground, ↑ = increase, ↓ = decrease, IC = initial contact, AFO = ankle-foot orthoses, ROM = range of motion

a. Gait characteristics suggested as cautious or compensatory



b. Gait characteristics suggested to increase fall risk

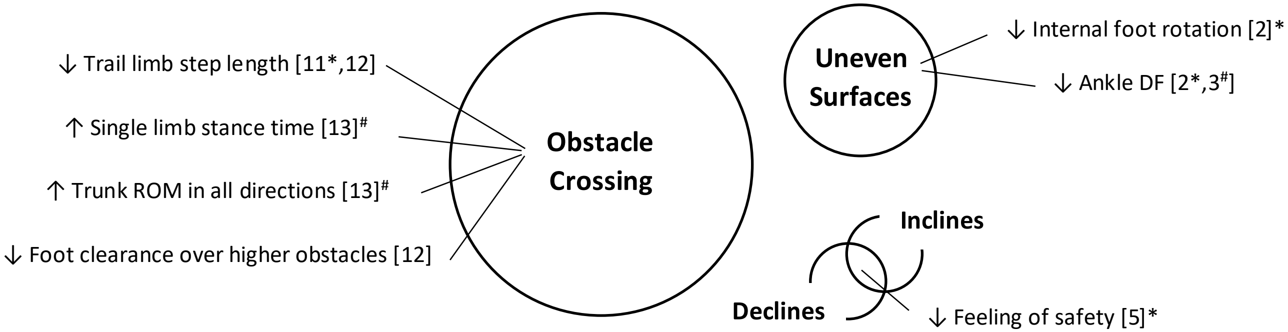


Figure 2.2. *Synthesis of gait characteristics identified in each challenging environment that were suggested by included papers to evidence (**a**) cautious behaviour or compensatory mechanisms to maintain stability or (**b**) increased fall risk. Size of circle (diameter in cm), scaled to number of characteristics, e.g., 8 cautious behaviour characteristics for declines = 8cm. Overlapping circles represent gait characteristics identified within two or more separate challenging environments from separate studies e.g., increased hip flexion is a cautious behaviour used by children identified in a study investigating incline walking and a separate study investigating uneven surfaces.*

** = Good, # = fair quality assessment score*

DF = dorsiflexion, PF = plantarflexion, TD = typically developing children, ↓ = decreased, ↑ = increased

[] = reference to papers in which the gait characteristic was identified with numbering as follows:

1 (Malone et al., 2015), 2 (Böhm et al., 2014), 3 (Romkes et al., 2020), 4 (Stott et al., 2014), 5 (Topçuoğlu et al., 2018), 6 (Ma et al., 2019), 7 (Choi et al., 2022), 8 (Hösl et al., 2016), 9 (Mélo et al., 2017), 10 (Camuncoli et al., 2024), 11 (Malone et al., 2016), 12 (Law and Webb, 2005), 13 (Coman et al., 2022), 14 (Flux et al., 2021), 15 (Sienko Thomas et al., 2002).

2.4 Discussion

This is the first systematic review to investigate the effect of challenging walking environments on fall occurrence and fall risk in children with CP. Sixteen studies were included, with three (Malone et al., 2016; Bailes et al., 2017; Flux et al., 2021) reporting the occurrence or absence of a fall. This primary finding demonstrates that the link between challenging environments and the causes of real-world falls experienced by children with CP is understudied. All studies reported the effect of challenging environments on gait characteristics that could indicate a risk of falling. All but one (Bailes et al., 2017) evidenced at least one example of cautious behaviour when negotiating a challenging environment. The detailed findings of this systematic review are discussed in two parts: the contribution of challenging environments to increased fall occurrence in children with CP; and whether gait characteristics compensate for or contribute to instability and fall risk within challenging environments in children with CP. Gait characteristics are discussed within context for the five different challenging environments identified (uneven surfaces (Böhm et al., 2014; Malone et al., 2015; Romkes et al., 2020; Coman et al., 2022), incline/decline walking (Stott et al., 2014; Hösl et al., 2016; Mélo et al., 2017; Topçuoğlu et al., 2018; Ma et al., 2019; Choi et al., 2022), obstacle crossing (Law and Webb, 2005; Malone et al., 2016; Bailes et al., 2017; Coman et al., 2022), treadmill perturbations (Flux et al., 2021) and stairs (Sienko Thomas et al., 2002)).

2.4.1 The link between challenging environments and real-world fall occurrence

This review highlights the limited number of studies reporting fall occurrence as a primary outcome measure when assessing children with CP walking in challenging environments. One study revealed that children with CP stumble once in every four attempts during a SWOC test (Bailes et al., 2017), which might imply increased fall risk in challenging environments; however, stumble locations on the SWOC were not reported so it is unclear whether any near-fall incidences occur due to an obstacle, a change in walking direction or an uneven surface, making it difficult to determine the potential causes/mechanisms of the near-fall. Moreover, the SWOC assessment was used as part of a wider intervention study and was not a comparison to TD children for the purpose of understanding fall risk or fall occurrence. Therefore, it is difficult to determine whether the SWOC test indicates a high fall occurrence or fall risk in children with CP. Despite this, the SWOC test is clearly able to highlight stumbles or near-falls in more challenging environments than level-ground. Thus, with improved reporting, the SWOC test is a potential avenue for clinical assessments of children who might be at higher fall risk in the real-world.

The focus of included studies within this review was on stability and fall avoidance strategies, rather than whether a fall is likely to occur in a particular challenging environment (Sienko Thomas et al., 2002; Law and Webb, 2005; Böhm et al., 2014; Stott et al., 2014; Hösl et al., 2016; Mélo et al., 2017; Ma et al., 2019; Coman et al., 2022). Consequently, only one study (Bailes et al., 2017) provided a definition of a near-fall, which did not align to standard definitions of a fall or near-fall as it was tailored to specific study methods (defined as contact with obstacles on the SWOC). A fall is described by the World Health Organization (WHO) (World Health Organization, 2021) as "an event which results in a person coming to rest inadvertently on the ground or floor or other lower level". Near falls, sometimes referred to as trips or stumbles, have been defined by Maidan et al. (2014) as "a stumble event or loss of balance that would result in a fall if sufficient recovery mechanisms were not in place" [p.646]. Several studies included in this review aimed to identify how balance and stability is affected in challenging environments (Malone et al., 2015, 2016; Topçuoğlu et al., 2018; Romkes et al., 2020). Yet, without knowing if falls occur in these environments, it is difficult to determine whether any instabilities typically lead to real-world falls or whether suggested cautious gait characteristics, used to maintain stability, are successful for preventing falls in these environments day-to-day. A suggestion for future work is to not only improve reporting and consideration of real-world fall occurrence but to also adopt standardized terminology for a 'fall' and 'near-fall' to allow consistency in reporting between studies.

2.4.2 The link between challenging environments, gait characteristics and fall risk

Although gait characteristics were identified in six studies which were assumed to be linked to fall risk (Law and Webb, 2005; Böhm et al., 2014; Malone et al., 2016; Topçuoğlu et al., 2018; Romkes et al., 2020; Coman et al., 2022) (Figure 2.2b), the link demonstrating that these factors do contribute to real-world falls was not proven. Children with CP adopt cautious behaviours and compensatory mechanisms over challenging environments to maintain stability by reducing walking speed and widening the BOS, making it easier to keep the COM within the BOS. Similar differences can be seen over level ground in children with CP (Chakraborty et al., 2020). Further investigation is required to determine whether the same cautious behaviours reported in laboratory environments occur in real-world challenging environments.

(a) Uneven surfaces

Children with CP exhibited cautious strategies, reflected by a number of changes to gait characteristics when walking on uneven surfaces compared to level ground, including reduced walking speed (Böhm et al., 2014; Malone et al., 2015; Romkes et al., 2020; Coman et al., 2022), increased step width (Böhm et al., 2014; Romkes et al., 2020), reduced cadence (Böhm et al., 2014; Romkes et al., 2020), and increased foot clearance (Böhm et al., 2014; Malone et al., 2015; Romkes et al., 2020) aided predominately by increased knee flexion (Böhm et al., 2014; Romkes et al., 2020), but also by increased hip flexion (Böhm et al., 2014; Romkes et al., 2020). These changes were suggested as cautious mechanisms to prevent instability due to the uneven surface, however could also be a reactive compensation to the instability faced during each step. One study reported significantly reduced frontal plane trunk motion in children with CP compared to TD children (Malone et al., 2015), a compensation strategy previously reported to conserve lateral stability (Tracy et al., 2019). Malone et al. (2015) and Coman et al. (2022) also identified similar frontal plane trunk ROM between level and uneven surfaces. Conservation of lateral stability was demonstrated in other studies (Böhm et al., 2014; Romkes et al., 2020) by increasing step width to widen the BOS and increase dynamic stability on an uneven surface. Moreover, increased step width is a recognised strategy used by children with CP to increase stability walking on level ground

(Chakraborty et al., 2020); however, seems to be done so to a greater extent when presented with an uneven surface.

Children with CP use conservative gait behaviours to compensate for instability caused by an uneven surface. Böhm et al. (2014) also suggested that changes to specific gait pathologies including increased out-toeing combined with reduced ankle dorsiflexion may cause a fall due to the potential of accidental foot contact with raised sections of the uneven ground. Despite this, children with CP showed alternative compensations to increase foot clearance on uneven surfaces by increasing knee and hip flexion instead, both of which reduce risk of foot contact with the ground. Two studies suggested that increase knee and hip flexion is done to prioritize stability on the uneven surface at the detriment to conservation of energy (Böhm et al., 2014; Romkes et al., 2020). Therefore, when fatigued this less efficient gait pattern may become unobtainable and could increase fall risk.

The findings from this review suggest there may be links to increased fall risk in children with CP when walking on uneven surfaces, due to the nature of compensation strategies and the possible impact of fatigue on foot clearance. However, there are too few studies to provide a robust evidence base and, within these studies, none quantified fall occurrence or history of falls as an outcome measure. Further work needs to confirm whether evidenced gait compensations used by children with CP are enough to control instabilities and prevent a fall in real-world environments as well as confirm any contribution fatigue may have on fall risk. Additionally, research that defines the type of uneven surfaces that children with CP find most challenging may be helpful in creating a clearer picture of the causes of real-world falls.

(b) Gradient walking

Children with CP can modify their gait characteristics in a similar way to TD children to successfully maintain stability and safely negotiate inclines and declines. When walking uphill, children with CP reduced their walking speed compared to level walking [22–24,33,34], and exhibited increased hip flexion (Stott et al., 2014; Hösl et al., 2016; Mélo et al., 2017; Topçuoğlu et al., 2018; Ma et al., 2019; Choi et al., 2022) and ankle dorsiflexion (Hösl et al., 2016; Topçuoğlu et al., 2018; Ma et al., 2019; Choi et al., 2022) in the same manner as TD children. Knee flexion, and forward trunk lean were also increased in children with CP to successfully ambulate the incline compared to level walking, but this increase was significantly greater for children with CP compared to TD children (Stott et al., 2014; Hösl et al., 2016; Mélo et al., 2017; Ma et al., 2019; Choi et al., 2022). The greater adjustment in knee and trunk kinematics may possibly compensate for the increased difficulty walking on an incline and underlying muscle weakness in children with CP (Stott et al., 2014; Armand et al., 2016). This is supported by the increase in step length on the affected limb identified by Camuncoli et al. (2024) and Choi et al. (2022), suggested to be a compensatory increase in work on the unaffected side in children with hemiplegia when walking uphill. Another important finding that may contribute to these greater adjustments is a reduced feeling of safety in children with CP when asked to ambulate an incline. Topçuoğlu et al. (2018) asked children about their feeling of safety, observed facial expressions, gaze direction and how vocal children were, which together indicated increased hesitancy when children with CP were faced with steep inclines.

During decline walking children with CP showed larger gait alterations in order to compensate for the challenging environment compared to TD children (e.g. reduced stride length, increased hip and trunk extension). Camuncoli et al. (2024) specifically suggest a shorter stride length is used when walking downhill to increase stability. This may again be linked with reduced feeling of safety when faced with steep declines as suggested by Topçuoğlu et al. (2018). Two studies demonstrate contradictory knee and ankle mechanisms for walking downhill (Stott et al., 2014; Topçuoğlu et al., 2018). Stott et al. (2014) identified increased knee flexion and ankle dorsiflexion at initial contact compared to TD children to control downward motion. Conversely, Topçuoğlu et al. (2018) identified increased plantarflexion and knee extension at initial contact to control downward motion through lengthening of the body. Mélo et al. (2017) also identified increased plantarflexion during downhill walking. These different strategies may be influenced by different measurement approaches. Stott et al. (2014) used 2D analysis with digital video cameras compared to 3D motion capture used by both Topçuoğlu et al. (2018) and Mélo et al. (2017). The accuracy of a video based 2D analysis is low compared to 3D analysis, due to increased measurement error during manual digitisation of video to calculate joint angles, shown here by large ranges in ankle dorsiflexion (-9° to 35°) and knee flexion (-3° to 32°) in children with CP (Stott et al., 2014). Choi et al. (2022) suggested another reason when they identified that children with hemiplegia show more plantarflexion on an unaffected limb when walking downhill. Stott et al. (2014) only included children with diplegia (GFMCS II), whereas Topçuoğlu et al. (2018) and Mélo et al. (2017) included GMFCS I and were therefore higher functioning and potentially better able to achieve plantarflexion during the decline (Choi et al., 2022). Choi et al. (2022) discuss that these ankle mechanisms for negotiating downhill walking in children with CP should be further investigated. Nevertheless, all studies in this review demonstrate that children with CP can successfully negotiate declines.

Children with CP show the ability to successfully negotiate both inclines and declines, suggesting that this this type of challenging environment may not be a significant contributor to real-world high fall occurrences, and that fall risk may be somewhat reduced by the cautious strategies identified in this review (n = 14, Figure 2.2a). Additional exploration of reasons for decreased feeling of safety on steep inclines and declines may offer deeper understanding of everyday experiences outside of such controlled environments, for example, if a reduced feeling of safety is linked to previous fall experiences or fear of falling.

(c) Obstacle crossing

Two studies suggest children with CP use compensatory gait mechanisms increased step width, increased foot clearance, and slower approach and crossing speed compared to TD children, to maintain stability in response to an obstacle (Law and Webb, 2005; Malone et al., 2016). However, slower crossing speed (Law and Webb, 2005; Malone et al., 2016; Coman et al., 2022) and increased foot clearance (Law and Webb, 2005; Malone et al., 2016), in combination with increased swing phase time (Coman et al., 2022), can be linked with longer single limb stance over an obstacle compared to level ground. Longer single limb stance time is inherently more unstable than double limb support due to reduced BOS and additional mechanisms needed to maintain balance (Levine et al., 2012). Distance between the trailing limb and the obstacle was also reduced in children with CP compared to TD children (Law and Webb, 2005; Malone et al., 2016); however this was only significant for a higher obstacle, demonstrated by Law and Webb (2005). Children with CP also exhibited increased inter-trial variability of the path of the toe while stepping over the obstacle, which might suggest higher likelihood of tripping by contacting the obstacle; however, no falls were reported by either Malone et al. (2016) or Law and Webb (2005). Malone et al. (2016) and Coman et al. (2022) identified increased anterior, lateral and rotational trunk motion in children with CP compared to TD children (Malone et al., 2016) and compared to level walking (Coman et al., 2022), which may lead to the COM moving outside the BOS more often, thus reducing stability and increasing fall risk. These trunk movements were suggested to be a result of an underlying lack of control of the trunk and pelvis segments together with compensatory movements for instabilities distally, such as at the ankle (Malone et al., 2016). Lack of trunk and pelvis control and distal instabilities imply overall reduced stability compared to TD children over obstacles that may increase fall risk.

Law and Webb (2005) identified reduced foot clearance compared to TD children when presented with a higher obstacle, unlike the smaller obstacle in Malone et al. (2016). Perhaps during the more challenging (higher) obstacle, the compensatory increase in foot clearance is no longer obtainable due to lack of ROM or muscle strength that allows increased knee and hip flexion or is jeopardized to allow less time on single limb support. The reason for this difference warrants further investigation if high obstacles (and associated foot clearance or single limb support time) are to be considered contributors to high fall risk in children with CP.

The high occurrence of stumbles identified by Bailes et al. (2017) might suggest that children with CP demonstrate insufficient compensatory gait adjustments in response to crossing an obstacle, which could increase risk of a fall. However, the lack of specificity of outcome measures within the SWOC test for determining where a stumble occurs makes it difficult to attribute any stumbles directly to crossing an obstacle. Malone et al. (2016) additionally suggested that vision may be an important factor in stepping over an obstacle safely for children with CP (Cappellini et al., 2020), therefore indicating a possible direction for future work.

(d) Treadmill perturbations

Children were able to maintain stability in the one study that assessed treadmill perturbations, showing no falls and sufficient recovery strides (Flux et al., 2021). Children with CP and TD children showed similar responses to a perturbation, including increased ankle dorsiflexion and knee flexion compared to walking without a perturbation. However, treadmill walking has previously shown differences to overground walking in TD children (Jung et al., 2021), and in children with CP (van der Krogt et al., 2014). Therefore, although limited evidence is presented here, it may be plausible that real-world perturbations do cause falls, however this treadmill task does not reflect a real-world perturbation that would cause a fall as is typically encountered day-to-day.

(e) Stair ambulation

Children with CP demonstrated slower walking speed on stairs compared to TD children and increased single limb stance time on the 'non-involved' (unaffected) limb (Sienko Thomas et al., 2002). This may suggest a more cautious strategy to ambulate the increased challenge presented by stairs. Children with CP also demonstrated increased dorsiflexion, increased foot clearance and better foot placement with AFO use (Sienko Thomas et al., 2002). This, coupled with unlimited handrail use and the inclusion of only higher functioning children with CP (hemiplegia) likely reduced fall risk in this study. To determine any role that stairs may have on everyday fall occurrence, future work should explore the difficulty of stair negotiation across different levels of ambulatory function (GMFCS I to III) and with and without handrail use, since this is not always possible during real-world challenging environments.

1.4.4 Limitations

A possible limitation of this review is the restricted age range in inclusion criteria. Six studies were excluded from this review because they included children with CP below 5 or above 18 years old (Kott and Held, 2002; Zipp and Winning, 2012; Cappellini et al., 2020; Harvey et al., 2021; Moll et al., 2022). Three of these studies documented occurrence of stumbles over either the SWOC (Kott and Held, 2002; Zipp and Winning, 2012) or a fixed obstacle (Cappellini et al., 2020). These studies were excluded because participants were either younger (Kott and Held, 2002; Zipp and Winning, 2012; Cappellini et al., 2020; Moll et al., 2022) or older (Harvey et al., 2021) than the inclusion criterion. The inclusion criterion in this review (5-18 years old) accounts for children with CP who fall more often compared to TD children (> 5 years old) (Massaad et al., 2004;

Boyer and Patterson, 2018) and those who experience most negative psycho-social consequences (9 - 17 years old) (Towns et al., 2020). Therefore, findings of excluded studies may have been less applicable to fall occurrence and fall risk outcomes. For example, inclusion of younger children by Zipp and Winning (2012), possibly led to an increased number of stumbles over the SWOC, in comparison to Bailes et al. (2017), because very young children fall regularly, regardless of CP (World Health Organization, 2021). Furthermore, the excluded studies show similar results to those discussed in this review, therefore, it is thought they would not add to the understanding of how challenging environments contribute to fall occurrence or fall risk in the real-world.

Another limitation of this review is the limited number of studies that quantify falls due to the primary focus of included studies on stability and fall avoidance rather than causes of falls. Reduced dynamic stability in any environment is an indicator of increased fall risk (Patla, 2003). The inherent link between instability and fall risk suggests that papers included in this review are likely to provide the most relevant outcomes that could identify whether movement patterns of children with CP over challenging environments contribute to or compensate for increased fall risk. The studies included in this review provide a comprehensive overview of the factors that may contribute to falls (Figure 2.2a and 2.2b).

2.4.5 Recommendations for future studies

Future work could firstly consider more reporting of fall occurrences in the real-world, then how and why real-world falls occur. Children with CP do stumble when negotiating the SWOC (Bailes et al., 2017), therefore a first step may be to isolate elements of the SWOC to understand over which obstacles or tasks stumbles are occurring. Future work could then consider exploring performance of children with CP on the SWOC test or similar tests that have applicability to real-world environments, such as an ‘obstacles and curb test’ (Algabbani et al., 2023), alongside a falls diary that children with CP and TD children can complete, to further investigate the link between challenging environments and falls.

Future investigation within each of the five challenging environments identified in this review should be undertaken to provide further insight into mechanisms of falls in children with CP. This coincides with a recent review suggesting more work is needed on understanding fall risk in children with CP and impact of challenging walking (Chakraborty et al., 2020) and another examining gait adaptations in children with CP in some challenging environments (Dussault-Picard et al., 2022b). Future investigations should specifically address hip and knee ROM, muscle strength, muscle weakness and single limb stance time when stepping over high obstacles (~20% leg length), the impact of fatigue on sagittal ankle, knee and hip angles when walking over uneven surfaces, qualitative reasons for reduced feelings of safety during incline and decline walking and finally, fall risk gait characteristics (e.g. foot clearance, foot placement) during stair negotiation across different GMFCS levels, with and without handrails.

All included studies in this review had the limitation that they undertook measurements within a controlled laboratory environment. Previous work suggests that children show improved gait characteristics within a clinical setting (Carcreff et al., 2020), therefore accurate reflection of how gait may change to contribute to or compensate for instability in challenging environments from this review may not reflect real-world places where falls occur. Investigation is required focusing on real-world challenging environments in which falls do occur outside the laboratory, informed by lived experiences of children with CP, to assess specific compensatory and contributory mechanisms of falls within those real-world places. This would extend knowledge beyond the current literature presented in this review.

Determining where falls occur, the influence of real-world environments and the impact of sensory challenges are important considerations for future falls research in children with CP. No studies in this review explored the impact that sensory or cognitive factors may have on instability within challenging environments. Reduced vision or cognitive ability, vestibular deficits, reduced concentration or environmental distractions, could contribute to increased fall risk or balance deficits for children with CP when walking in challenging environments (Sansare et al., 2022). Visual factors affecting falls were suggested by Malone et al. (2016) as an avenue for future work during obstacle crossing. Furthermore, Sansare et al. (2022) recently confirmed that visual information is important for maintaining balance and deserves more attention when planning treatment and interventions for fall prevention in children and adolescents with CP. Additionally, UK guidelines for clinical movement analysis, which typically informs treatment for children with CP explicitly states that environments should be non-distracting, emphasising the role distractions may play on gait and walking behaviour in children (Stewart et al., 2023).

To find out what makes an environment challenging and likely to lead to a fall, exploration first needs to identify where real-world falls occur, and the multi-faceted reasons why falls occur. This could be achieved by learning from the insights and lived experiences of children with CP and their families about falls in their everyday environments or by monitoring behaviour in the real-world during tasks like those discussed in this review.

2.5 Conclusion

This review sought to systematically synthesise literature on whether challenging environments impact falls in children with CP. Existing knowledge stating that children with CP fall often is extended in this review, highlighting that challenging environments are a cause of near-falls and children with CP respond by utilising cautious or compensatory stability strategies. However, the link between these gait adaptations and fall occurrence in challenging environments has not been demonstrated. Findings from this review cannot confirm which challenging environments may contribute to high fall occurrence in the real-world. However, obstacle crossing, uneven surfaces, steep declines and stair ambulation may warrant further detailed investigation, and specific recommendations have been provided. The 16 studies included in this review highlight a broader lack of investigation into falls and fall risk in real-world environments for children with CP, given the limited evidence available. Nevertheless, this review provides a comprehensive overview of extrinsic factors (e.g. increased obstacle height) and intrinsic factors (e.g. reduced foot clearance) that may contribute to falls, while also highlighting key areas for investigation in order to understand how challenging environments contribute to falls in the real-world for children with CP. Specific recommendations of how future work might address this are offered within this review, that are essential to bring us closer to understanding falls, informing fall prevention and reducing the negative consequences of falls for children with CP.

Chapter 3

Study 2. Engaging with Children and Parents to Develop Participatory Informed Methods

The contents of this chapter are in review for publication to Health Expectations and have been published as a special issue abstract in Gait and Posture:

- Journal Article in Review:
    - Walker, R.L., O'Brien, T.D., Barton, G.J., Carter, B., Wright, D.M. and Foster, R.J., (2024) Talking the Walk (Along): Lessons learned from engaging with children with cerebral palsy and their parents for investigating lived experiences of falls - *Submitted to Health Expectations 19.07.2024 (in review)*
- Special Issue Abstract:
    - Walker, R.L., O'Brien, T.D., Barton, G.J., Carter, B., Wright, D.M. and Foster, R.J., (2022) How children with cerebral palsy and their parents helped co-design 'The Walk-Along Project' protocol to investigate causes of daily falls. *Gait & Posture*, *97*, pp.S268-S269. https://doi.org/10.1016/j.gaitpost.2022.07.162.

The contents of this chapter have been disseminated as presentations at the following academic meetings:

- European Society for Movement Analysis in Adults and Children (ESMAC) Annual Meeting 2022, Dublin
- European Academy of Childhood Disability (EACD) Annual Meeting 2023, Ljubljana
- British Sociological Association Co-Production Forum 2022, Online

Abstract

<u>Background</u>: Children with cerebral palsy (CP) regularly fall over, but causes of day-to-day falls are not well understood. Further insight may be revealed by engaging with children with CP and their families during patient and public involvement and engagement (PPIE) and adopting a participatory, child-centred perspective. PPIE involves designing, conducting and disseminating research with the public and has been used in health research with children, but has not been utilised to inform research of falls with children with CP. <u>Research Question</u>: What can be learned from PPIE with children with CP and their parents, who engaged with a researcher to inform a novel adaptation of the walk-along interview method for investigating how real-world falls occur. <u>Methods of Engagement</u>: Eight children with CP (8-17 years) and six parents engaged as PPIE participants in consultations and activities with the researcher about a walk-along interview method, specifically tailored to children with CP. <u>Outcomes of engagement</u>: PPIE participants identified places to walk (e.g. parks, streets), how to conduct interviews (e.g. 'stop and talk') and four areas of questioning (intrinsic, environmental, functional and sensory), that informed the design of the walk-along interview. These outcomes demonstrate that PPIE generated unique insights for a participatory informed protocol. <u>Discussion</u>: Strength was brought to PPIE through developing good relationships and using creative activities. Challenges during PPIE included contrasting views and availability, which were managed through adaptation, communication and consensus. This work supports and expands previous PPIE and child-centred work, reinforcing that children and parents can positively help create impactful research designs, by developing and refining a method to collect real-world information about falls, specifically tailored for children with CP. This work offers critical reflections on conducting PPIE, showing that engaging in participatory informed methods to refine a protocol can offer unique insight into the worlds of children with CP and strengthen the design of future studies.

3.1 Introduction

Research is yet to investigate lived experiences of falls from the perspectives of children with CP. The previous systematic review (Chapter 2) synthesised previous laboratory investigations that have studied stability during activities designed to replicate challenging day-to-day places; for example, walking over uneven polyurethane floor panels to replicate uneven surfaces potentially faced in the real-world (Böhm et al., 2014; Romkes et al., 2020). The findings of the systematic review (Chapter 2) and findings of additional work, suggested that instabilities exist for children with CP, but do not suggest any direct link between challenging environments and real-world falls (Chakraborty et al., 2020; Dussault-Picard et al., 2022a). It may be that a direct link has not yet been established because the challenging environments used in these studies, were not informed by children's lived experiences and thus, do not reflect the places children experience falls most in the real-world.

The lack of knowledge on fall risk in children with CP could be because we have not yet investigated the environments that children tell us are likely to cause falls, based on their everyday lived experiences. Further insight into the causes of falls in children with CP in real-world environments may be revealed by engaging with children with CP and their families during patient and public involvement and engagement (PPIE) and adopting a participatory child-centred perspective (Lansdown, 2005), to involve children, and their day-to-day experiences, in the design and conduct of learning how falls occur. PPIE involves designing, conducting and disseminating research with the public (National Institute for Health Research (NIHR), 2021) and has been used in a child-centred way within health research (Rouncefield-Swales et al., 2021), but not yet for researching falls in children with CP. Understanding and informing research with the lived experiences of children with CP and their families is fundamental to design future work that could help us learn more about falls and how to prevent them.

3.1.1 Aims

This chapter aims to evaluate and critically reflect on the process and outcomes of using patient and public involvement and engagement (PPIE) with children with CP and parents or guardians of children with CP (hereafter referred to only as 'parents') who engaged with a researcher to share ideas on a participatory informed protocol for assessing how and why real-world falls occur in children with CP. In particular, the chapter describes how the children and parents informed the development of a walk and talk (walk-along) interview method to be used with children with CP in real-world challenging environments (Chapter 4).

3.2 PPIE underpinnings

3.2.1 Why engage with and involve children in research?

Lansdown (2005) expresses the significance of hearing children's voices in research, not only listening to but taking on board children's views as important and unique, regarding them as experts of their own experiences. Patient and public involvement and engagement is commonly used to gain input on research from outside the research team. The National Institute for Health and Care Research developed an initiative that supports PPIE within public health and social care research formerly known as INVOLVE (2015). They describe public involvement as work "being carried out 'with' or 'by' members of the public rather than 'to', 'about' or 'for' them" and engagement is described as the process "where information and knowledge about research is provided and disseminated" (NIHR, 2024). UNICEF (2020) emphasises that child participation focuses on them having a say in issues that concern or impact them (e.g. research that concerns them).

Previous work shows that meaningful PPIE can be conducted with children and young people in order to advise on studies in health research; however, the level of involvement of children and young people varies (Forsyth et al., 2019; Rouncefield-Swales et al., 2021). For example, children could be involved in shaping and design of study protocols (Forsyth et al., 2019),or be involved in every stage of research (design, development, analysis and dissemination) (Rouncefield-Swales et al., 2021). Previous work suggests that researcher-led PPIE can be as meaningful as child-led PPIE and that quality of PPIE depends on the specific project (Staley, 2015; Rouncefield-Swales et al., 2021).

3.2.2 Why consider PPIE in a study about falls in children with CP?

Although the researcher had an outline protocol regarding assessing how falls occur in real-world environments in the everyday lives of children with CP, undertaking PPIE with children with CP and their parents had the potential to enhance our protocol and in doing so, offer another example of how children with CP can be involved in research.

Previous work investigating instability and fall risk in children with CP may have not considered the real-world lived experiences of children with CP who can inform methods for understanding how falls happen everyday. Identifying where and how falls happen through scientific study relies on known truths about how children with CP experience the world around them. For example, assuming that a step up would cause instability and thus high fall risk, when perhaps children would ask for help or avoid walking up steps in the real-world. PPIE has the potential to explore authentic lived experiences of children with CP and their parents to increase applicability and practicality of a research protocol for a novel purpose and specific research group (falls in children with CP).

Furthermore, conducting PPIE in this work offers opportunity to provide a transparent example of how to involve children with CP in research that concerns their everyday lives. This is important given literature suggests that more high-quality PPIE work is needed with children (Bailey et al., 2015; Gaillard et al., 2018; Rouncefield-Swales et al., 2021) and especially important given the rarity of conducting PPIE in stability and falls research. Moreover, PPIE provides the rare opportunity for children with CP and their parents to feel valued in research that concerns them, in a more novel way than they may be used to, e.g. being involved clinical scientific studies. Key literature emphasises that children and young people should have a say in research (Preston et al., 2019; Rouncefield-Swales et al., 2021; Dan, 2023), including specifically those with disabilities (Carter et al., 2014; Bailey et al., 2015; Bray et al., 2018; van Schelven et al., 2020). PPIE has been successful with children with chronic conditions and disabilities, including CP (Carter et al., 2014; Bailey et al., 2015; Graham et al., 2017; Bray et al., 2018; van Schelven et al., 2020), and this has resulted in positively informing research about day-to-day lived experiences, similar to the current study.

Involving children with CP and their parents within the current study may therefore extend understanding and offer a framework of how PPIE can be conducted in the context of designing a protocol to investigate falls.

3.2.3 Ensuring a child-centred value-base for PPIE work

Undertaking PPIE with stakeholders (e.g. children with CP) and involving their experiences to produce outcomes (e.g. research) can be described in several ways, e.g. co-production, co-design (Nabatchi et al., 2017; Preston et al., 2019). The PPIE in this PhD adopted a researcher-led consultation approach, underpinned by co-production principles (Preston et al., 2019), whereby children and parents provided views on a protocol, which informed decisions made by researchers resulting in a participatory informed protocol for qualitatively investigating causes of falls in children with CP. Similar terminology has been used previously to describe the varied level of involvement of children and young people in the development of research methods (Taylor et al., 2015; Rouncefield-Swales et al., 2021). Although key parameters of the protocol were predefined, children and their parents were provided freedom to shape the project. This was achieved through creating a safe space for open conversation about daily experiences allowing the researchers to learn from, acknowledge and respect the separate and unique expertise of both children with CP and their parents. To create a safe and supportive space, a transparent set of PPIE values specific to our work, was created and informed all interactions (Table 3.1).

Table 3.1. *PPIE values specific to this work and examples of how these were instilled during PPIE.*

Value	Meaning (specific to this project)	Example within PPIE: Child	Example within PPIE: Parent
Child-centred	Keeping the child's thoughts and experiences at the heart of decision making.	Creative tasks and one-to-one conversations were used for informing the protocol, which allowed children to have their individual voices heard without prompt or interruption.	Parents were consulted about the child-centred aims of the project and were provided the opportunity to expand and discuss the thoughts of children.
Safe Space	Having a comfortable place for open conversation about daily life experiences and falls.	PPIE was hosted at Stick 'n' Step, a local charity that children regularly attended and therefore already have regular conversations about walking, cerebral palsy and falls in this environment.	Parents asked for, and were provided with, the option to chat over the phone about their child's previous experiences, offering both convenience for time and the ability to talk in their own home.
Right to Engage	Ensuring that children and parents know they can be involved with PPIE as little or as much as they wish.	Volunteering took place at the local charity for months prior to PPIE, to allow children to be comfortable with the research and in choosing whether they would like to participate.	Parents were familiar with the researcher prior to PPIE participation due to volunteering. Flyers were requested by parents before participating, which were then provided to give full information.
Flexibility and Responsiveness	Allowing children and parents freedom to shape the project with their opinions.	Parents and children had freedom to shape the project. For example, if child and/or parent engaging with PPIE did not like our pre-determined ideas, we would discuss and consider changes.	
Respect	Acknowledging the voices and opinions of children and parents.	Follow up discussions were had with both children and parents after making decisions about the protocol to ask if the decisions were representative of PPIE consultations. Additionally, occasional contradictory opinions of children and parents were addressed directly.	

3.2.4 Engaging children in novel participatory informed methods

Specifically, the PPIE reported in this chapter focused on developing participatory informed methods to refine a walk and talk interview technique (Carpiano, 2009) for use within a study investigating the causes of day-to-day falls in children with CP. Walk and talk interviews are a method by which a participant and researcher take a walk and engage in a conversation based on environmental cues around them (Carpiano, 2009). Walkalong interviews have generated rich data with older adults about neighbourhood environments and pedestrian practices (Van Cauwenberg et al., 2012; Zandieh et al., 2016; Lee and Dean, 2018).

The rationale for the team's interest in walk and talk interviews was the anticipation that this technique could provide clarity and depth on how falls occur in everyday environments by understanding children's experiences through environmental interactions (Ergler et al., 2021). The advantage of using this method rather than simply relying on recall-based interviews or laboratory-based studies is that thoughts, interactions and environmental features can be explored that provide specific examples of where and how children may have experienced a fall in the past. There is evidence in adults with walking disabilities that this method offers rich insights of how each person experiences their disability day-to-day (Butler and Derrett, 2014). However, we found no evidence that this method has been used with children with CP.

To establish both the reasonableness of the proposed method and how we should best implement it specifically for children with CP, we set three main PPIE objectives to learn from children with CP and their parents: (i) *where* interviews should take place (based on children's daily walking places and previous experiences of falls), (ii) *how* to conduct safe and insightful interviews outdoors with children with CP (based on what would make children and parents feel comfortable while also getting an accurate representation of day-to-day life) and (iii) *what questions* they think need to be asked during interviews to understand how falls occur in the real-world (based on day-to-day, real-world experiences of falls).

This chapter presents the practicalities of engaging with children and their parents in consultations to inform the development of a walk-along interview protocol, specifically tailored for children with CP. This chapter aims to share how insights from both children and parents were crucial in refining a participatory informed method. It is important to mention that one of the outcomes from our PPIE was the change of the name from ‘walk and talk’ to ‘walk-along’; this explains why both terms are used in this chapter. This chapter is presented in accordance with the GRIPP-2 (Staniszewska et al., 2017), (Appendix 3).

3.3 The practicalities of engaging with children and parents for the Walk-Along Project?

3.3.1 How did we recruit children and parents to engage in our PPIE?

The lead investigator (RW) volunteered at Stick ‘n’ Step (Stick ‘n’ Step | Supporting children with cerebral palsy, 2020), a charity local to the Liverpool City Region, for 125 hours across 8 months. Stick ‘n’ Step offers conductive education for children with CP. Parents of children who attend Stick ‘n’ Step, and their children were approached, and the lead investigator talked about the project and how children and parents could help if they wished to take part in PPIE, which would be separate from any participation in conductive education at Stick ‘n’ Step.

Ethical approval is not required for PPIE consultations, however this work abided by typical PPIE ethical considerations and principles (Suri et al., 2024). This included: 1) building transparent relationships (children and parents being aware of the PPIE and research), 2) volunteering kept separate from PPIE activity, 3) presence of a familiar member of staff at Stick ‘n’ Step, 4) fully informing children and parents of the purposes of PPIE in advance of any PPIE consultations and 5) having anonymity and confidentiality in consultation outcomes. Moreover, children and parents were reassured they could engage as much or as little as they wished and were under no obligation to engage and could stop engaging at any point. The lead investigator had appropriate safeguarding and training as a requirement for volunteering e.g. DBS check. Permission was granted verbally from parents for children to engage in PPIE consultations.

3.3.2 Who did we engage with?

Eight children with CP (aged 8–17 years old) and six parents of children with CP (not all related to the participating children) decided to engage over a period of 6 weeks. The lead investigator spoke to six children on one occasion and to two children on two occasions (total of ten 1-to-1 chats) about walk and talk interviews. Three children also participated in a session asking about the small cameras attached to chest harnesses that were planned for use in the walk and talk interviews. The children tried this equipment on and provided feedback. Six parents engaged in short (~15 minute) conversations: two parents opted for separate face-to-face conversations and four opted to talk by telephone. All face-to-face consultations took place before or after Stick 'n' Step sessions.

3.3.3 How involved were children and parents in development of participatory informed methods?

Children acted as active-consultants rather than full collaborators (Preston et al., 2019) as their role was to help develop a participatory informed method with a pre-approved outline created by the research team. Based on notes taken and activities conducted during initial PPIE consultations, the researchers devised an infographic and a protocol for walk and talk interviews; these addressed every element that we had learned. The infographic and protocol were taken back to children and parents to allow further feedback and engagement to ensure we had effectively acknowledged their thoughts and opinions within the participatory informed protocol. A schematic of the PPIE process and how children and parents were involved in the development of the participatory informed method for investigating falls is represented in Figure 3.1.

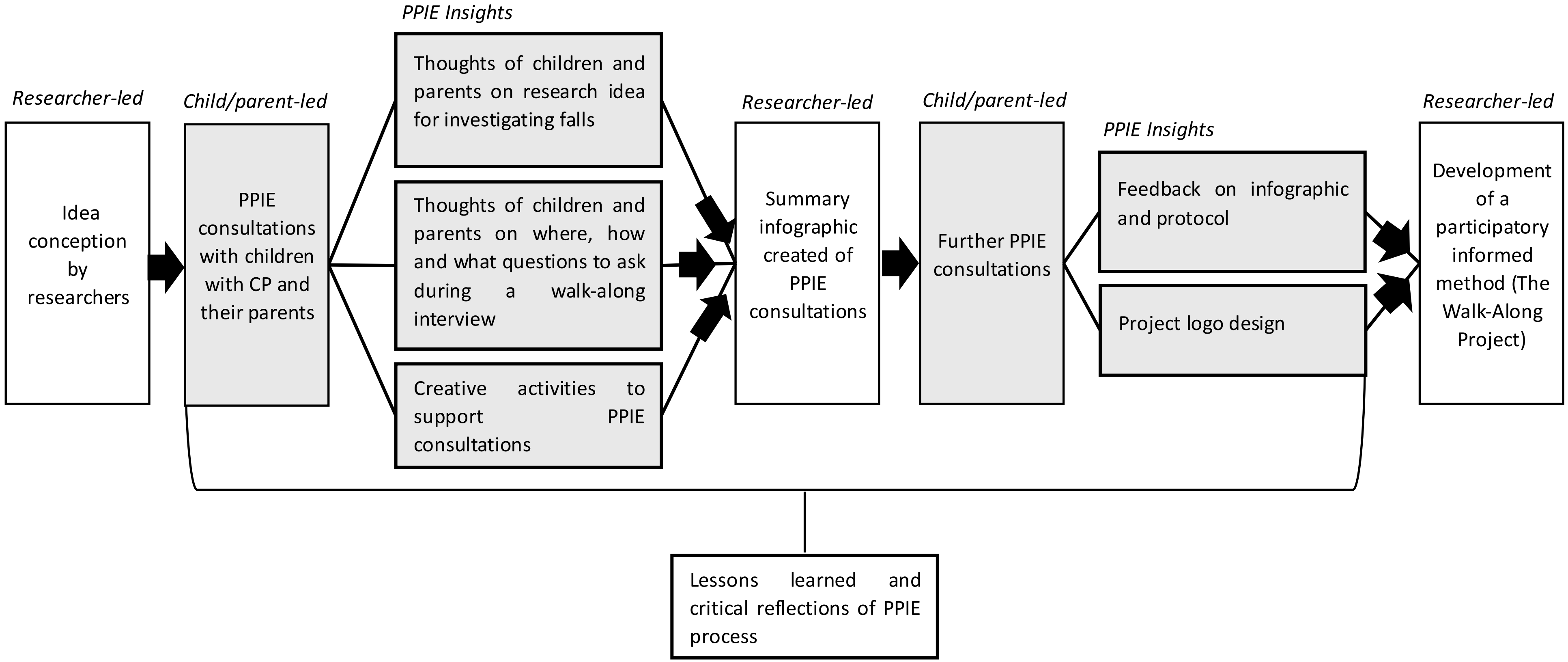


Figure 3.1. *Schematic of PPIE process. Grey boxes indicate child and parent involvement into participatory informed methods*

3.3.4 How did we engage with children and parents?

The consultations with children and parents lasted approximately 15 minutes; conversations with the children were supplemented with creative activities, described below. Consultations started by talking about falls, with the children and parents giving a general opinion on whether falls were an issue in day-to-day life followed by questions about whether they thought walk and talk interviews were a good idea and whether they thought it would be a practical approach to use.

Consultations were guided by discussing the children's daily walking places and any past experiences of falls to inform *where* to conduct walk and talk interviews. This was followed by discussing what they thought would ensure children and parents felt comfortable during the walk, while also getting an accurate representation of day-to-day life (e.g. the option of walking near challenging environments) to inform *how* to conduct walk and talk interviews. Finally, questions were asked about any day-to-day real-world experiences of how falls happen to inform *what questions* should be included in walk and talk interviews. Two activities were designed to enhance conversations had during PPIE. Completion of Activity 1 was prioritised over Activity 2, with Activity 2 only proceeding when time was available. Although both activities were available for all children, children's preferences and the time available shaped what was engaged with. Finally, children engaged in an activity to develop a logo for the future study, to represent their contributions to participatory informed methods (Activity 3).

3.3.4.1 Activity 1: Photo elicitation for describing challenging places

The first child-centred activity used photographs chosen by the research team to reflect challenging environments that they believed pose a fall risk in everyday life. Images were taken from Microsoft Word Stock Images (Microsoft 365, Microsoft Corporation Washington, USA) and selected based on previous work that suggests children with CP show stability differences compared to typically developing children over uneven surfaces (Dussault-Picard et al., 2022a). Images were used that showed both level (e.g., a street with no obstacles) and uneven environments (e.g., obstacles such as toys in the house, cobbles on the street) that children might face in the real-world on the way to school, the shops, the park or in the playground etc. The lead investigator presented a random selection of 6 to 8 images to the children and asked them to place red or green stickers onto the photographs, using red stickers for place they believed could cause a fall or green stickers if it was somewhere safe. Following this, children were asked why they had placed red or green stickers each photograph; this led to detailed conversations around what may cause a trip or a fall in the real-world and that this should be considered in our walk and talk interview design. A detailed example of the type of conversations that occurred this first activity can be seen in Box 1.

Box 1. Example unique insight from creative methods

Children were presented with several photographs (Figure 3.2). One (see below) showed a child indoors with many toys around the room.

5 out of 8 children initially placed a red warning sticker onto the picture, to indicate that this is somewhere with high fall risk. However, after further conversation, children explained that this would not typically cause a fall in each children's own home, because they would tidy their own toys away to avoid the risk.

At the end of each conversation, a photograph was taken of all the stickered images and this was then annotated to summarise the conversation (see Figure 3.2 for examples of final photographs).

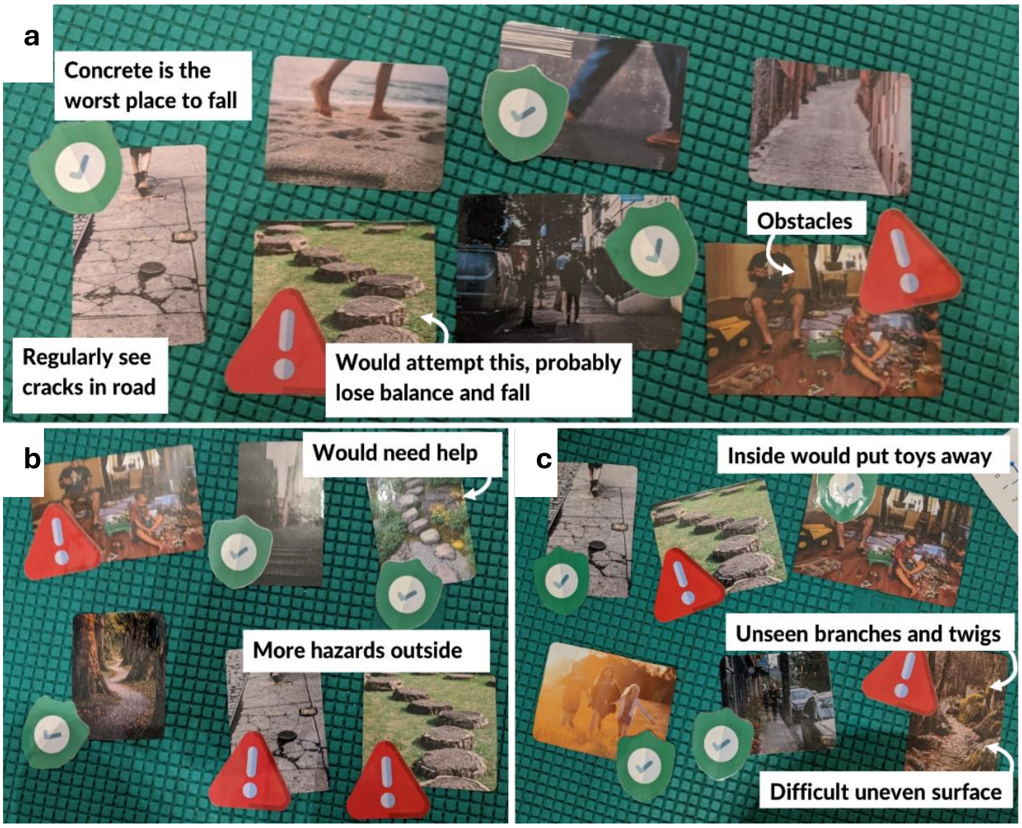


Figure 3.2. *Three examples (a, b, c) of an activity used during separate conversations with three children. Annotations are researcher notes interpreted from conversations had during PPIE consultations about each photo. Photographs sourced from Microsoft Stock Images, Stickers sourced from Flaticon.com*

3.3.4.2 Activity 2: Rating the importance of question topics

Activity 2 involved presenting children with nine fall-related statements that they were asked to rate for importance for determining causes of falls. These statements were determined by the research team as areas of interest for questioning during walk and talk interviews. These areas included recent fall experiences, regular walking places, feelings about walking and falling over, tiredness, fear, running, confidence and distractions. Children were given the choice of arrows or pictures of animals to place along a scale next to the statement (0 = not important, 10 = important) (Figure 3.3). This activity took longer than Activity 1 and was therefore only used by two children when time was available either due to additional time provided for that engagement session or after having completed the first activity quickly. Both children who completed this task required additional explanation as it was a more complex activity.

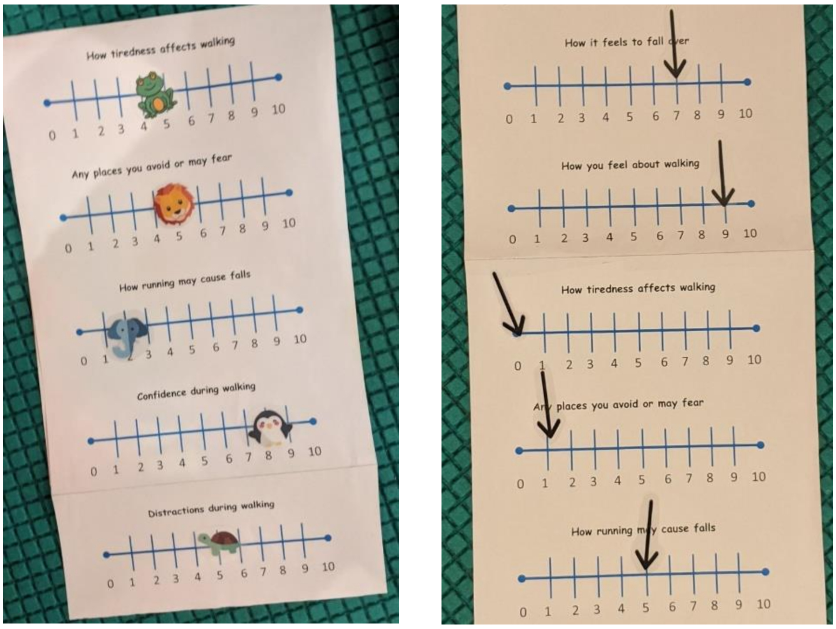


Figure 3.3. *Activity 2 example responses from two children when asked to rate statements according to their importance for determining causes of falls.*

3.3.4.3 Activity 3: Bringing the project together, together

The term 'walk and talk' interviews which we used in the PPIE is just one of a range of different terms (e.g., walking interviews (Jones et al., 2008; Butler and Derrett, 2014), go-along interviews (Carpiano, 2009; Pawlowski et al., 2016), walking-whilst-talking method (Stevenson and Adey, 2010) or walk-along interview (Veitch et al., 2020)) used in the literature to describe the same method. After the suggestion from children and parents that they would prefer to stop and talk during the walk, to be able to observe surroundings, rather than continually walking and talking during the interview, we decided to adopt the term walk-along interviews. Children were asked what they thought of using the term walk-along interview, and they preferred this to walk and talk interviews. Therefore, the term walk-along interview is used for the remainder of this work and the main study.

The final element of participatory informed methods involved five children helping to develop the study logo. The children were given a list of potential study names and invited to colour in and add some drawings to the names. The children drew stick figures walking and standing and falling over, orthotic boots, splints and grass (Figure 3.4a). One child chose not to help with the design and instead drew a picture of a train, another only had the time to colour in three letters of the logo, thus these designs are not included in Figure 3.4. One child was shown the logo and asked to describe what they would include, rather than write on the logo by their own choice and they suggested that the logo should include images of people, grass and a football. The children chose the name of the study - The Walk-Along Project – and based on the rainbow colours they liked and used, and the core images they wanted, the lead investigator wove these ideas into the final logo design (Figure 3.4b). The logo represents the involvement of the children's lived experiences and ideas throughout entire project.

a.

People walking on letters
Yellow orthotic boots on 'LL'

Colourful lettering
Grass underlining
Orthotic boots (orange)
Walking person

b.

Figure 3.4 *(a) Children's initial drawings with key elements written underneath that were taken to inform the final logo and (b) final logo that contained person walking, grass underlining, orthotic boots on the letter 'L' and with colours that appealed to one of the children.*

3.4 Outcomes of engagement

The primary outcome of this engagement work was that PPIE consultations helped inform several aspects of a walk-along interview protocol to be used for investigating children's lived experiences of falls in the real-world. The detail into the conversations, lived experiences and ideas from children and parents and how this helped develop the participatory informed methods are described below. These are linked to the PPIE objectives and the questions we asked during our conversations and activities and lead directly into Chapter 4.

Critical reflections, including impacts, strengths and challenges of PPIE are presented in the discussion section (3.5).

3.4.1 What do you think of the idea of using walk and talk interviews for our study?

Children and parents responded positively when asked what they thought of using walk and talk interviews to look at real-world fall risk. They suggested it would be easier to recall how falls happen in the real-world day-to-day if they were talking about them in those environments that might typically cause a fall. Most parents said they would be happy to take part, as long as they knew the walk was 'safe' (note: the ways in which to make the walk 'safe' were discussed in later conversations). Children's typical response was that it was a "good" idea and they elaborated on this in Activity 1 by placing stickers on photos of activities (Figure 3.2).

3.4.2 Where should we conduct walk and talk interviews?

Children and parents were asked where it would be convenient to take a walk for them (e.g. close to home) and where they typically walk day-to-day (e.g. to school or the park) to inform where walk and talk interviews should take place, that would be suitable for them and most reflective of day-to-day walking places.

Conversations regarding where best to walk and discuss falls during the walk and talk interviews began by asking children and parents where they typically walk day-to-day and where falls occur most in the real-world. Locations suggested by children and parents included outdoor spaces such as high streets, parks and woodlands. When probed about these locations, several reasons were proposed about why they would be good locations for walk and talk interviews, because these places:

1. are 'the worst places for falls', (e.g., falls on concrete highstreets could cause most injury),
2. contain the most hazards that increase fall risk more (e.g., obstacles such as branches or uneven surfaces),
3. are where children and parents regularly walk, and
4. are important to children and parents to be able to walk in during day-to-day life (e.g., to go to the shops, school or meet friends).

Conversations revealed places that they did not think were suitable for walk and talk interviews as they would be uncomfortable and could be generally unsafe in terms of wellbeing, or unsafe due to an increased fall risk. However, parents and children explained they would be happy to talk about these places during interviews. These places included:

1. crowded places due to other people potentially pushing into the child and causing a fall, and because crowds were generally uncomfortable for children,
2. areas with busy roads as this may be unsafe due to the potential for a fall into a road, and
3. anywhere with loud noises which could cause distress and which could invoke a startle reflex (meaning when a loud noise could alert the child and cause a disruption to balance and possibly result in a fall).

Key to making walk and talk interviews appealing for potential study participants, were that they should be somewhere either close to the participant's home or nearby the local charity they regularly attended. These settings were suggested mostly by parents due to convenience. When talking about the importance of familiarity for the chosen walking route, both children and parents suggested that they would be happy walking somewhere familiar as there would be a higher risk of a fall walking somewhere that they had not been before. However, children and parents also suggested that they would walk in unfamiliar places if they were offered a map of the chosen walking route prior to the interview as the map would help to ease any uncomfortable feelings.

A summary of the discussions from the consultations is included in Figure 3.5. Following feedback from children and parents, some changes were suggested such as including asking questions about environments not encountered on the walking route (e.g., busy roads and crowds) as this could provide additional information. These were summarised and the infographic updated to include 'fine to approach and discuss'.

3.4.3 How should we conduct walk and talk interviews?

An important part of our PPIE with children and parents revolved around how to conduct safe and insightful walk and talk interviews. The photo-sticker activity (Figure 3.2) prompted agreement between children and parents that whereas they can typically manage the home environment to avoid trips and falls (Box 1), outdoor environments can be more unpredictable and therefore lead to more falls. Therefore, it was suggested that the most insightful interviews could be achieved by walking outdoors in environments with some challenging surfaces (e.g. uneven surfaces) that parents were comfortable with but still reflected the day-to-day places in which children often encounter falls. Conversations then focused on how to conduct safe walk and talk interviews in these environments. These discussions are summarised in Figure 3.5.

Parents suggested several ways to create a 'safe' walk and talk interview. Predominantly, this involved a pre-planned route with opportunity to change the route as needed, and to note anything they or their child may be uncomfortable with. Appropriate weather was additionally key for comfortable interviews and 20-30 minutes was suggested as a good length of time to walk to prevent tiredness. Finally, it was suggested that children should be offered regular breaks or opportunities to stop and talk about surroundings during the walk rather than walking whilst talking. These provisions for safety of children, were acknowledged within PPIE to reflect usual walking considerations taken by children and parents. For example, children may be at higher fall risk when tired, yet several parents and children explained how they would take scooters or a tricycle (trike) on walks for when children tired.

The conversations with the children who tested small portable video cameras for their suitability to help capture the environments walked through during the walk-along interviews revolved around safety and comfort of the cameras. The children suggested that chest mounted cameras would be most comfortable provided some familiarisation took place before the interview and there was an option to not wear the camera. Parents suggested that children could take photos of environments that they thought might increase risk of a fall as this would maintain the child's engagement and provide rich visual information about the environment to supplement the conversations during the interview.

3.4.4 What questions should we ask during walk and talk interviews?

Children and parents also talked about what they thought caused day-to-day falls, which helped us to design questions and be aware of factors relevant to the environments in which walk and talk interviews would take place. These broadly fell into four categories: intrinsic (e.g. being distracted or losing concentration); environmental (e.g. obstacles, inclines, weather); sensory (e.g. spatial awareness, vestibular); and functional (e.g. fatigue, footwear). An infographic was developed to summarise all information shared during our PPIE consultations (Figure 3.5).

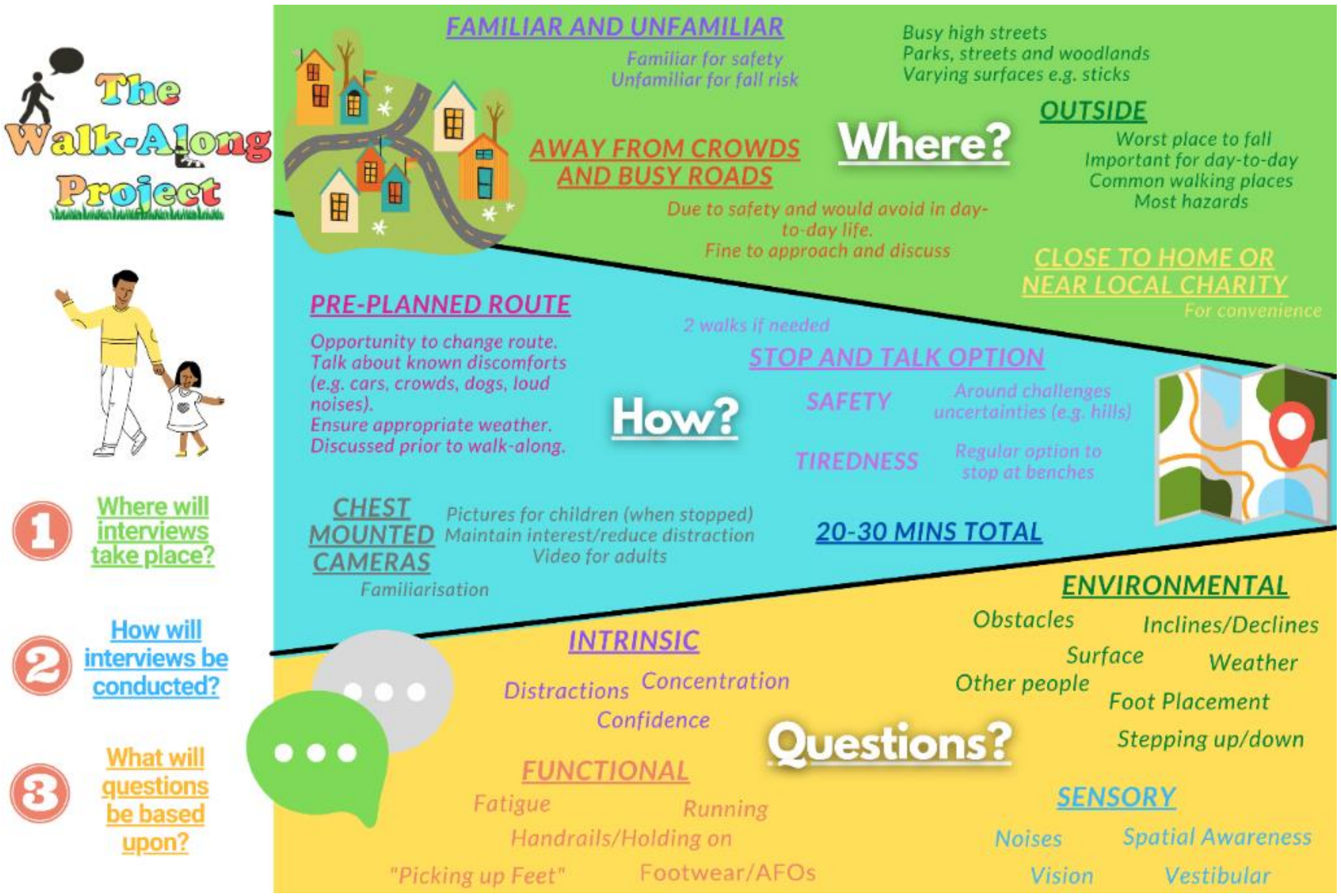


***Figure 3.5**. Infographic representing a summary of all information shared during PPIE consultations, to inform (1) Where interviews should take place, (2) How to conduct safe and insightful interviews and (3) Areas of questioning during interviews.*

3.5 Discussion

The aim of our PPIE was to produce participatory informed methods and adapt a walk-along interview specifically for children with CP and their parents and the real-world challenging environments they face day-to-day. This participatory informed method would be specifically produced for use within a study investigating the causes of day-to-day falls in children with CP. We wanted to learn about the thoughts and experiences of children with CP and their parents. In the previous section we have described the outcomes of our PPIE and clearly demonstrate how our PPIE informed the development of a novel walk-along interview protocol for investigating falls in children with CP. The full walk-along protocol is described in Chapter 4. In the following discussion we evaluate and critically reflect on the process and outcomes of PPIE with children with CP and their parents.

3.5.1 Strengths of PPIE

The strengths within our PPIE contributed to the overall success of the process (and the actual study when this was undertaken). Firstly, relationships and trust with children and parents were built by the lead investigator volunteering with Stick ‘n’ Step for over six months prior to the start of our PPIE engagement. This helped children to be comfortable in talking to the lead investigator and allowed her to develop her engagement skills and understanding of the lives of and mobility challenges faced by the children. Ultimately this allowed deeper insight into and understanding of lives of children with CP.

Secondly, creative methods used during PPIE consultations offered children interesting, child-centred and informal opportunities to provide unique insights specific to their lives and interests. The example in Box 1 revealed detailed insight into how children are aware they can control indoor environments (e.g., putting toys away and being tidy) to reduce fall risk specifically for children with CP and shows how regular occurrences of falls can impact daily life choices. The children shared insights into other ways in which they use compensatory behaviours day-to-day to reduce falls (e.g. avoiding uneven surfaces when outdoors) that may not be considered by typically developing children. This success in using creative methods to develop PPIE discussions is consistent with past engagement work using creative methods with adults (Kelemen et al., 2018) and with children aged 11 to 18 years old (Spencer et al., 2023).

A third strength of our PPIE was that it was clearly informed and underpinned by a strong value base that recognised and respected children's capacity and contributions (see Table 3.1). Lansdown (2005) expresses the importance of respecting and listening to children's views in a format and space that is suitable for the children. Our PPIE was a flexible, responsive child-centred, safe place in which children had the right to engage and in which we respected their ideas and wove them into the study protocol.

Finally, flexibility was key, both in the method of engagement (telephone call or in-person) and in time of day we met for conversations with children and parents. Typically, parents preferred a telephone call rather than in-person conversation. Offering flexibility allowed more parents to engage in PPIE in their own time. Additionally, conversations typically took place before or during Stick 'n' Step sessions. Although this was convenient, parents were keen that the PPIE did not result in children missing out a large part of their session. This meant that conversations were flexible in terms of duration. For some parents, short conversations happened over the course of a few weeks. Adopting a flexible approach was crucial and aligns with findings from a systematic review focused on involving children in research, which found flexibility is necessary to allow involvement of children and young people with disabilities (Bailey et al., 2015).

3.5.2 Overcoming challenges

One challenge we faced when conducting our PPIE were some instances where there were contrasting opinions from children and parents. For example, when one child was asked how often they fell, they explained that they 'never' fall over. However, their parent then reminded them that they had fallen getting out of the car that morning. This example demonstrates how important the opinions of both children and parents were to our PPIE. The child in this example may have simply forgotten about their fall earlier that day, or maybe they did not see this as a typical fall experience as they were negotiating their way out of a car. Gaining context into why these contrasting opinions occurred was important for us to ensure that the views of children and parents were equally integrated into our research design. This required careful adaptation, communication and consensus during the PPIE as well as when the researchers were drawing on the PPIE findings to refine the protocol.

Distractions were a challenge during PPIE conversations and activities. Occasionally children would talk less about falls and more generally about their lives (e.g. what happened in school that week). One older child also began to ask questions beyond the scope of the PPIE (e.g. asking the researcher “what is your 5-year plan?”). This challenge was managed by accepting the distractibility of children and being interested in their lives, using creative activities (Figure 3.2) to maintain interest and being flexible in the way in which the PPIE happened.

Another challenge of PPIE revolved around availability. Many PPIE consultations were time restricted as the Stick ‘n’ step sessions took priority and therefore occasionally occurred over multiple consecutive weeks. It was important for the lead investigator to accommodate the schedule of children and parents and be efficient and flexible in undertaking telephone calls or face-to-face conversations. Ideally, the same children and parents who had contributed ideas at the start of PPIE would have been available at the end to hear the feedback about our outcomes and design of our walk-along interview, but busy lives and other factors meant this did not happen for some parents and children. This may be seen as a limitation, but the involvement of new children and parents broadened the engagement.

3.5.3 Impact of PPIE

This work demonstrates the use of PPIE with children (aged 8 to 17 years old) with CP and their parents to develop a participatory informed method for investigating falls. It shows that children and parents can offer deep and enthusiastic insights into an area of research that typically may not consider the use of engaging children and parents in PPIE when developing and conducting research. This supports previous child-centred work using walk-along interviews with typically developing children to generate rich insights into how they experience outdoor environments (Pawlowski et al., 2016; Veitch et al., 2020; Ergler et al., 2021). Generally, PPIE allowed us to explore children's lived experiences of an everyday issue and gain feedback on our suggested protocol's applicability to their everyday lives, feasibility of conducting this research in the field, including what equipment to use, and what parents would define as a safe walk for our study.

Historically, falls and stability research addressing children with CP, uses quantitative assessments of gait and walking (Dussault-Picard et al., 2022a). Some work has explored perceptions of clinicians and physiotherapists to inform clinical balance assessments (Sibley et al., 2013; Van Ooteghem et al., 2020). However, to the best of our knowledge, we are the first to use and publish robust PPIE work that draws on the thoughts and experiences of children with CP to shape a novel walkalong interview protocol for investigating everyday causes of falls. Specifically, our PPIE work has used novel insights from children with CP and their parents (e.g. suggestions from children and parents that walk-along interviews should take place outdoors, where environments are more uncontrolled compared to indoors) that improved our protocol's applicability (e.g. enabling us to investigate in known high-risk places and guide conversations during walk-along interviews that children can relate to) and feasibility (e.g. enabling the walk-along interview process to be possible for a group with specific needs, for example stopping to talk rather than walking while talking). Our PPIE has narrowed the focus of the walk-along interview protocol to the most important considerations for causes of falls in the real-world, informed by lived experiences, which will hopefully give a more detailed insight into how falls happen day-to-day compared to previous work.

Patient and public involvement and engagement with children with CP and their parents provided clarity for writing a proposal of the walk-along interview method, and to contribute to a wider protocol that has since been ethically approved. Definitions provided earlier for PPIE were appropriate and consistent for this specific PPIE. The participatory informed walk-along interview method developed in this work extends previous walkalong methods that have been used with older adults (Van Cauwenberg et al., 2012; Zandieh et al., 2016; Lee and Dean, 2018) and typically developing children (Ergler et al., 2021). The PPIE work gave us confidence to use the walk-along interview method as an adaptable method for children and those with walking impairments, improving both applicability to real-world scenarios and feasibility for children with CP, as earlier discussed. Sharing the lessons learned from PPIE in this work hopefully offers further evidence for the use of PPIE in health research and with children (Bailey et al., 2015; Gaillard et al., 2018; Rouncefield-Swales et al., 2021).

Following PPIE, the walk-along interview method has been successfully used with 12 children with CP and their parents (Chapter 4). The success of PPIE to develop participatory informed methods is evident in the recruitment of children to The Walk-Along Project and the enjoyment and positive feedback we have gained from the children and parents who have participated in the study and walked and stopped and talked and used the video and still cameras. The Walk-Along Project has generated rich child-centred datasets that reflect deep insights into children's understandings of everyday falls and which has an extensive rich resource of photographs and videos of the places where falls occur and the challenging walking environments faced daily by children with CP.

3.5.4 Lessons learned

A key practical lesson learned from conducting PPIE with children was that flexibility in conversations and time constraints for different children meant that both activities were not used with all children. Perhaps fewer statements and a simpler second activity would have allowed room for this. However, by allowing conversation to flow and continue, and sidestepping the use of Activity 2, meant that rich insights were continually being generated. Another lesson from the activities chosen were that photographs used during the photo-sticker activity (Figure 3.2) did not necessarily align to places children encountered in their own day-to-day lives (e.g. Box 1 example), so although places were identified as high fall risk, it may not be something they themselves struggle with day-to-day. Using photos as a prompt for conversation rather than at face-value was an important lesson as we were able to explore not just where children thought their fall risk might increase, but why they thought this.

Finding the balance of what is 'safe' and what are perceived as high fall risk places was learned during conversations and protocol design. Ensuring interviews would be 'safe' may have constrained the use of riskier locations. However, if children and parents were unsure about safety, we were unlikely to have generated the rich insights we gained during the interviews in the study that followed this PPIE, or they would not choose to participate. In conducting PPIE, we discussed with parents and children additional measures we could use that would allow interviews to be conducted safely, without missing potentially important information about day-to-day situations that might increase a fall. An example of this are conversations around unfamiliar places, which allowed us to find a balance between walking in unfamiliar places that might increase fall risk, and walking in familiar local places, that could reveal places where children had experienced a fall.

It is also important to acknowledge that the decision to avoid places deemed to be unsafe was done so following conversations with parents who explained that although they would always avoid such places day-to-day, they would still be happy to discuss these places during the walk-along interviews. Home video diaries were offered as an addition to walk-along interviews, to provide an extended insight into every day falls rather than the snapshot generated from walk-along interviews.

3.5.5 Limitations

Despite its strengths, we acknowledge the limitations of our PPIE. A key limitation is the lack of ethnic and gender diversity across the children and parents who participated in our PPIE. A more diverse group of children and parents could have shared different perspectives on daily life, this is noted elsewhere as something that should be acknowledged for future work (Bailey et al., 2015). Our PPIE participants were all approached through the same charity that among other things involves stability tasks and fall avoidance (Tuersley-Dixon and Frederickson, 2010). However, accessibility to this charity is not readily available for all children with CP, so our PPIE is not representative of the wider population of children with CP. For future PPIE exploring falls in children it would be of interest to seek the lived experiences of a more diverse range of children, including those without ongoing exposure to sessions that encourage stability and fall avoidance.

Another limitation to this work, due to time constraints, is the lack of engagement as a group. All PPIE consultations were one-to-one between the child and investigator or parent and investigator. Engaging as a group may have benefit overall outcomes due to the interactions and responses between participants, particularly for children (McLaughlin, 2015; Preston et al., 2019).

Perhaps another limitation to our PPIE is that although our engagement with children and parents was respectful, collaborative and committed, our engagement is best described as researcher- rather than child-led as we brought some established ideas to our PPIE. Arguably, the children acted more as active-consultants than full collaborators (Preston et al., 2019) as their role was to help develop a participatory informed protocol with a preapproved outline created by the research team. For example, we asked for their insights into the walk and talk interview method rather than starting with a blank sheet and asking for their suggestions about how best to collect data. We also brought ideas for the study name to the children rather than asking them to think of a name. In future PPIE we would recommend a more open type of engagement in which children and parents have the space and opportunity to act more fully as collaborators. However, despite these limitations and our acknowledgement of our PPIE being researcher-led, there was a considerable amount of engagement and children's perspectives informed the study protocol.

3.6 Final thoughts and conclusion

Meaningful PPIE with children and young people can be considered an important part of research. This chapter tells a story of how child-centred PPIE with children with CP and their parents meaningfully contributed to a research design and discusses the strengths and challenges in doing so. The PPIE was greatly strengthened due to the amount of time dedicated to forming strong, trusted relationships in the community through volunteering. Overall, PPIE with children with CP and parents of children with CP, helped strengthen and refine a method to collect real-world information about falls, specifically for children with CP, in an area with limited reported use of PPIE or consideration of children's views in research and methods design.

Chapter 4

Study 3. The Walk-Along Project

The contents of this chapter are in review for publication to PLOS ONE and have been published as a special issue abstract in Gait and Posture:

- Journal Article in Review:
  - Walker, R.L., O'Brien, T.D., Barton, G.J., Carter, B., Wright, D.M. and Foster, R.J., (2024) "I'd probably trip over it because it's bumpy": A qualitative exploration of the lived experiences of children with cerebral palsy walking in challenging environments - *Submitted to PLOS ONE 20.07.2024 (in review)*
- Special Issue Abstract:
  - Walker, R., O'Brien, T.D., Barton, G.J., Carter, B., Wright, D.M. and Foster, R.J., (2023) "I'd go slow and hope I don't fall" Exploring lived experiences of children with cerebral palsy walking in challenging environments, *Gait & Posture*, 106, 219-220. https://doi.org/10.1016/j.gaitpost.2023.07.263

The contents of this chapter have been disseminated as presentations at the following academic meetings:

- European Society for Movement Analysis in Adults and Children (ESMAC) Annual Meeting 2023, Athens
- European Academy of Childhood Disability (EACD) Annual Meeting 2023, Ljubljana

Abstract

Background: Children with cerebral palsy (CP) experience regular falls, but their lived experiences of falls in the real-world are unknown. Exploring the perspectives and past experiences of children and parents is important to gain deeper awareness into the causes of falls that happen in real-world environments, especially since typical walking analyses are carried out over level-ground and therefore overlook everyday challenges to balance (e.g. uneven pavements when walking to school). Walk-along interviews can generate rich insights into children's everyday life by discussing experiences while walking. Research Question: Using lived experiences and walk-along interviews to determine everyday challenging environments of children with CP: where and how do falls happen in the real-world? Methods: Twelve ambulatory children with CP (12±3 years old, 6 hemiplegia, 6 diplegia) and their parents took part in an outdoor walk-along interview, where previous fall experiences and everyday challenging environments that may increase fall risk were discussed. Action cameras and clip on microphones captured walking environments and conversations, which were later synchronised, transcribed and analysed in NVivo using interpretive description. Results: Two overarching themes were generated ('places where trips and falls occur' and 'things children do to control falls') plus five key themes ('walking on bumpy and unstable ground', 'taking care, walking slower and avoiding places', 'distracting environments are dangerous environments', 'close calls and falls', and 'feelings and fears'). The most common challenging environment to cause increased risk of falls based on previous experiences were uneven surfaces (e.g. grass potholes) with distractions (e.g. a dog barking). Discussion: The Walk-Along Project revealed novel insights about places that might increase fall risk in children with CP, beyond what is currently known. The importance of considering both environmental challenges (e.g. uneven surfaces) and sensory challenges (e.g. distractions) is highlighted through the lived experiences of children with CP. Future work should consider how interacting factors (e.g. distractions in uneven environments) increase fall risk in children with CP, in order to understand mechanisms of falls for potential fall prevention programmes.

4.1 Introduction

Walk-along interviews are capable of generating rich insights into how children interact and view environments around them and their lived experiences of their surroundings (Ergler et al., 2021). Thus, using walk-along interviews with children with CP and their parents has the potential to reveal deep insights into daily lived experiences of falls that have not yet been documented. During the PPIE (Chapter 3) children told us how best to conduct a walk-along interview that would be both applicable to and feasible for children with CP and their everyday lived experiences.

Walk along interviews involve taking a walk while talking about day-to-day experiences, by answering questions that are prompted by environmental surroundings (Carpiano, 2009). This method allows the recall of past experiences in familiar places and for children, is suggested to create a more informal environment by reducing the power imbalance both between researcher (adult) and participant (child) meaning a hierarchical relationship is less likely to develop which avoids children attempting to give the 'right' answer rather than the true answer (Eder and Fingerson, 2002; Carpiano, 2009). A key reason for using walk along interviews is to gain rich information about people in their environment, both through interviewing and observing (Carpiano, 2009). This method is particularly insightful for children since it offers children the opportunity to share experiences through their body language and gestures in response to the surrounding environment, adding more than just verbal communication, as in typical sit-down interviews (Ergler et al., 2021).

Previous walk-along interviews have explored neighbourhood walking environments and pedestrian practices with older adults (Van Cauwenberg et al., 2012; Zandieh et al., 2016; Lee and Dean, 2018). One study used walking interviews with adults with post-injury walking disabilities (Butler and Derrett, 2014), which revealed deep understanding of how each person experienced their disability day-to-day, including examples of how walking is performed in certain areas. Furthermore, walk-along interviews have been explored with children both inside the home environment (Stevenson and Adey, 2010) and outside, in the playground (Pawlowski et al., 2016) or in the local neighbourhood (Horton et al., 2014; Ergler et al., 2021). All studies using walk-along interviews with children express the ability to generate rich information about the lives and experiences of children as they happen. These interviews offer insights into how children interact and view environments around them. Despite this, to current knowledge this interview method is yet to be used with children with CP to explore real-world experiences of falls and the challenges that children with CP face in their typical real-world environments.

4.1.2 Aim

The aim of The Walk-Along Project was to explore the real-world (natural and/or built) environments that children with CP find challenging and determine those that might cause a fall or increase fall risk based on their lived experiences.

4.2 Methods

4.2.1 Participants

Participants were recruited through various charitable organisations or schools in Northwest England to take part in a walk-along interview. Children were eligible to participate if they were between 7 and 16 years old, had a diagnosis of spastic cerebral palsy (GMFCS level I – III), were able to walk without walking aids, able to understand English and have adequate vision and good hearing capabilities, as judged by gatekeepers and/or parents or guardians. Children were excluded if they had any other orthopaedic or neurological condition that may alter their ability to walk. GMFCS was self-reported by parents or guardians. All children who could walk without mobility aids at the time of taking part were included in the study, which may have included some children with a past clinical classification of GMFCS III. The study was approved by University Ethical Review Committee (ref: 22/SPS/022). Three charity gatekeepers assisted with recruitment for The Walk-Along Project between 13th May 2022 and 3rd December 2022. All accompanying adults who took part in this study were parents, despite inclusion of either parents or guardians. Parents and children were provided with tailored information sheets before providing written informed consent and assent, respectively.

4.2.2 Procedure

Definitions of both a ‘trip’ and a ‘fall’ were provided to parents and children prior to starting the walk-along interview. The word ‘trip’ was used in this case to encompass any loss of balance that would not lead to a fall. For example, due to a misplacement of a foot, a slip or dynamic losses of balance or stumbles due to interactions with objects in the environment or the environment itself. This aligned with a recent definition of a ‘near fall’ in literature (Maidan et al., 2014). A trip was described to children and parents as any disturbance to walking (such as tripping over an object) or loss of balance (such as a stumble), that would not lead to a fall whereby they would come to rest on the floor. The definition of ‘trip’ was kept intentionally broad so that children and parents were able to talk about all types of perturbation events in day-to-day environments that might result in a fall to the floor. ‘Trip’ was chosen as a word that children would be able to associate with and understand as informed by language used during previous PPIE. A fall was defined as any stumble event causing a disturbance to balance, that results in coming to rest on the ground or floor. This was in accordance with the World Health Organization’s definition of a fall (World Health Organization, 2021) and a recent definition of ‘near fall’ in literature and was explained in child-friendly terms (e.g. “When I talk about a fall, I mean a trip or stumble meaning you have lost your balance and ended up falling all the way down to lie on the floor”).

Children with CP and their parents were provided a ‘mud map’ (simplified map drawn by investigator, Figure 4.1) and a Google map, respectively, of a walking route predetermined by the lead investigator (RW) in a location agreed by parents during recruitment. Multiple locations were discussed during recruitment with each parent to identify a convenient, accessible place, local to their living area, for them to attend a walk-along interview. In every case, the predetermined route was chosen to represent environments that children encounter regularly in their day-to-day lives, as informed by previous PPIE and in recruitment conversations. In most cases (11 out of 12 interviews) the walking route had areas in which they had walked before on numerous occasions. Each chosen route included environments (e.g. potholes or uneven paths) that were identified during PPIE conversations to increase the risk of a trip or a fall and would therefore offer insight into children’s day-to-day lived experiences of falls. Children and parents were given the opportunity to change the walking route both prior to and/or during the walk, should anything concern them.

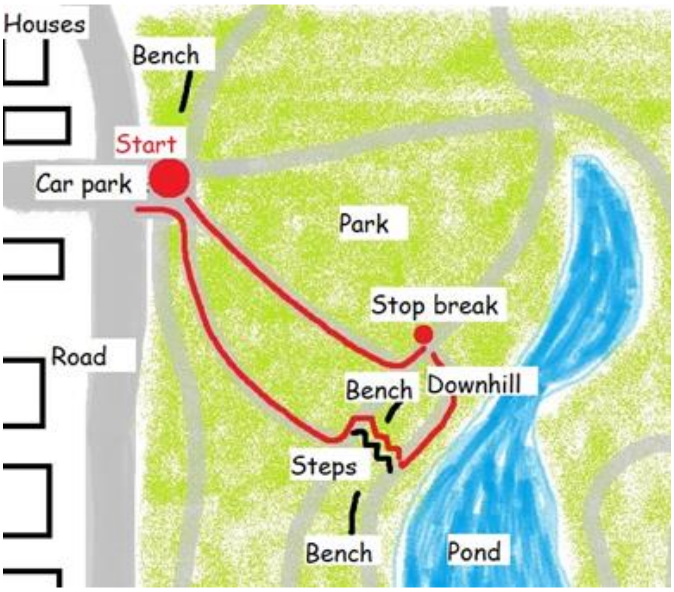


Figure 4.1. *Example mud map drawn by the investigator of a walking route agreed by parents prior to a walk-along interview.*

The walk-along project intended to explore lived experiences of children with CP and their parents when navigating day-to-day environments that might increase the risk of a trip and/or fall. The walk-along interview method used in this project offered the opportunity for children, parents and investigator to engage with the surrounding environment through conversations, gestures and photo elicitation (Pyle, 2013; Ergler et al., 2021), in order to gain a well-rounded picture of environments that might cause increased fall risk to children with CP. To achieve this, The Walk-Along Project recorded conversations with microphones, captured walking environments with video cameras and explored lived experiences through child-led photo elicitation with an additional camera.

Prior to the start of the walk, the investigator used chest harnesses to attach Kaiser Baas X450 action cameras (Kaiser Baas Pty Ltd, Melbourne, Australia) to themself and to the child, if the child was comfortable. These chest mounted cameras captured videos of the environments encountered during the entire walk-along interview. Recording began by manually pressing record on each device, with default camera recording settings (capture rate: 30 fps, resolution: 4K). A third Kaiser Baas X450 camera was used in addition to video cameras for taking photos during the walk (resolution: 14MP, Field of View: 160°). Two wireless RØDE GO II clip-on microphones (RØDE Microphones, Sydney, Australia) were attached to the clothing of parents and children for high-quality audio-recording of conversations between the child, parent and lead investigator, that video cameras could not capture. Microphones were operated by the lead investigator's Android mobile phone app, RØDE Central (Version 2.0.5, RØDE Microphones, Sydney, Australia), using default microphone settings (sample rate: 48 kHz, maximum sound pressure: 100dB).

Children and their parents walked with the investigator (RW), following the predetermined route that reflected a place they would typically walk. Children were given the map before the walk to look at the route; none of the children chose to carry the map during the walk. The investigator directed the walk and asked questions using a predetermined semi-structured interview schedule and discussion guide (Appendix 6). Questions included: 'how do you feel about the walk we are taking today?' and 'can you see anything on this walk that might cause a trip or a fall?'. Any questions asked during the walk-along interview were first directed to children, and then parents were given the opportunity to expand on the child's answer. Children were told they could stop the walk at any time to take photos with the third action camera of anything in the environment that they believed could cause a trip or a fall. Photos taken by children prompted further discussion in the walk-along interview. Children were given a certificate and sticker for taking part.

Following the walk-along interview, children and parents were invited to complete a two-week video diary and asked to include any videos, images, and/or written entries about places where the child might or did experience trips and/or falls in their day-to-day lives.

4.2.3 Data processing

Two audio recordings (parent and child) were downloaded with RØDE Central software (Version 2.0.5, RØDE Microphones, Sydney, Australia), and then synchronised together in Adobe Audition (Version 23.3, Adobe, CA, USA). Recordings also identified any spoken conversation from the lead investigator. Two video recordings (from cameras worn by the child and investigator) were synchronised using Kinovea (Version 0.9.5, Kinovea, Charmant, J and contributors) and then matched to the synchronised audio recordings, using both a visual (hand wave on screen) and audio ('let's go') cue from the investigator during the start of the walk-along interview.

Audio footage was reviewed in Microsoft Media Player (Version 11.2309.6.0, Microsoft Corporation Washington, USA) and video footage reviewed in Kinovea, from a synchronised starting point. The lead investigator then manually transcribed interview and video diary conversations verbatim in Microsoft Word (Microsoft 365, Microsoft Corporation Washington, USA) whilst including photos and videos where appropriate of the surrounding environment. For example, if a child spoke about a particular surface, an image of that surface taken from matched video footage, was included in the transcription. Any photos taken by the children using the handheld action camera were also added to the transcription at the point of conversation in which they were taken. All photographs were taken for use in The Walk-Along Project using equipment owned and provided by the research team.

4.2.4 Data analysis

Transcriptions were imported into NVivo (Version, 1.7.1, NVivo for Windows Enterprise, Lumivero, 2017) for coding by the lead investigator. Coding was completed by labelling transcripts and video diaries in NVivo. Codes emerged from the data with an inductive approach, rather than pre-defined. The lead investigator read each transcript and identified codes based on conversations. Multiple codes could be given to sections of transcripts. For example if child said "I would probably trip over this surface because it is bumpy and uneven" this could be coded as 'challenging environment' and 'uneven'. Transcripts were re-read after initial coding to check if any codes had been missed or incorrectly labelled and to ensure consistency throughout all interviews. Codes were analysed in NVivo to identify those that were most common. Then, key themes were generated based on the most frequent codes and interpretation of these codes with relation to the environments that children with CP suggested they find challenging and to determine those that might cause a fall or increase fall risk. For example regular coding occurred for 'fall experiences' when each child talked of a past experience of a trip or fall. This was grouped into a theme relating to children's experiences of falls in challenging everyday environments. Full description of development of key themes is described in section 4.3. Data saturation was reached when no new codes or themes were being reported; this occurred following the 12 interviews with children and their parents. Data from all conversations with children and parents contributed to the key themes generated. Two separate approaches to data analysis were used.

Analytical approach 1 drew on Interpretive Description (Thorne, 2016) and inductive coding. No a priori codes were used. After an iterative process we created two top level codes: 'challenging environment' or 'non-challenging environment'. The code 'challenging environment' encompassed any environment where a child said a fall could happen. The code 'non-challenging environment' represented any environment where it was implied that the child felt safe or where a trip or fall would not happen. Further iterative analysis resulted in the creation of sub-codes that unpacked and provided insight into different factors related to challenging and non-challenging environments. These sub-codes helped challenge and refine the descriptors linked to the overarching codes. The sub codes allowed the analytical lens to focus on details about the types of challenging environment. For example, if a child or parent identified an uneven pavement to be a fall risk, this was coded as both a 'challenging environment' and 'uneven surface'. Further sub-codes included sensory challenges, e.g. noise, vision or distractions in the environment. Additional codes were identified from commonalities across the datasets, including fall occurrences', 'feelings about walking', 'cautious behaviour', 'tiredness before and after walk', 'parent intervention', 'awareness of surroundings', 'fall mechanism' and 'familiarity of walking route'. As analysis deepened, codes were drawn into two overarching themes and five key themes.

Analytical approach 2 (frequency counting of codes) was undertaken following completion of approach 1 and was used to identify the most common challenging environments reported by the children and/or discussed during walk-along interviews. These frequency counts were considered both cumulatively and in terms of distribution across individual participants. Children were assigned pseudonyms alphabetically in order of participation e.g. participant 1 = Albert (Table 4.1).

4.3 Findings

4.3.1 Overview of key information

Twelve ambulatory children (2 girls and 10 boys, aged between 8 and 16 years old) with CP and their parents (8 mothers, 4 fathers) took part in the walk-along interviews. The children's GMFCS levels ranged from I to II; six children had diplegia, and six had hemiplegia. Each walk-along interview lasted approximately 25 minutes. Two children (Dominic and Freya) returned video diaries following the walk-along interview. Dominic's diary was a video of an uneven concrete path, with gravel and potholes, that he said would typically create a trip and fall on his walk to school. Freya spoke to the camera for three minutes about her trip or fall experiences that week. Individual participant demographics (pseudonyms, age, sex, GMFCS) and challenging environments described by each child and parent are listed in Table 4.1.

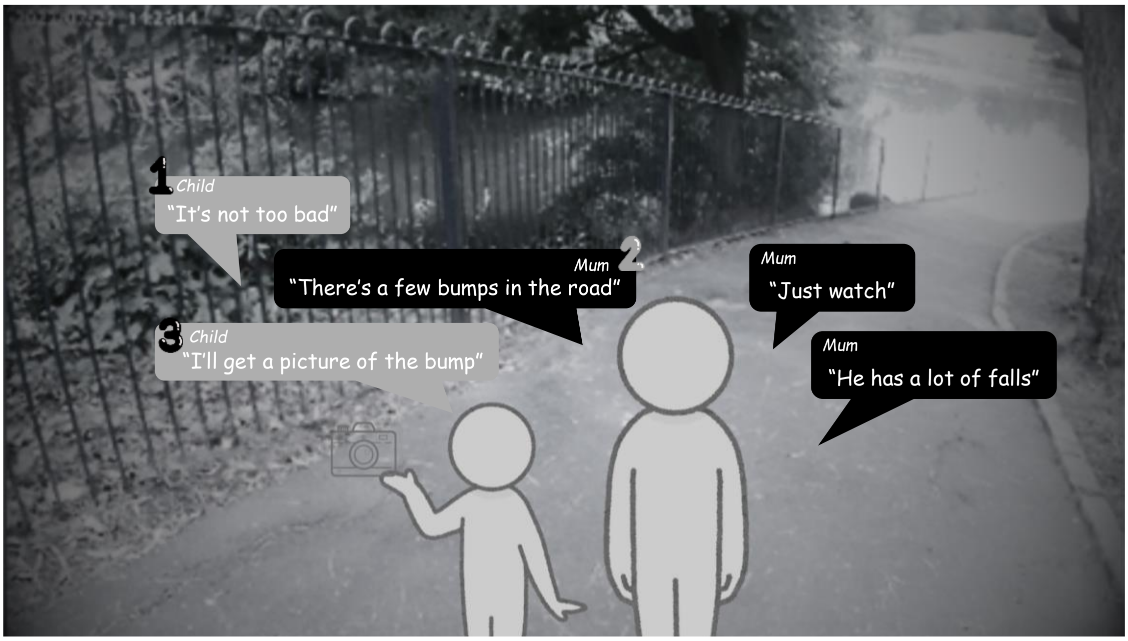
Table 4.1. *Demographics of child and summary of challenging and non-challenging environments reported during walk-along interviews.*

Participant (pseudonyms)	Demographics (Sex, age, GMFCS, accompanying parent)	Child-reported: challenging places	Parent-reported: challenging places	Child & parent-reported: non-challenging places
Albert	Boy, aged 9 years with diplegia (GMFCS I/II), Mother	- Downhill - Uneven surface (change in surface, cobbles, tree roots)	- Obstacles (e.g. branches, tree roots) - Tiredness - Concentration	- Other people - Uphill - Stepping up/down (stairs)
Ben	Boy, aged 9 years with diplegia (GMFCS I/II), Mother	- Obstacles - Uneven surface (grass, crack in path, tree roots, unseen gutter/potholes) - Slippery surface (gravel)	- Uneven surfaces - Running - Not looking - Lack of concentration	- Pavement - Flat surface - Other people
Connor	Boy, aged 11 years with diplegia (GMFCS II), Mother	- Grass - Uneven surfaces (pavement, potholes)	- Not looking and uneven surface - Stepping up/down (kerbs) - Distractions	- Downhill - Flat
Dominic	Boy, aged 16 years with right hemiplegia (GMFCS II), Mother	- Uneven surfaces (grass, raised surface, potholes) - Stepping up/down (kerbs) - Slippery surface (gravel) - Distractions	- Uneven surfaces (pavement, potholes) - Slippery surface (gravel) - Distractions	- Familiar places
Elliot	Boy, aged 14 years with diplegia (GMFCS II), Father	- Uneven surfaces (pavement and grass, grids, pebbles, potholes) - Running/fast walking - Not looking	- Stepping up (kerbs) - Uneven pavements - Noise - Non-dominant limb	- Being 'careful' - Stepping up/down (low kerbs, stairs) - Uphill
Freya	Girl, aged 13 years with right hemiplegia (GMFCS I) Father	- Uneven surfaces (tree roots, tactile paving, grid, stones) - Lack of awareness - Tiredness	- Non-dominant limb - Slippery surface (stones) - Tiredness	- Familiar places - Being 'careful' - Stepping up (tall kerbs) - Indoors
George	Boy, aged 12 years with right hemiplegia (GMFCS I/II) Father	- Uneven surfaces (potholes) - Slippery surface (gravel) and downhill - Footwear (less contact between foot and sole e.g. wellies) - Obstacles (tree roots)	- Footwear (less contact between foot and sole e.g. wellies) - Uneven surfaces (pavement)	- Stepping up (kerbs, stairs) - Slippery surface (mud) - Obstacles - Uneven surfaces (grass, grids, cobbles, sand) - Tiredness
Henry	Boy, aged 15 years with diplegia (GMFCS I/II), Mother	- Uneven surface (raised pavements, potholes, cobbles) - Stepping up/down (kerbs) - "When young"	- Uneven surfaces (raised pavements, potholes) - Not looking - Distractions - Noises and crowds	- If 'careful' - If concentrating - If taking time
Isaac	Boy, aged 15 years with right hemiplegia (GMFCS I/II), Mother	- Uneven surfaces (pavements, cobbles, potholes)	- Stepping up/down (kerbs) - Uneven surfaces (potholes, pavement/stones) - Obstacles - Vision - Tiredness - Downhill - Running	- Flat

Jasmine	Girl, aged 8 years with diplegia (GMFCS I-II), Father	- Uneven surfaces (potholes, grids) - Stepping up/down (tall kerbs)	- Foot placement and balance - Not looking - Distractions - Small obstacles - Footwear - Tiredness - Other people - Stepping up/down (kerbs)	- Walking slower - Crossing roads (concentrating) - Flat pavement - Low kerbs - Uphill
Kenny	Boy, aged 12 years with left hemiplegia (GMFCS I/II), Mother	- Unseen uneven surfaces (potholes, grass) - Stepping up/down (unseen kerbs) - Obstacles (e.g. bottle) - Downhill, uneven and running - Tiredness	- Uneven surfaces (pavement, grass, potholes) - Not looking - Distractions - Slippery surface (gravel) - Tiredness	- Flat grass
Leo	Boy, aged 10 years with right hemiplegia (GMFCS I/II), Mother	- Downhill - Uneven surface (grids, potholes, grass) - Stepping up/down (kerbs)	- Uneven surfaces (tree roots) - Stairs (no handrail) - Tiredness - Balance	- Slightly uneven grass - Smaller gravel stones

During the walk-along interviews children and parents shared their perspectives about falls and the things they found challenging or otherwise. Visual summaries or vignettes were created as a means of presenting an overview of each walk-along interview. Examples of two vignettes are presented in Figure 4.2 (Appendix 4 for all 12 vignettes).

a.



b.

Figure 4.2. *Example of two vignettes (pseudonymised participants Albert and mum (2a) and Jasmine and dad (2b)) showing conversations between child and parents in settings identified as presenting a challenge. Speech from children is indicated in grey speech bubbles and parents in black speech bubbles. Where conversation was consecutive between parent and child, numbers indicate the order in which conversations were had. (Note: Background photographs taken by participants during the walk-along interviews. Canva (online graphic design tool) used to add figures and speech bubbles (all graphics freely available under Canva's Content License Agreement).*

Uneven environments were discussed the most across all walk-along interviews. The distribution of uneven surface codes for each participant is shown in Figure 4.3. The second most common code across all interviews was 'multifactorial', which indicated when more than one challenging environment could contribute to falls and increased fall risk. For example, an uneven surface with a distraction present. All children reported challenging environments that involved 'pavement', 'obstacles', 'potholes or dips' and reported that 'distractions', 'not looking and vision' or 'foot placement' might increase their fall risk in a challenging environment. In 11 interviews, 'grass', 'downhill', 'kerbs', 'balance', 'stepping up or down', 'vision and uneven surfaces' and 'distractions and uneven surfaces' were discussed with reference to challenging environments that might cause falls and increase fall risk in the real-world.

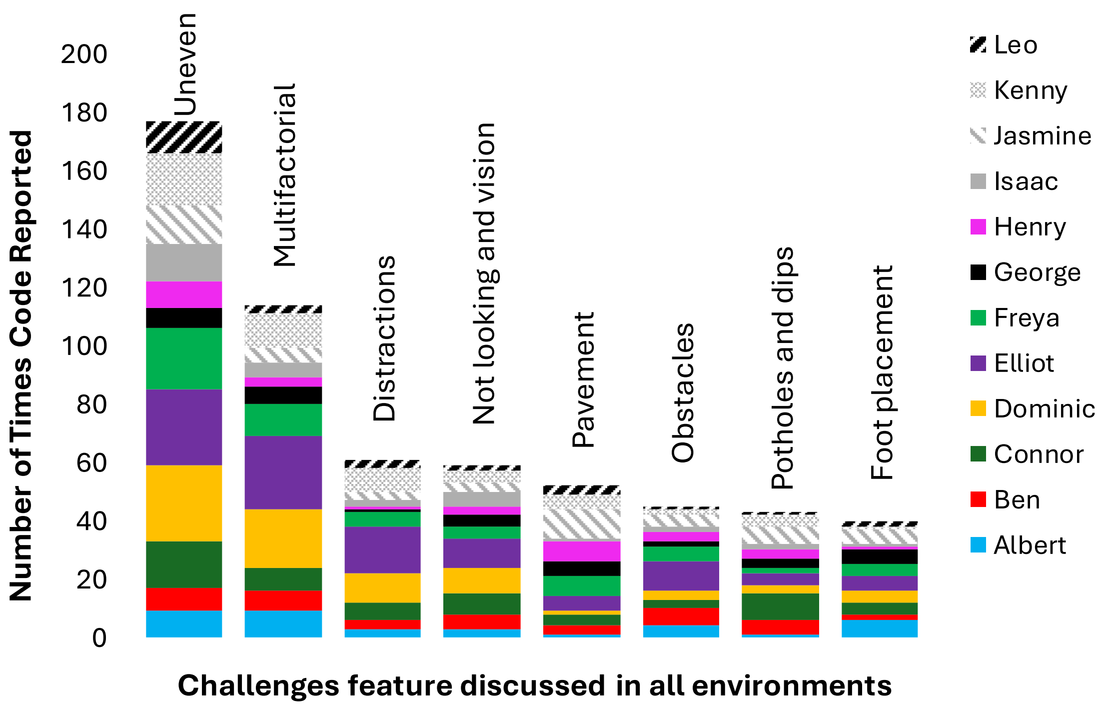


Figure 4.3. *The frequency of top codes relating to challenging environments reported across all 12 interviews. Legend shows distribution of code for each participant.*

4.3.2 Presentation of overarching and key themes

Drawing on commonalities in data from the walk-along interviews and video diaries two overarching themes (‘places where trips and falls occur’ and ‘things children do to control falls’) plus five key themes were identified that explored what, how and why real-world environments are challenging and cause falls or increased fall risk for children with CP. Three key themes sit within the overarching theme ‘places where trips and falls occur’ and two themes sit within ‘things children do to control falls’ (see Figure 4.4).

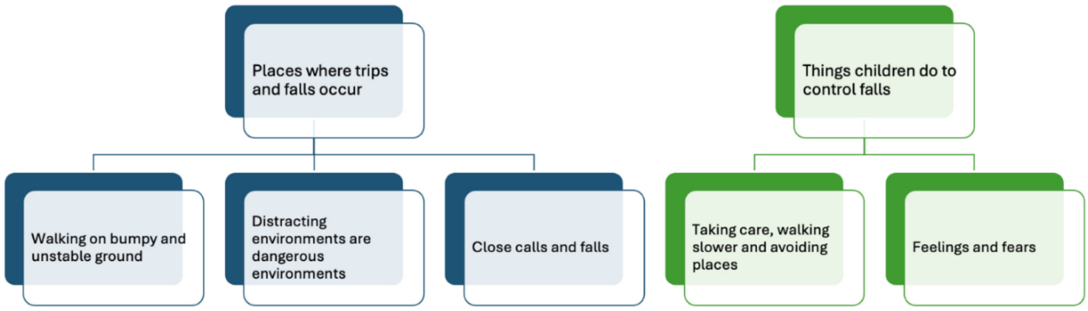


***Figure 4.4**: Overview of overarching and key themes*

4.3.3 Places where trips and falls occur

Walking on bumpy and unstable ground

This theme describes the places that were commonly suggested by children and parents to cause trips or falls in the real-world, based on their lived experiences.

Photos taken by children during walk-along interviews indicate that uneven pavements and grass surfaces are the most common challenging environments that might increase falls and the risk of a trip or fall in the real-world, for example cracks in pavements or paths, tree roots under the surface of the pavement, tactile paving, cobbles, hidden potholes in the grass, ‘bumpy’ (non-level) grass, or long grass (Figure 4.5). These types of environments were noticed and photographed most by children on walk-along interviews, with children describing that these places are likely to cause a disturbance to balance if stepped on or they could cause a trip or stumble if unnoticed.

Figure 4.5. *Photographs taken by participants of places they suggested could cause a trip or a fall during walk along interviews for use in The Walk-Along Project. All photographs can be seen in Appendix 5.*

The most discussed challenge was uneven surfaces with all the children talking about these and typically often referring to these surfaces as “bumpy and unstable ground” (Jasmine). Freya explained why tactile paving was problematic for her "it’s all like bumpy and there’s like different levels and my foot might like get caught in one of them”. Dominic, talking of uneven ground and unexpected hazards, identified grass as a potential challenge saying “…this grass you could probably just not expect it and trip over”, and George, talking about the raised surface of a manhole cover (see Figure 4.6), explained:

> *“Erm, it’s very uneven…so I’m just standing, I put one foot there [off the raised surface], (see photo) and one foot there [on the raised surface] it’s like boosting my other foot up, it’s very uneven.”* *(George)*

Figure 4.6 *Photograph from video footage of George stepping onto a manhole cover during a walk-along interview whilst describing how it is uneven.*

Distracting environments are dangerous environments

This theme encompasses the main interacting factor that was commonly suggested to increase the fall risk, despite the cautious behaviours implemented by children.

All the children talked about how the preventative measures (taking care, walking slower and avoiding places) were much harder to implement if a distraction was present (e.g. dogs barking, other people playing football, cars driving past). Distractions caused children to ‘not look’ or ‘not concentrate’ where they were going whilst walking over an uneven surface. When walking on tactile paving, Kenny explained “if I’m not concentrating then I could stumble”. Children often described that these distractions could be both auditory or visual. Elliot explained that he could “probably fall and trip” if “someone is shouting me or something...and I’m talking to them and I’m not aware of something there” and Dominic demonstrated his trailing foot tripping on a raised grid by saying:

> *“If I am walking in this direction and am looking at [people playing nearby] football I could go like that…”* (Dominic)

Being able to directly see a challenging environment was described as important as if a challenging environment was obscured e.g. a pothole in long grass, then a fall was more likely. George explained that he could “potentially fall into…potholes”, and went on to explain that this was because it may be unnoticed while walking:

> *“It kind of catches you by surprise, cause you’re walking one minute, then the next your foot is just stuck in the ground.”* (George)

Many previous fall experiences talked about by children with CP additionally included some form of distraction, a lack of concentration or not looking at or seeing a challenging environment. One child confirmed he had tripped on a kerb “cause I wasn’t looking” (Connor). Kenny explained that he had fallen when he was younger in a “fox hole or a rabbit hole... I accidentally put my foot on it and it felt like I kind of twisted my ankle”. He attributed this to not noticing it as he “didn’t realise it were there” and his mother added “distractions”. Another source of distraction were friends as Freya explained:

> *“I was also talking to my friends so that caused me to stumble over some like roots that were coming out the ground and also some weeds that were in the cracks of the pavement, they made me trip over and like stumble a little bit.”* (Freya)

Close calls and falls

This theme describes the lived experiences of past trips and falls in addition to near falls that were experienced during the walk-along interviews.

Eleven out of twelve children spoke at least once during walk-along interviews about their previous experiences of falls. The most common environment identified to have caused previous falls was grass potholes. Other examples included tree roots under pavement paths, uneven pavestones, obstacles, concrete potholes, gravel and cobbles.

Some walks, local to where the children lived, revealed the exact places where they had fallen in the past. Connor pointed out a ditch and when asked by the investigator if someone could fall down that Connor said “I fell down that” (see Figure 4.7) and his mother agreed “yeah you have done before. I am pretty sure we’ve been here before” (Connor’s mother).

Figure 4.7 *Photograph of a pothole taken by Connor that he described he had fell down previously.*

During the walk-along interviews six children experienced a trip or stumble, leading to a loss of balance that was then recovered, without leading to a fall. Two children (Connor and Jasmine) lost their balance after stepping on the edge of uneven potholes on a concrete path while trying to take a photograph in the environment (potentially the act of taking the photograph had been a distractor). Kenny became unbalanced and had to take a step backwards after stepping up onto the edge of a kerb, Leo stumbled while trying to step on an uneven grid in the grass, Henry showed instability walking over cobbles. Ben was distracted, did not see a grass pothole (see Figure 4.8) that he stepped into losing his balance although he recovered quickly. His mother described this as a “close call” and when asked if he had seen the hole, he replied “Nope, no clue”:

Mother: You nearly tripped didn't you… that was a close call

Interviewer (RW): What happened there?

Ben: I don't know

Mother: You were looking at the boy on the scooter

Ben: No, I was looking at the camera

Interviewer (RW): Ahh, you didn't see the hole? (see photo)

Ben: Nope, no clue

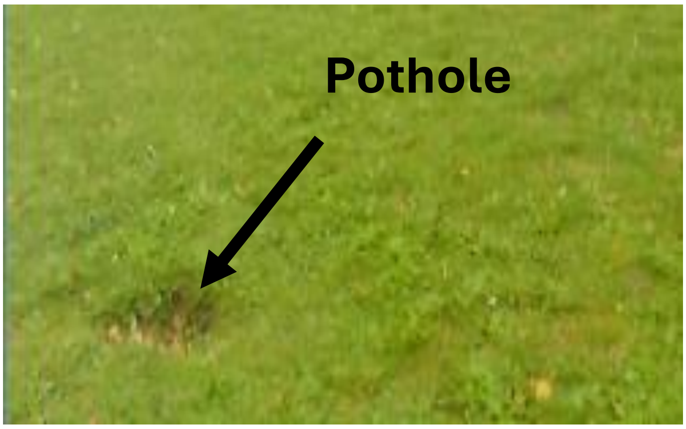


***Figure 4.8** Photograph from video footage of a pothole that Ben stepped into during a walk-along interview.*

4.3.4 Things children do to control falls

Taking care, walking slower and avoiding places

This theme describes the behaviours children suggested they would implement to prevent a fall as well as the awareness of older children to know how falls may happen.

Walk-along interviews revealed that children undertake three preventative behaviours to reduce the risk of a fall in challenging environments and these all involved children becoming aware of a potential challenge and also recognising that these actions might not prevent a fall. The actions were 'taking care', 'walking slower' and 'avoiding places'. Taking 'care' about walking on an uneven grass surface for Elliot meant "obviously, I have to take my time with it a bit…and obviously be careful, but I might trip". Several children talked of slowing down, "I'd just go slow on a grass surface and hope I don't fall" (Jasmine). Avoidance was a strategy the children talked about, with a typical statement being "If I see an uneven bit, I'll try to swerve [avoid] it" (Dominic).

For younger children, taking care was also more apparent through parent intervention to prevent their children falling, compared to older children. This intervention included parents suggesting behavioural ways they would intervene when walking outside: “I’ll grab his hand” (mother of Albert) and included comments made during the walk-along interview such as “be careful” (mother of Connor). Dominic’s mother explained how specifically they would intervene when Dominic was younger:

> *"When they’re younger they’re not aware of what their surroundings are so all the time I [used to] say…watch this.”* (Dominic’s mother)

Although more common in younger children, parent intervention was also apparent from some parents of older children. Isaac’s (aged 15) mother told Isaac to “watch where you’re going” during the walk-along interview, and Elliot’s (aged 14) father warned “watch that can there” when Elliot nearly walked into an obstacle (drink can on floor).

Older children were able to take more care in their challenging environments through greater awareness of surroundings (e.g. knowing where to slow down or be careful). This was more common in older children who were able to look back and see how their situational awareness had improved, for example “when I was younger, I didn’t use to [look at the floor], and I’ve just figured out that I need to look at the floor to know where I’m going” (Henry). However, better situational awareness of hazards did not necessarily mean that trips could be avoided, Elliot explained:

> *“Obviously when you’re younger you don’t know what’s a hazard so you might run into it but now, I might, well I’m still not the best with it, but I might be able to, like I can recognise what I’m more likely to trip over.”* (Elliot)

Older children showed additional awareness of how a fall might happen in challenging environments. Scenarios described by older children included tripping by catching their trail limb on a raised uneven surface, a disturbance to balance due to poor foot placement on an uneven surface and slipping on gravel. Freya demonstrated (see Figure 4.9) how she might trip “if I’m like scraping my foot across then I would probably go like that and trip over”.

Figure 4.9 *Photograph from video footage of Freya demonstrating how she might make contact with the foot on a raised pavement edge leading to a trip.*

Feelings and fears

This theme describes insights into how falls impact daily life and the consequences (e.g. pain) that falls have regularly for children with CP.

Children seemed comfortable talking about their regularly experienced real-world falls often coming across as being quite relaxed about them and seeing them as just part of everyday life. There were no conversations that implied specific attitudes toward falling. However, some children and/or parents discussed the impact that falls can have on day-to-day life, for example, missing school or gaining an injury. One mother recalled that "a couple of times he's set off to school and he's come back because he's fallen" (Dominic's mother). A typical response from a child regarding how falls can increase pain and injury came from Jasmine who explained:

> *"Cause when I was like really little I was like falling all the time like, mostly in school I was like on the playground and I didn't have any tights on and I was like, I was always hurting my knees"* (Jasmine)

Another example described by Leo showed a reduced feeling of safety in a challenging environment, describing a scenario where in school there is "a grass area" and "rocks that we can play on". However, he then described that he is "a little bit cautious of going round there because they could probably hurt me". Another example in challenging environments was described later after coming across an uneven grid during the walk-along interview:

> *"This [environment] could do pretty bad damage because it has these little [bumpy bits] on it…it could probably hurt you seriously, so, let's not try and do that"* (Leo)

This reduced feeling of safety was further evidenced by Dominic, a boy with hemiplegia, who spoke repeatedly about how their right (affected) arm, would bend at the elbow, as a physical response to heightened anxiety in challenging environments:

> *"Every single time it triggers, like my brain triggers 'oh wait an uneven surface', my right arm goes up straight away"* (Dominic)

4.4 Discussion

This is the first study to explore rich, robust qualitative data based on the lived experiences of children with CP using a walk-along interview technique about the types of real-world challenging environments that might increase falls or fall risk. The three themes relating to 'places where falls occur' highlighted that uneven pavement and grass potholes are most likely to cause falls when negotiating challenging everyday environments, and especially so in distracting environments. This detailed insight into the places where past falls have occurred or where fall risk is perceived as highest extends previous work regarding falls in children with CP (Boyer and Patterson, 2018), that have shown the high frequency of falls experienced day-to-day, but lack the detail into specific environments that cause additional perturbations in walking that increase falls in children with CP. This work further adds novelty in its approach to investigating falls in children with CP, compared to typical human movement approaches.

The lived experiences shared by children about what they do to control falls because of the consequences or fear of the consequences (e.g., injury, pain) that may occur from falling had not been anticipated when designing the project but arose from conversations commonly had during walk-along interviews. The two overarching themes are used to structure the discussion to offer context about the types of real-world challenging environments that increase falls and fall risk, the preventative behaviours commonly used by the children and the consequences of falls in the real-world.

4.4.1 Places where trips and falls occur

The Walk-Along Project now provides robust child-centred evidence for the importance of considering environmental distractions within real-world challenging walking environments when trying to understand the causes of increased fall risk in children with CP. Unlike this study, previous research has investigated stability of children with CP over challenging environments in movement analysis laboratories (Dussault-Picard et al., 2022b). In laboratory environments with uneven surfaces, obstacle crossing and walking on inclines, children with CP have demonstrated reduced walking speed and increased step width. These walking alterations have been suggested as cautious walking behaviours to compensate for instability (Böhm et al., 2014; Malone et al., 2016; Topçuoğlu et al., 2018; Romkes et al., 2020; Coman et al., 2022). However, little is known either about whether these walking alterations occur in the real-world or if they do occur what impact such walking alterations have on real-world falls and fall risk. Therefore, it is difficult to offer meaningful recommendations for fall prevention in these real-world environments for children with CP. Previously, the systematic review led found little evidence assessing links between challenging environments and fall risk in children with CP (Chapter 2). Work is yet to explore how stability and fall risk may be affected over a challenging environment (real-world or laboratory based) with a distraction present. Children with bilateral CP have shown minimal differences in walking parameters with an additional distraction or visual stimulus during routine gait analysis in a laboratory over level ground (Bartonek et al., 2016; Bailey et al., 2021). Work with older adults demonstrates that in the real-world, attention is moved away from a walking path ahead, and toward other people in the environment, whereas in a laboratory setting attention was focused to the walking path ahead (Zukowski et al., 2020). The Walk-Along Project, perhaps, mirrors this finding revealing that in real-world settings children with CP divert their attention from the walking path, although as seen in previous studies (Bartonek et al., 2016; Bailey et al., 2021) this does not occur in the laboratory over level ground

4.4.2 Things children do to control falls

Children with CP walking slower and more carefully in the real-world aligns with previous laboratory work. To increase walking stability and try to prevent a fall, children with CP walk slower compared to typically developing children over level ground and over uneven surfaces in laboratory environments (Chakraborty et al., 2020; Dussault-Picard et al., 2022b). This cautious behaviour might link to an increased anxiety or fear of the consequences of falling (e.g. injury) and reduced balance confidence in these challenging environments. In a previous study, children with CP have demonstrated reduced feelings of safety when negotiating steep inclines and declines, as shown by increased focus, less talking and more gaze focus towards the floor (Topçuoğlu et al., 2018) and shown reduced balance confidence compared to typically developing peers (Towns et al., 2020). In the current study, this was demonstrated by children through physical responses (Dominic) or discussion of pain previously caused by falls (Jasmine) and fear of potential consequences of falls in challenging environments (Leo). In real-world challenging environments, this reduced feeling of safety may actually be linked to increased fall risk, because less attention is available for the task (Young and Mark Williams, 2015).

Children compensate for instability and high fall risk in challenging environments by adapting their day-to-day activities. Two children reported walking longer or different routes to school to avoid a path where they had fallen previously. While taking a different walking route may have other benefits to an individual, avoidance behaviours such as missed school or reduced activity participation as a result of falls also have the potential to impact children's day-to-day quality of life. This is of interest given the importance of school shown by children with CP in previous quality of life measures (Dickinson et al., 2007). This strongly suggests there is scope for inclusion of falls and fall-avoiding behaviours as an item in typical quality of life measures in children with CP. Although, it is established that pain is associated with reduced quality of life in children with CP (Dickinson et al., 2007) and children in The Walk-Along Project described pain resulting from falls (e.g. hurting knees on the playground at school), this has not been explored in detail but may have direct impact on quality of life measures.

The Walk-Along Project also revealed that when children become distracted, they are less likely to implement cautious behaviours to reduce fall risk (taking care, walking slower and avoiding places), because their attention and vision is moved away from looking where they were walking. Thus, as suggested by children, if a distraction is present in a challenging environment, the number of falls and fall risk increases. This finding might suggest that cautious behaviours implemented by children with CP are conscious actions rather than habitual behaviour, since, as suggested by The Walk-Along Project, distractions interrupt the action of being more cautious. This was identified by both younger (e.g. Ben) and older (e.g. Dominic) children. Perhaps this supports the use of behavioural interventions, for example, learning to maintain cautious behaviours when in highly distracted environments (e.g. taking care at the park or when walking with other people), in order to create more habitual cautious behaviours when in challenging environments that increase fall risk.

Vision is an important factor into maintaining balance for children with CP. A previous study showed when standing still in a moving room, children with CP sway in the direction of the moving room with larger and more variable postural sway compared to typically developing children (Barela et al., 2011). When walking, vision is used in a feedforward manner, by looking two steps ahead to plan a walking path (Patla and Vickers, 2003). Therefore, when children with CP are distracted, this causes a disruption in visual processing of the challenging environment ahead, and any anticipatory adjustments to even small perturbations, as suggested in The Walk-Along Project, may not be implemented, thus leading to a trailing limb causing a trip, or a misplaced foot step. Although all children are likely to become distracted in some environments, this issue is particularly pertinent for children with CP since they already show balance deficits and visual impairments compared to typically developing children (Fazzi et al., 2012; Roostaei et al., 2021), therefore compensatory mechanisms that may be interrupted are more important for maintaining stability. Furthermore, the response to a trip or loss of balance may be impaired in children with CP compared to typically developing children, as demonstrated in previous studies with standing perturbations (Burtner et al., 2007), therefore increasing the likelihood of a fall following a trip or stumble.

The Walk-Along Project has generated novel insights from children with CP and their parents about the influence of both visual and auditory distractions have on fall risk in real-world challenging environments. This provides scope for further research to investigate the potential mechanisms of falls or increased fall risk experienced by children with CP when a distraction is present in a challenging environment.

4.4.3 Implications for future practice and fall prevention

The Walk-Along Project offers implications for developing protocols that replicate real-world walking environments that include audio and visual distractions, as this may improve understanding of mechanisms of falls and fall risk in children with CP. This extends previous work that investigates stability and walking behaviour in laboratory-based challenging environments such as uneven surfaces (Böhm et al., 2014; Malone et al., 2016; Topçuoğlu et al., 2018; Romkes et al., 2020; Coman et al., 2022; Dussault-Picard et al., 2022b), but which do not have an accompanying distraction. Further exploration of falls and fall risk in challenging environments with a distraction both within and outside of the laboratory, could offer deeper understanding into common mechanisms that contribute to falls in these environments for children with CP. In doing so distractions could be incorporated into regular assessments and implemented within the community to identify children with CP who might be at high fall risk. Such insights could inform future fall prevention programmes.

Moreover, The Walk-Along Project supports views previously indicated in the literature (Malone et al., 2016; Cappellini et al., 2020) that visual factors that contribute to falls need further investigation. Future work or practical interventions on scanning strategies may help children identify hazards in a distracted environment. Individual differences in children should also be considered when determining which children may be at highest fall risk and therefore benefit most from such interventions. For example, Dominic (16 years old) identified that he often becomes distracted when walking day-to-day and that his diagnosis of ADHD, might contribute. Isaac’s mother offered another example when she explained that Isaac’s vision is impaired, so he struggles to see obstacles in the environment, thus she has to provide parent intervention e.g. telling Isaac to watch where he is going. An implication from this is the importance of identifying children who might be at high fall risk due to multiple, individualised factors. A further key takeaway from this work is the poor quality of everyday environments, albeit specific in this study to the local region, since potholes, broken pavements and similar factors are hazards to most people, especially children and those with CP.

Another important potential outcome from The Walk-Along Project lies in the development and use of wearable technology for children with CP for assessing falls and fall risk in the real outdoor world. The development of sensors and markerless technologies could enable information about fall and fall risk behaviours to be explored in the real-world, which could inform future fall prevention programmes.

4.4.4 Strengths

The Walk-Along Project has revealed novel insights into the day-to-day environments that children with CP find challenging and that might increase falls or fall risk. The first strength of this work is that the methods have been informed by careful and detailed PPIE, with children with CP and their parents (Chapter 3). Prior PPIE informed the design of a tailored walk-along interview technique for children with CP, which was used in this study. This early work ultimately makes The Walk-Along Project grounded in the thoughts and opinions of children with CP from conception to implementation.

The second strength of this work is the pioneering use of the walk-along interview technique with children with CP for investigating real-world falls. This extends the population of children who have been involved in interviews and specifically, walk-along interviews as previous studies have been confined to typically developing children (Stevenson and Adey, 2010; Teachman and Gibson, 2013; Horton et al., 2014; Pawlowski et al., 2016; Ergler et al., 2021). We show that this method is acceptable and safe for children with CP and present practical recommendations of conducting this method.

The final strength highlighted of this study are the novel insights that have been revealed, potentially paving the way for new advances to be made in researching falls in children with CP. The Walk-Along Project aimed to explore real-world environments, suggested by parents and children with CP to be challenging for children with CP, and determine those that might increase fall risk based on lived experiences. This study not only identifies real-world environments that are challenging for children with CP, but using detailed lived experiences, also dives deep into the potential causes of falls in these real-world challenging environments and offers insight into both the consequences of falls and the adaptive behaviours that children with CP implement day-to-day, in order to avoid potential falls.

4.4.5 Limitations

This study is limited by a lack of participant diversity, for example, only two children identified as female. A further limitation to this is that this study did not collect socio-economic data or geographical setting or living places. It is acknowledged that lived experiences of children may differ depending on sex, gender, age, ethnicity, socioeconomic background and geographical living environment, which should be considered in the interpretation of findings of this study. Furthermore, child participants were all ambulatory without the use of walking aids, meaning that fall/fall risk experiences explored during The Walk-Along Project might not generalise to children with less functionality and those requiring walking aids. Despite this, The Walk-Along Project aimed to inform future fall prevention programmes for children with CP who experience the most falls and previous studies show that most falls occur for children with CP without walking aids, compared to those requiring walking aids (Boyer and Patterson, 2018).

This study was limited by a relatively small sample size of 12 children with CP and parents. Although similar studies using walk-along interviews with both children (Stevenson and Adey, 2010; Ergler et al., 2021) and adults (Butler and Derrett, 2014) have used similar or smaller sample sizes, and others show that data can become repeated using a fixed walking route with small samples (Jones et al., 2008), a larger number of participants may have allowed for better comparison between younger and older children and generated stronger themes around age and experience of falls.

A further sample limitation may be the self-report of GMFCS by parents/guardians from previous medical appointments. For some older participants, this appointment may have been many years earlier and therefore GMFCS categorisation provided by clinicians may have changed and this may result in error in GMFCS reporting. Despite this, all children who took part in this study were able to walk without walking aids, and had self-reported GMFCS I to II. The ability to walk without walking aids is considered as important as self-reported GMFCS in this study, given that most falls occur for ambulatory children with CP.

An additional aspect that needs careful consideration is the interpretation of 'feelings and fears' associated with falling as shown by this study. We present evidence in this study that children saw falls as part of everyday life, and often hurt themselves and this resulted in them avoiding some places and experiencing anxiety in more high risk fall places. We did not find any evidence of embarrassment associated with falling as suggested by previous literature (Towns et al., 2020). However, thoughts and feelings relating to falls were not the primary focus of these walk-along interviews. Thus, few conversations occurred during walk-along interviews about how children felt when they fell and those that did occur were not in-depth. If the focus of the study had been different it is acknowledged that more detailed responses about how children felt when they experience falls would have been likely and may or may not have aligned with past literature.

Finally, there was a low response of participation in video diaries (n=2) following the walk-along interviews. Children with CP and their parents were given the choice to participate in video diaries. Greater participation in the video diary component of the study may have provided more detailed insight into specific examples of falls and challenging environments children experience on a day-to-day basis in the real-world. This may have also revealed challenging environments that walk-along interviews did not offer discussion for, such as busy indoor spaces.

4.5 Conclusion

This is the first study to explore the lived experiences of ambulatory children with CP in challenging environments using walk-along interviews to investigate real-world fall risk. The Walk-Along Project has revealed novel insights about environments that are challenging, cause falls or increased fall risk and additional insight into the preventative behaviours that children use to avoid falls in their real-world environments. The influence of a distracting environment was an important factor linked to high fall occurrence and fall risk in the real-world. This is vital information for understanding mechanisms of falls in day-to-day environments, informing future fall prevention programmes such as training protocols over "bumpy and unstable ground" and thus targeting the negative psychosocial factors associated with increased falls. Finally, it seems fitting in this child centred study that we turn to a child to provide a concluding statement. Leo (age 10yrs), upon beginning the walk-along interview and being asked '*how do you feel about the walk today*', compassionately shared:

> *"[This walk], will help you and people who don't have CP understand how people who have CP…fall*". (Leo)

Chapter 5

Study 4. Walking Over Replica Real-World Challenging Environments

Sections of this chapter have been published in Gait and Posture in the following formats:

- Special Issue Abstracts:
  - Walker, R., O'Brien, T.D., Barton, G.J., Carter, B., Wright, D.M. and Foster, R.J., (2024) Children with cerebral palsy avoid stepping in potholes with mediolateral changes in foot placement that cause laterally instability. *Gait & Posture*, 113, 242-243. https://doi.org/10.1016/j.gaitpost.2024.07.259
  - Walker, R., O'Brien, T.D., Barton, G.J., Carter, B., Wright, D.M. and Foster, R.J, (2023) Designing a novel protocol to investigate mechanisms of falls in children with cerebral palsy, informed by lived experiences, *Gait & Posture*, 106, 218-219. *https://doi.org/10.1016/j.gaitpost.2023.07.262*

Sections of this chapter have been disseminated as presentations at the following academic meetings:

- British Association of Sport and Exercise Sciences Biomechanics Interest Group Meeting (BASES BIG) 2023, Online

Abstract

Background: In previous PPIE (Chapter 3) and walk-along interviews (Chapter 4), children with CP and their parents revealed that most falls happen on uneven surfaces and when distracted. A unique protocol for investigating stability in challenging environments informed by children's lived experiences was designed to evaluate strategies used by children with CP that may or may not lead to a fall. Research question: How do children with cerebral palsy show instability in replica real-world challenging environments? Methods: Ten ambulatory children with CP (3 hemiplegic, 7 diplegic, 10.9±1.3 years) and nine TD children (10.9±2.4 years) walked with and without a distraction on a TV screen (e.g. dog barking) over a bespoke walkway, consisting of two challenging surfaces: uneven artificial grass with potholes and uneven artificial pavement with raised edges. Three-dimensional motion capture was used to extract outcomes relative to challenging features of the walkway (e.g. when stepping over a pothole). Results: Children with CP had more occurrences of instability (e.g. negative MOS) during interaction with walkway features, compared to TD children (N=42 vs. N=4), despite walking slower and with greater step width, compared to TD children. The most frequent cause (N = 10) of instability for children with CP was a late mediolateral adjustment of foot placement to avoid grass potholes. TD children showed instability once following a step onto a pavement edge, and twice from stepping into potholes. Discussion: Children with CP demonstrated suboptimal avoidance strategies that were not exhibited by TD children, due to the presence of a challenging environment. Although children with CP exhibited known cautious behaviours (walking slower, with increased step width and reduced step length), the avoidance strategy appeared late in approach to a walkway feature, leading to instability either directly (e.g. tripping on a pavement edge) or through avoidance of walkway features (e.g. avoiding a pothole). Instability in children with CP may have resulted from a lack of preplanning the appropriate foot placement to negotiate challenging environments, particularly when distracted, or from factors associated with CP impairments (e.g. reduced selective motor control, muscle weakness or limited ranges of motion). Establishing the underlying mechanisms of how children with CP navigate replica high fall risk environments, helps understand the causes of falls and has identified suboptimal strategies that can be targeted by fall prevention programmes.

5.1 Introduction

All children encounter challenging natural and built environments regularly in the real-world, such as uneven surfaces on the walk to school or in the park. The Walk-Along Project (Chapter 4) evidenced that these environments are a problem for children with CP as they increase the risk of a fall due to potential trips and stumbles over inconsistencies in the walking path such as potholes or uneven pavements. The systematic review (Chapter 2) highlighted that children with CP use more cautious gait characteristics and compensatory stability strategies to a greater extent than typically developing (TD) children to reduce the risk of a fall when walking over challenging environments. For example, by reducing walking speed, lowering time spent in the more unstable single limb support phase and increasing step width, creating a greater base of support (BOS) to maintain COM within. A number of gait characteristics were also suggested to increase fall risk on uneven surfaces, for example reduced ankle dorsiflexion in swing phase (Böhm et al., 2014; Romkes et al., 2020). However, there was little evidence to link compensatory strategies or fall risk behaviours to real-world fall occurrences. This is likely because the environments (e.g. stepping over custom made polyurethane floor panels, stepping over bags of pebbles, or stepping over a single obstacle in a laboratory) do not accurately replicate the situations where children with CP experience falls in the real-world and lack the audiovisual distractions, which are important factors as evidenced by children's lived experiences.

Factors that influence falls may include those that are extrinsic to the person such as the environment (e.g. uneven surfaces), that provide a greater challenge to maintain dynamic stability. Factors could also be intrinsic, for example, a persons ability to adapt to the environment. For children with CP this ability may depend on impairments either physical or sensory (e.g. reduced vision, reduced range of motion), especially given the heterogeneity of the group.

During walk-along interviews (Chapter 4), children with CP reported they were most likely to lose their balance and fall when walking on/over uneven surfaces (e.g. grass potholes or uneven pavements) in combination with experiencing a sensory distraction (e.g. talking to a friend or dogs barking in the park) in the real-world. The systematic review (Chapter 2) revealed the types of gait characteristics children with CP implement as cautious walking strategies, but detail into the mechanisms of trips and falls in challenging environments with a distraction present is yet to be documented. It is important to consider how the sensory environment impacts risk of falls, not only because children suggests this makes it more difficult to avoid a fall, but because sensory systems, such as vestibular, proprioception and especially vision, play a large part in stability, balance and postural control when walking (Shumway-Cook and Woollacott, 2007; Martin et al., 2010; Pavão et al., 2018). Previous work emphasises the importance of the role of sensory deficits and vision when children with CP walk (Malone et al., 2016; Sansare et al., 2022). Vision is used in a feedforward manner when walking, by planning a walking path at least two steps ahead (Patla and Vickers, 2003). Therefore, if attention and vision is moved away from the walking path towards a distraction, it may increase the risk of a destabilising interaction with a challenging environment (e.g. misplaced foot into a pothole, or trip over a pavement edge). Thus, it is important to consider the influence of distractions when investigating how children with CP avoid falls in replica real-world challenging environments.

To identify children with CP at high fall risk and inform fall prevention methods, the strategies that children typically use to prevent falls and any behaviours that may increase fall risk in the real-world need to be identified. This can be done using protocols that replicate day-to-day places that naturally increase environmental (uneven surfaces) and intrinsic (visual and auditory distractions) challenges for children with CP. Strategies that children typically use to prevent falls and any behaviours that may increase fall risk could be revealed by performing 3D motion analysis over a bespoke walkway that replicates the challenging environments children with CP have told us increase fall risk (Chapter 4). Three-dimensional motion analysis allows us to study human movement and quantify variables such as foot placement, MOS, and spatiotemporal variables including walking speed, that could provide mechanical insight into fall avoidance strategies in challenging environments. Additionally, no studies to date have used three-dimensional motion analysis to investigate how children with CP negotiate challenging environments with the inclusion of a sensory distraction.

5.1.1 Aims

The aim of the current study was to identify potential mechanisms of falls and fall avoidance in children with and without CP, when negotiating challenging real-world replica environments, with a sensory distraction.

5.2 Methods

5.2.1 Participants

Children with CP with their parents or guardians were recruited from a local charity organisation in Liverpool, Stick ‘n’ Step. Children with CP could take part if they were: 1) medically diagnosed with cerebral palsy (hemiplegia or diplegia); 2) ambulatory children (able to walk without walking aids); 3) aged 7 to 15 years old; 4) able to comprehend and understand communication and instruction in English to consent and safely participate; and 5) have good hearing and adequate vision or corrected vision with glasses, to safely ambulate in well-lit areas.

Age-matched TD children were identified by members of the research team through existing links within the local community. Typically developing children could take part if they met the same inclusion criteria as children with CP, but were free from any neurological condition and able to stand unaided, independently ambulant and free from the use of walking aids over short distances. All TD and CP children were excluded if they had: 1) reduced binocular visual acuity of 0.5 logMAR or greater that cannot be corrected by glasses; 2) cognitive or behavioural condition which prevents the individual from following instructions or 3) any orthopaedic or neurological condition (other than cerebral palsy) that may alter ability to walk.

Ten children with CP (3 females, 7 males) and nine TD children (3 females, 6 males) participated in this study. Parents/guardians provided CP diagnosis and GMFCS of their child based on previous medical appointments. All children were GMFCS I-II (3 hemiplegia, 7 diplegia), apart from one child, whose parent reported GMFCS II/III, from a historical clinical classification years earlier. The child could walk without mobility aids at the time of taking part so was eligible for inclusion in the study.

Table 5.1. *Participant characteristics and group comparison statistics. Bold indicates statistically significance differences. Executive function is calculated as Trail Making Test-B time minus Trail Making Test-A.*

	CP (mean (SD))	TD (mean (SD))	P value (α = 0.05), test statistic (U) and effect size (d)
Age (years)	10.9 (1.3)	10.9 (2.4)	P = 0.932, U = 45, d = 0.06
Height (m)	1.45 (0.1)	1.49 (0.2)	P = 0.653, U = 45, d = 0.25
Mass (kg)	35.8 (10.5)	42.0 (14.1)	P = 0.438, U = 45, d = 0.51
Diagnosis	3 hemiplegia, 7 diplegia	N/A	N/A
GMFCS	I = 4, I/II = 2, II = 3, II/III = 1	N/A	N/A
Visual Acuity (logMAR)	-0.04 (0.1)	-0.20 (0.1)	**P = 0.008, U = 45, d = 1.70**
Contrast Sensitivity (logMAR)	1.78 (0.2)	1.79 (0.1)	P = 0.806, U = 45, d = 0.70
Quadrant Test (/4)	3.7 (0.3)	3.7 (0.3)	P = 0.794, U = 45, d = 0.15
Trail Making Test A (s)	37 (12)	21 (6)	**P = 0.003, U = 45, d = 1.55**
Trail Making Test B (s)	119 (69)	89 (39)	P = 0.488, U = 45, d = 0.53
Executive Function (s)	83 (65)	68 (36)	P = 0.935, U = 45, d = 0.28

5.2.2 Bespoke walkway

A bespoke challenging walkway was designed and built to have three layers and 16 possible walking paths (Figure 5.1). Materials used and corresponding dimensions for the walkway were as follows:

- Walkway base: Created using 16, 0.8 m x 0.8 m x 6 mm plywood boards held together with plastic edge trims
- Middle layer: Created using of interlocking foam mats (each 0.6 m x 0.6 m x 1.5 mm) to cover an area of 36 m^2
- Walkway surface: Created using 18 m^2 AstroTurf artificial grass and 18 m^2 grey self-adhesive vinyl tiles

The walkway surface was split into two sections to replicate day-to-day environments with challenging features (uneven pavements, grass potholes). The uneven pavement surface with raised edges was created by stacking black interlocking floor mats at various depths across the walkway, which were spray glued to the wooden base, then covered with grey self-adhesive vinyl tiles (Figure 5.1). Grass potholes were created by cutting holes into interlocking floor mats then spray glued to the wooden base, then artificial grass stapled on top (Figure 5.1).

The total size of the walkway including uneven features and level surface was 6 m x 6 m (3 x 6 m artificial grass, 3 x 6 m artificial pavement). The area of the walkway that contained grass potholes or uneven pavement was 3.6 m x 3.6 m. A level surface of artificial grass or self-adhesive vinyl tiles with interlocking mats surrounded the sections of the walkway with grass potholes or uneven pavement. At both ends of the walkway was a 75” (190.5 cm diagonal) television (TV) screen that played a visual and audible distraction on screen. Distractions were the same for all children and were created based on suggestions during walk-along interviews (Chapter 4) that children said would distract them in the real-world (e.g. a dog barking) (Figure 5.2). There were six different audiovisual distractions. For trials on grass, the audiovisual distractions were 1) a dog barking in a field, 2) a dog barking in a park then running toward the camera or 3) People walking by and playing on a grass field on a windy day. For pavement trials, the audiovisual distractions were 1) A dog walking along a path and barking, 2) A van driving past a pavement and beeping its horn and 3) walking next to a busy road with cars driving past and a police siren. Each child saw each of these distractions once, one for each distracted trial on grass and pavement. Distractions were shown on screen from the beginning of the trial and were played throughout the entire trial.

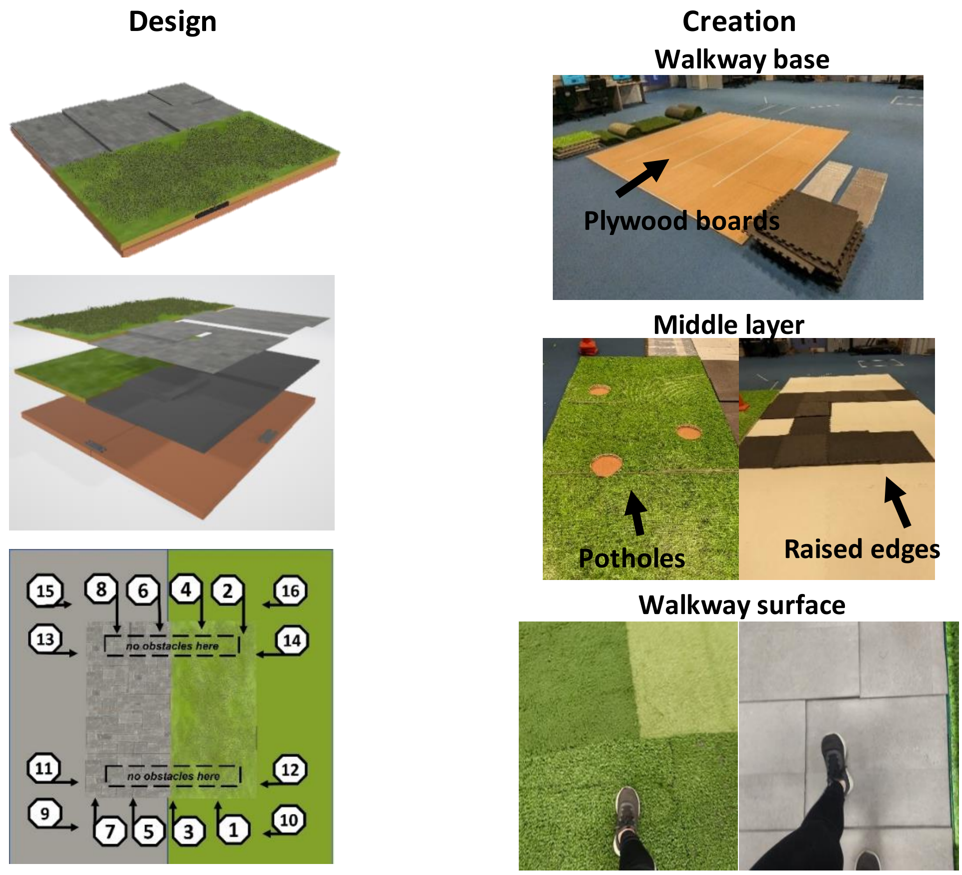


Figure 5.1. *LEFT: Design of bespoke walkway using Paint 3D (Microsoft Corporation, 2018) and RIGHT: Photographs taken during manual creation of the bespoke challenging walkway.*

Figure 5.2. *LEFT: Bespoke challenging walkway consisting of 6 x 3 m artificial grass and 6 x 3 m artificial pavement surface and two TV screens at the end of the walkway, with example walking paths shown by footsteps. RIGHT: Two still images from example distraction videos that were played on TV screens positioned at the end of each walkway (top: van driving past and beeping, bottom: dog barking in field)*

5.2.3 Procedure

Children and parents or guardians were invited to attend the Biomechanics Research Laboratory at Liverpool John Moores University for two hours. Informed consent and assent were obtained in writing from parents/guardians and children, respectively. Ethical approval for this study was granted by Liverpool John Moores University Research Ethics Committee (23/SPS/029). Following informed consent/assent, personal information including age, sex, GMFCS and cerebral palsy diagnosis were recorded.

5.2.3.1 Fall history

Children were asked the following questions about their previous history and frequency of trips and falls (Boyer and Patterson, 2018):

1. Is tripping or falling an issue for you?
2. How often do you experience a (at least one) [trip/fall]?
    a. Never b. Monthly c. Weekly d. Daily
3. How many [trips/falls] occur during that time period (if monthly, weekly or daily)?
4. Where do these [trips/falls] typically occur?
5. Why do you think that you [trip/fall]?).
6. What impact do falls have on your daily life if any?
    a. How does that make you feel?
    b. Do you avoid any activities because of tripping or falling?

5.2.3.2 Visual and cognitive assessment

Visual and cognitive assessments were completed at the start of each data collection session to assess eligibility of participations (section 5.2.1) and as additional outcome measures. Visual acuity and contrast sensitivity was assessed for each child using the Freiburg Visual Acuity Test (FrACT 10) (Bach, Graefes Arch Clin Exp Opthalmol, 2007; Bach, Optom Vis Sci, 1996). FrACT is a computer-based assessment tool. Each child was seated two metres away from a computer screen that was positioned at eye-level for each child, then conducted two C optotype tests. The child was asked to press the corresponding C shape on a handset that appeared on the screen at either differing sizes or differing contrasts. Visual field of view was assessed for each child using a quadrant test. The field of view was divided vertically and horizontally in line with the nose and eyes, respectively. Each child fixated on the lead investigator's index finger held at the centre of the visual field, then asked to report the number of fingers held up in each of the four quadrants of the visual field. A cognitive assessment was then conducted using the Trail Making Test A (TMT-A) and B (TMT-B). Each child was required to connect a series of ascending numbers on paper for the TMT-A (e.g. 1 – 2 – 3 – 4), then connect a number to corresponding letter for TMT-B (e.g. 1 – A – 2 – B), with time of completion recorded. Executive function time was calculated as TMT-B time (seconds) minus TMT-A time (seconds).

5.2.3.3 Anxiety and balance confidence

Generalised anxiety, and fall-specific confidence were measured using a series of questions adapted from the Movement Specific Reinvestment Scale (Masters et al., 2005). Specific questions are shown in Appendix 8. Prior to starting the first trial on pavement and grass, children were asked how confident they felt about "walking along the challenging walkway, without falling or losing balance", rated on a scale of 1-100%. At the end of the first pavement and grass trials in both distracted and non-distracted conditions, children were asked how fearful and stable they felt during the trials, rated on a scale of 1-100%.

5.2.3.4 Walking trials

Prior to starting experimental trials, participant height, mass, leg length, knee width and ankle width were recorded. A 10-camera Qualisys Arqus (Qualisys, Gothenburg, Sweden) motion capture camera system captured movement of children walking along the bespoke walkway using 40 reflective markers that were placed on anatomical landmarks of the body (Figure 5.3). Eighteen markers were placed on the feet, lower limbs and hips, following a modified Helen Hayes model (Kadaba et al., 1990), which was adapted for wearing of shoes and orthoses. Additional markers were placed on the trunk, arms and head for accurate tracking of the COM and a cluster of 3 markers were placed on each foot for tracking of the foot segment. Virtual landmarks were created at the most anterior and posterior edges of the base of the shoe, using a digi pointer as described in section 5.2.5 for walkway landmarks. The most anterior edge was placed at the front centre of the shoe tip, for children that presented in-toeing, this was moved laterally (Figure 5.4). The posterior edge was placed at the centre of the heel.

Figure 5.3. *A typically developing child with reflective markers attached and wearing eye tracking glasses, phone for use with eye trackers can be seen attached to participants' right arm. Permission to use image granted by parent.*

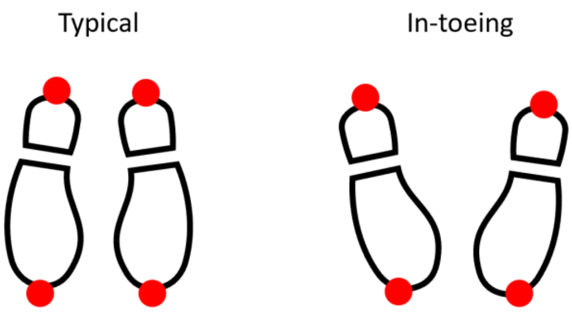


Figure 5.4. *Placement of virtual landmarks on the base of the shoe for a typical stance (left) and an in-toeing stance (right). Icons sourced from Microsoft Stock Images.*

Children completed 18 walks along the bespoke challenging walkway in different directions (shown by numbers in Figure 5.2), which were randomised trial-by-trial using a custom MATLAB script (Appendix 7). Each child was assigned a random combination of three of the four walking paths on grass (paths 1 to 4, Figure 5.1) and pavement (paths 5 to 8, Figure 5.1). Children walked over the allocated grass and pavement paths under both distracted and non-distracted conditions. Children would therefore only ever walk over the same path twice, for distracted and non-distracted conditions and the order of these paths were randomised. During distracted trials, a video was played on a TV screen at the end of the walkway in which children were walking towards. During non-distracted trials, the TV screen remained blank. An additional ('catch') trial was undertaken in a different direction without any potholes or raised surfaces (walking paths 9 to 16, Figure 5.1). Catch trials were placed after every two trials, to reduce the learning effect of where each pothole or uneven surface was situated during other trials. An example order following the paths specified in Figure 5.1 is as follows:

- Trial 1: Path 1 (non-distracted)
- Trial 2: Path 6 (non-distracted)
- Trial 3: Path 9 (catch)
- Trial 4: Path 1 (distracted)

Participants carried out a familiarisation walk around the perimeter of the walkway before beginning walking trials, to get accustomed to the type of surface (AstroTurf and vinyl flooring). All walks took place with the lead investigator and a parent or guardian walking alongside the child participant.

5.2.3.5 Eye tracking

Children were asked to wear a pair of eye tracking glasses (Pupil Invisible, Pupil Labs, Berlin, Germany), used to determine where and when children look while walking with and without the distraction. The glasses contained a small camera in the frame to record the field of view each child had and one small camera under each eye that tracked pupil position and recorded where each child was looking. The eye tracking glasses were connected to a mobile phone (OnePlus 8, Android), that was attached to the child participant's arm using a cohesive bandage wrap. A button was tapped on the mobile phone at the start and end of each trial to start and end recording with the eye trackers.

Fall history, balance confidence and fear, visual and cognitive assessment scores, physical measurements and observations during the walkway trials were all recorded on paper during data collection sessions (Appendix 8).

5.2.5 Data analysis

Motion capture data were labelled using Qualisys Track Manager (QTM 2023.2, Qualisys, Sweden). A model was created in Visual 3D (v2024.07.2, C-Motion, Canada) for estimations of segment position, and centre of mass. Virtual landmarks were created of key challenging walkway features (uneven pavement edges and grass potholes) using a digi pointer with a spring compression mechanism and reflective markers with known distances. Trials were captured of the lead investigator placing the tip of the digi pointer on all key features (e.g. the centre and edges of a pothole) and compressing the digi pointer, to create a virtual landmark later in Visual 3D of the locations of walkway features when each child negotiated the walkway. Virtual landmarks were filtered with a 0.5 Hz low-pass Butterworth filter to eliminate any small noise from tracking that could be magnified in later calculations (e.g. foot clearance). Events were created at heel strike for both the left and right feet using the minimum centre of gravity (COG) velocity of each foot in the Z direction, adapted from O'Connor et al. (2007). Due to the high variability, each event for all children was manually adjusted for accuracy, as suggested for similar methods using vertical foot velocity with pathological populations (Bruening and Ridge, 2014) and for uneven surface interactions (Eckardt and Kibele, 2017), e.g. gait cycles where a perturbation or recovery step occurred.

Spatiotemporal parameters including walking speed, step width and step length were extracted for each type of walking condition (grass and pavement, distracted and non-distracted). Step width was calculated as the mediolateral (X direction) distance between the left and right position of the foot COG at every heel strike. Step length was calculated as the distance between the proximal end of a foot at heel strike to the proximal end of the contralateral foot at heel strike. All parameters were adapted for direction of walking on the walkway (e.g. negative or positive relative to the origin).

Stability was assessed with MOS as described in Chapter 1, using extrapolated COM (XCOM) (Hof et al., 2005) and adapted depending on walking direction in relation to the origin of the walkway:

MOS = XCOM – BOS
Where:

- *XCOM =* $\dfrac{\text{COM + COM Velocity}}{\sqrt{(g/\ l)}}$
- *COM = full body centre of mass*
- *g = gravitational acceleration, 9.81 m/*s^2
- *l = pendulum length, the 3D distance between the respective ankle joint centre (L or R) and COM*

Anterior BOS was defined by the most anterior marker on the foot (left or right first metatarsal head), lateral BOS was defined by the most lateral marker on the foot (left or right lateral malleolus). Positive MOS implies XCOM behind the anterior or inside the lateral BOS and therefore indicates stability, negative MOS implies XCOM ahead or outside the anterior or lateral BOS, respectively, therefore indicates instability.

Parameters indicative of fall risk (foot clearance and foot placement) were extracted relative to features of the challenging walkway in Visual 3D (v2024.07.2, C-Motion, Canada). Foot clearance was calculated as the difference between the vertical position of the left or right virtual toe marker and the vertical position of the closest virtual landmark on the walkway, when the anterior posterior difference between the two points equalled zero (Figure 5.5a). Foot placement was calculated as the 3D COG position of the left and right feet during heel strike of the same foot relative to the 3D position of the closest virtual landmark on the walkway, e.g. 3D position of the COG of the left foot at left heel strike to a pothole centre (Figure 5.5b). Kinematic data were filtered using a 6 Hz low-pass Butterworth filter, figures were created in MATLAB (R2024a, MATLAB, MathWorks, UK).

a) Foot clearance b) Foot placement

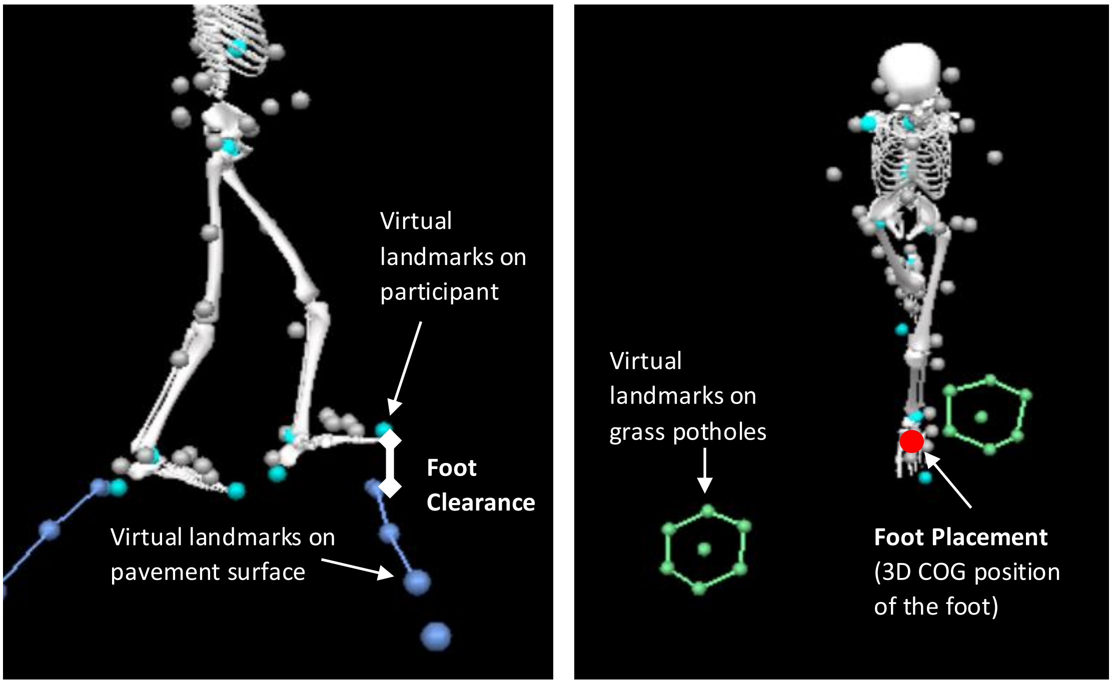


Figure 5.5*. Schematic of a) foot clearance and b) foot placement*

Eye tracking data were analysed using Pupil Player (v3.5.1, Pupil Labs), by stepping through each frame of video data and annotating the fixations on either a particular walkway feature of interest, e.g. a pothole that has been stepped in, or the distraction screen. Eye tracking data were time-synchronised to 3D motion capture data using a verbal cue at the start of each trial. After starting the recording of the eye tracking device, the lead investigator gave a countdown (e.g. 3…2…1…go), then 3D motion capture began recording. Eye tracking recordings with audio were then later synchronised to start at the same verbal cue. Percentage and timing of fixations on walkway features and on the distraction screen were output into Microsoft Excel (Microsoft 365, Microsoft Corporation Washington, USA), by calculating the time looking at a distraction or a walkway feature as a percentage of the time between the start of the trial and an occurrence of instability.

All trials were observed for potential occurrences of instability (e.g. stepping into a pothole) and these were matched in post-processing to instances of MOS instability. These instances were then grouped according to the type of interaction with a walkway feature and summarised as individual case-examples of instability on the walkway.

5.2.6 Statistical analysis

All variables including: participant characteristics (age, height, mass, visual acuity, contrast sensitivity, quadrant score, TMT-A, TMT-B, executive function), spatiotemporal parameters during each trial (walking speed, step width and step length) and confidence and anxiety measures (balance confidence, feelings of fear and feelings of stability), were visually inspected for normality using box plots and measures of skewness and kurtosis, then checked for homoscedasticity using plots of residual vs fitted values. Statistical analysis was conducted using MATLAB (R2024a, MATLAB, MathWorks, UK).

Differences for participant characteristics were analysed between groups (CP and TD) using a Mann-Whitney U test to assess for differences between groups for non-parametric data, as data showed non-normality. Effect sizes were calculated using Cohen's D (d), where small differences = 0.2, moderate differences = 0.5 and large differences = 0.8.

Spatiotemporal parameters were analysed between groups (CP and TD) and within groups for different walkway conditions (grass distracted, grass non-distracted, pavement distracted, pavement non-distracted). Walking speed, step width and step length were assessed each with a two-way mixed design ANOVA. Mauchly's test of sphericity was conducted on each variable and when data violated sphericity, a Greenhouse-Geisser (<0.75) or Huynh-Feldt (>0.75) epsilon correction was used. Significant main effects were followed with post-hoc tests using a Bonferroni correction for multiple comparisons. Effect sizes were calculated for main effects with partial eta squared (η^2), where small effects = 0.01, medium effects = 0.06 and large effects = 0.14.

Balance confidence, feeling of fear and feeling of stability showed non-normality and high levels of skewness and kurtosis. Therefore, a Kruskal-Wallis test was used for comparing between group means and Friedmans test was used for within group comparison as non-parametric alternatives to a mixed methods ANOVA.

5.3 Results

5.3.1 Participants

There were no significant differences for age, height, mass, contrast sensitivity, quadrant test score and TMT-B between children with CP and TD children. Children with CP showed significantly worse visual acuity, compared to TD children and took significantly longer to complete TMT-A compared to TD children (Table 5.1).

5.3.1 Fall history

Falls history questionnaires revealed that children with CP experience more falls and near-falls compared to TD children. Self-reported reasons for trips and falls in children with CP included walking in uneven environments, not noticing challenging features of the environment and tripping over their own feet. For TD children, self-reported reasons for trips and falls were most often due to playing sport (e.g. football) (Table 5.2). When asked about the impacts that falls have on daily life, children with CP most often expressed feelings of embarrassment, frustration or similar, whilst also expressing that this is part of normal life and they typically get back up and carry on. TD children expressed similar views of getting back up and carrying on, but also regularly described pain or injury as a negative impact of falls.

5.3.1.1 Fall occurrence

Three of 10 children with CP reported that they fall at least once a day, with the highest being five per day, two children with CP suggested they fall at least once a week. TD children reported no falls daily, only one TD child suggested they fall once a week and six out of nine suggested they fall once a month or less.

5.3.1.2 Trip occurrence

Six out of 10 children with CP reported that they experience a trip at least once a day. One child reported experiencing 10 to 15 trips per day. Two TD children reported tripping once a day, five out of nine TD children reported a trip once a week or less.

Table 5.2. *Summary of answers to falls history questionnaire. Impact of falls were categorised into positive (green), neutral (yellow) and negative (red) responses.*

Falls	**Trips**	**Where falls occur**			**Why falls occur**				**Impact of falls**					
		Outside	Inside	School	Behaviour	Environment	Functional	History	Laugh or feel 'powerful'	'Get back up and carry on'	Cause to be more cautious	Avoid activities	Feel shocked, embarrassed, angry or sad	Have pain or injury
Children with CP														
max 5 per day	10-15 per day	•	•		Tiredness Running Not looking	Obstacles Kerbs				•			•	
1-2 per day	2 per day	•	•	•	Running Tiredness	Unseen obstacles Loud noises Other people	Over own feet			•	•P		•	
5 per week	2-3 per day	•	•		Don't see things	Unseen uneven surfaces without signs (pavements/kerbs/lips of the carpet)	Over own feet	Can walk without sticks or frame. Uses assistance outside and on uneven surfaces. Less falls since operation, being older and more aware.	•	•	•	•	•	
2 per week	1-3 per day	•			Not paying attention Tiredness	Uneven surfaces (kerbs/thick grass) Unseen obstacles	Poor balance	Trip more when younger Depends on the day or activity		•	•		•	
3-4 per month	1-2 per week	•	•		Lack of focus Not looking ahead	Distractions House obstacles	Over own feet	Careful walking to the shops or park	•	•				
2 per month	1 per day	•			Don't see things Not aware Tiredness. Running	Unseen uneven surfaces (kerbs/pavestones/tree roots) Obstacles	Don't lift foot Footwear Over own feet	Less falls since operation (less toe walking) Lots of parent intervention		•		•	•	•
1 per month	3 per month	•		•	Running		Over own feet			•	•			
1 per month	2 or 3 per day	•		•		Other people Uneven surfaces (gravel) Obstacles	Clumsy Poor balance		•	•		•		
< 1 per month	3 per week	•	•	•		School flooring Raised surfaces Distractions	Uncomfortable footwear/Splints	More falls when young				•	•	
Never (rarely)	1 per month	•		•	Not watching or looking behind Running	Other people		Better balance since ear operation					•	

Table 5.2. *Continued*

Typically Developing Children

3 or 4 per month	3 or 4 per week	•		•		Other people Uneven pavements		Running		•			•
1 or 2 per month	1 per day			•	Distracted		Shoes			•		•	
1 or 2 per month	1 or 2 per month				Hard to notice potholes Not concentrating Not looking	Other people Uneven pavements Grass potholes	Flat feet [P]	Football/Sports					•
1 per month	1 per day	•	•		Not looking, With friends On phone	Potholes or uneven ground during football		Football		•			
1 per month	1 or 2 per week	•		•	Not looking Being distracted	Obstacles						•	
1 per month	1 or 2 per month			•		Slip over wet grass during sports		PE, basketball, football, rugby					•
< 1 per month	1 per week		•					Gymnastics		•			•
Never	1 or 2 per month		•	•		Rocks if playing		Running/playing in playground				•	
Never	Never			•		Other people Busy corridors			•	•			

5.3.2 Interactions with the walkway causing instability

Children with CP had more occurrences of instability, shown through visual observations and confirmed by MOS, when walking over the challenging walkway (N = 42) compared to TD children (N = 4). Most of these occurrences (Children with CP = 37, TD children = 3) happened due to a destabilising interaction with walkway features, for example instability due to a step into a pothole. All interactions from children with CP can be seen in Appendix 9. For children with CP, 17 out of 37 destabilising interactions with walkway features were with a distraction present on screen. For TD children, one out of three interactions leading to instability was with a distraction present on screen.

5.3.2.1 Interaction 1: **Trip over a pavement edge**

5.3.2.1.1 Summary of mechanism

Two children with CP experienced a trip over a pavement edge. This occurred six times with one child demonstrating four trips. In all cases balance was recovered following the trip. For both children, a trip involved contact between the swing leg and leading pavement edge, but the timing of contact during swing phase differed; one participant experienced contact with the edge during initial swing, the other during mid-swing. Typically, this contact resulted in a change to anterior MOS for one gait cycle, an example during both initial- and mid-swing is shown in Figure 5.6. Each type of avoidance and accompanying gaze fixations are shown in Table 5.3a and Visual 3D appearances of each avoidance in Table 5.3b. All MOS figures are shown in Appendix 9. On one occasion (Table 5.3a, #5), the foot contacts the pavement edge, but MOS showed little difference to other gait cycles during the trial.

5.3.2.1.2 Influence of distraction

Four out of six trials where contact with a pavement edge occurred were experienced with no distraction. Two were distracted, of which one was visual only. Both children that demonstrated numerous trips on the walkway wore glasses, which caused a disturbance to eye tracking data, therefore fixation information were not available. In earlier questionnaires about daily activity, both children mentioned not looking as a reason for experiencing trips and falls day-to-day. One participant (#3, #4, #5, #6, Table 5.3a), also spoke of a recent experience tripping over a pavement edge because they did not see it.

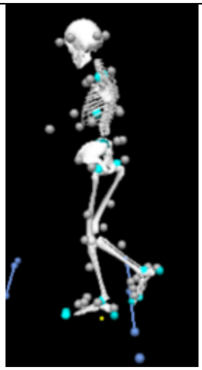
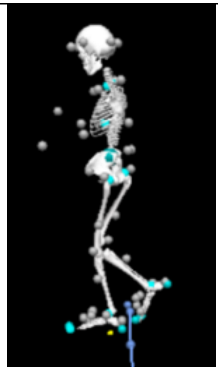
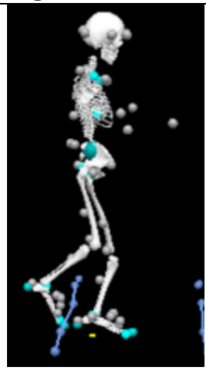
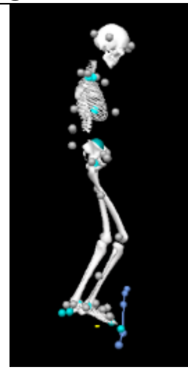
5.3.2.1.3 Typically developing children

Typically developing children did not demonstrate any trips over a pavement edge on the walkway and showed little change in MOS when walking on pavement (Figure 5.6).

Table 5.3a. *Descriptions of each interaction with the walkway leading to a trip demonstrated by children with CP. # = Occurrence of instability number*

#	Description	Type of trial	Fixations
1	The foot contacts the third pavement edge during mid-swing. Anterior MOS decreases on the left prior to contralateral heel strike and remains negative at the following right heel strike.	Non-distracted	N/A
2	The foot contacts the first pavement edge during mid-swing. Anterior MOS on the right is delayed from entering a positive value at heel strike.	Distracted (no sound)	N/A
3	The right foot contacts the first pavement edge during initial swing. Anterior MOS is reduced prior to right heel strike in following steps.	Non-distracted	N/A
4	The right foot contacts the first pavement edge during initial swing. Anterior MOS for the following right heel strike is reduced.	Non-distracted	N/A
5	The foot contacts the first pavement edge during early swing. Step width is increased following this with no obvious changes to MOS during the trip.	Non-distracted	N/A
6	The foot contacts the first pavement edge during early swing. Anterior MOS on the right is reduced at ipsilateral heel strike following the trip compared to other gait cycles.	Distracted	N/A

Table 5.3b. *Visual 3D appearances of interactions with the pavement edge demonstrated by children with CP, grouped by phase of gait cycle*

Initial Swing				Mid-Swing	
					

A.

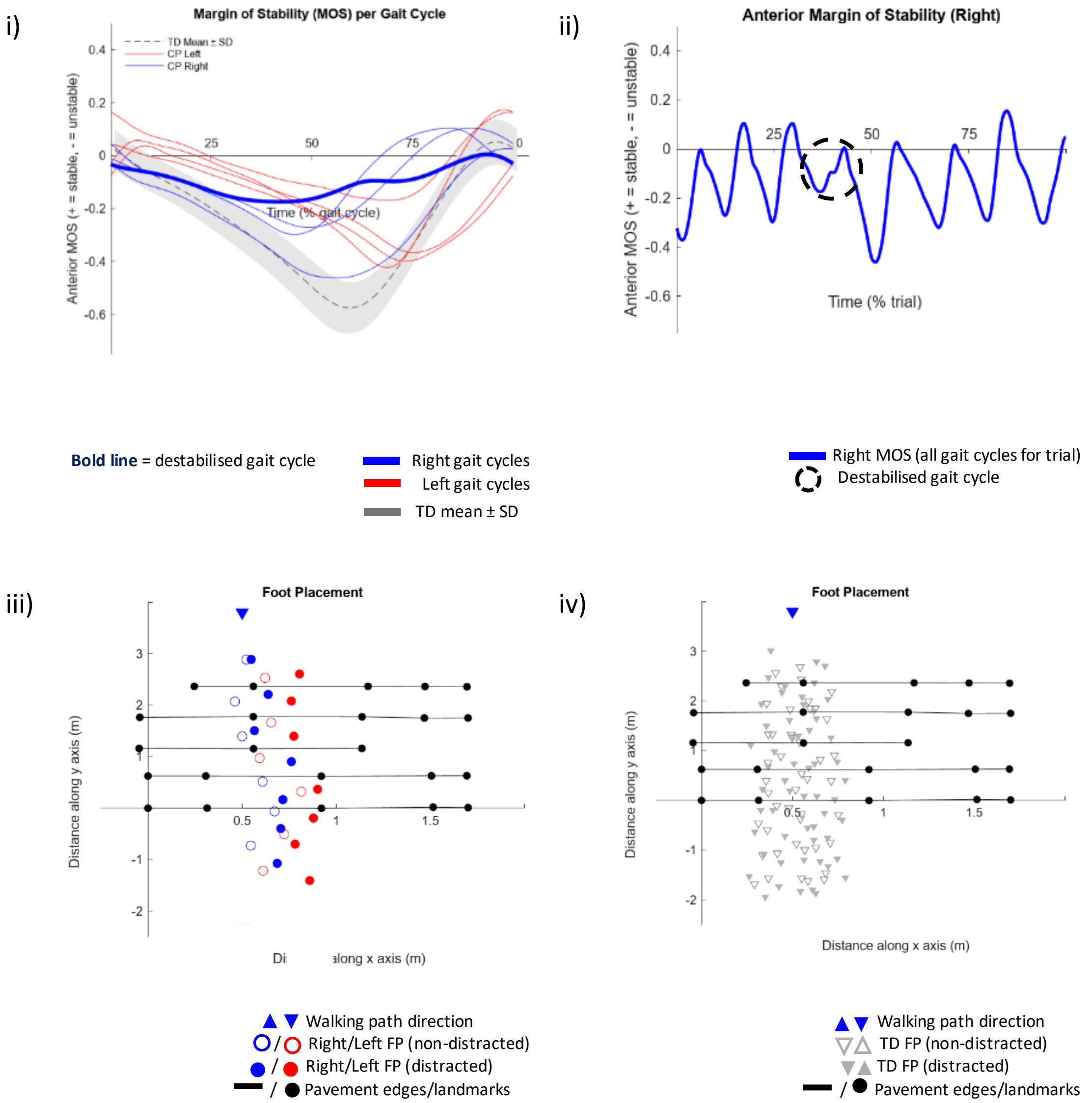


Figure 5.6. A) *An example trial of instability for a child with CP (#2) showing a change in anterior MOS when tripping over the third pavement edge during mid-swing. i) Anterior MOS for each gait cycle during the trial for a child with CP and all TD children of the same walking path, ii) Anterior MOS over the entire trial for the child with CP, iii) Foot placement for a child with CP over the pavement during the trial, iv) Foot placement (FP) of TD children along the same walking path.*

B.

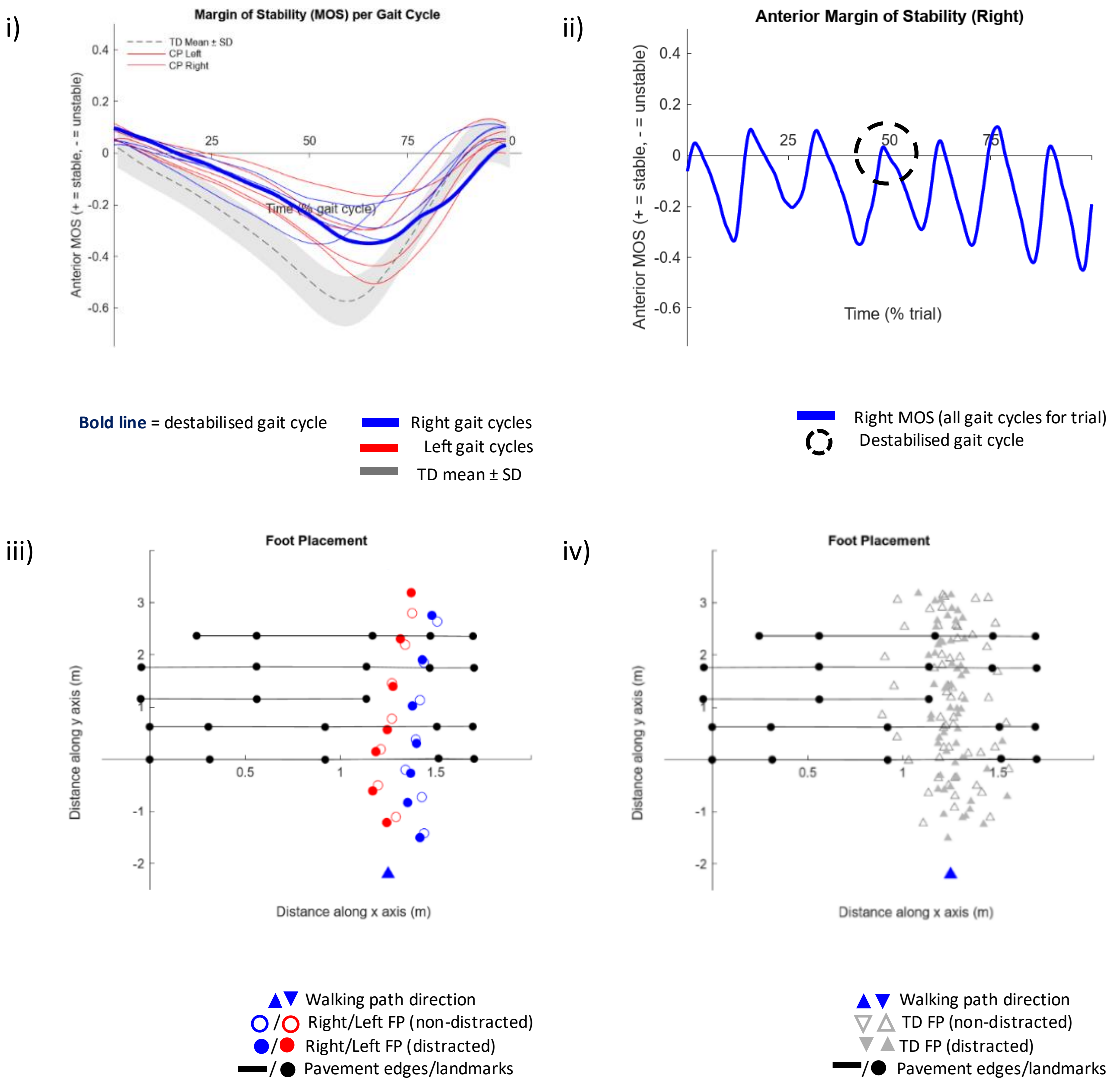


Figure 5.6. B) *An example trial of instability for a child with CP (#4) showing a change in anterior MOS when tripping over the first pavement edge during initial swing. i) Anterior MOS for each gait cycle during the trial for a child with CP and all TD children of the same walking path, ii) Anterior MOS over the entire trial for the child with CP, iii) Foot placement for a child with CP over the pavement during the trial, iv) Foot placement (FP) of TD children along the same walking path.*

5.3.2.2 Interaction 2: **Step onto a pavement edge**

5.3.2.2.1 Summary of mechanism

Five children with CP stepped onto a pavement edge leading to instability. For most (n = 5) this involved an anterior perturbation to stability (#1, #2, #3, #4, #5, Table 5.4a), including two trials that show both anterior and lateral instabilities (#2, #5). On one occasion only lateral instability was observed (#6). For the instances where lateral and anterior instability were shown, children stepped on multiple edges during the trial. Typically, an anterior instability involved an acceleration of the COM forwards, leading to reduced anterior MOS at the following heel strike. Each type of avoidance and accompanying gaze fixations are shown in Table 5.4a and Visual 3D appearances of each avoidance in Table 5.4b. An example of a change to anterior MOS can be seen in Figure 5.7, all MOS figures are shown in Appendix 9.

5.3.2.2.2 Influence of distraction

Two occurrences of instability following stepping onto a pavement edge were distracted, four were non-distracted. Three of the five children that experienced instability following stepping onto a pavement edge wore glasses, therefore fixation data were unavailable. In one trial (#3) the child was talking through the trial, suggesting they were distracted. Two children showed late fixations on the pavement edge where instability occurred (61% and 54% of the way through trial prior to unstable gait cycle) and showed little time fixating on the pavement edge (0.4 and 0.5 seconds).

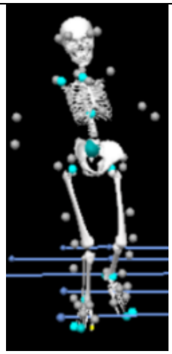
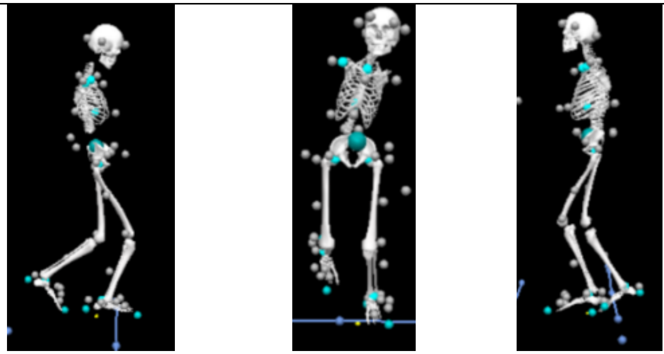
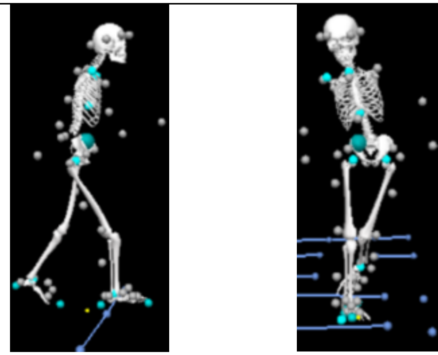
5.3.2.2.3 Typically developing children

The TD children demonstrated less variable and more stable MOS when walking on the pavement surface. Out of 54 walks across pavement, all TD children demonstrated stepping onto a pavement edge at least once across 29 walks (12 distracted, 17 non-distracted). Of these 29 trials, one TD child showed lateral instability after stepping onto a pavement edge. Visual 3D appearance of the interaction and MOS are shown in Figure 5.8. This trial was a non-distracted trial, but the child did not spend any time during the trial looking at the specific pavement edge.

Table 5.4a. *Descriptions of each interaction with the walkway when stepping onto a pavement edge demonstrated by children with CP. # = Occurrence of instability number*

#	Type of instability	Description	Type of trial	Fixations
1	Anterior	The right foot steps onto the fourth pavement edge, prompting a single short step with the opposite leg in the axis of perturbation. MOS enters negative in the anterior direction at ipsilateral heel strike and remains lower than other gait cycles at contralateral heel strike.	Non-distracted	N/A
2	Lateral and Anterior	Multiple pavement edges are stepped on throughout the trial. Anterior MOS becomes progressively more negative at heel strike. Lateral MOS is reduced during the time on the walkway.	Non-distracted	N/A
3	Anterior	The left foot steps onto the first pavement edge. COM velocity and forward trunk lean increases, causing a more negative anterior MOS at contralateral heel strike, step width increases to recover.	Distracted	N/A
4	Anterior	The right foot steps onto the second pavement edge. Anterior MOS is reduced at the following heel strike. A trip is also seen in subsequent steps, showing again reduced anterior MOS at heel strike.	Non-distracted	Fixation on edge: 6% (0.4 s) Time of first fixation on edge: 54% (2.8 s prior to unstable gait)
5	Lateral and Anterior	The left foot steps onto the fourth pavement edge, then crossing of limbs is seen, then the right foot steps on the final pavement edge, leading to crossing of limbs again. Lateral MOS and anterior MOS is reduced.	Non-distracted	Fixation on edge: 8% (0.5 s) Time of first fixation on edge: 61% (2.7 s prior to unstable gait)
6	Lateral	The right foot steps onto the final pavement edge, lateral MOS at this time is reduced for a full gait cycle compared to others.	Distracted	N/A

Table 5.4b. *Visual 3D appearances of interactions with the pavement edge demonstrated by children with CP, grouped by type of instability*

Lateral Instability	Anterior Instability	Lateral and Anterior Instability
		

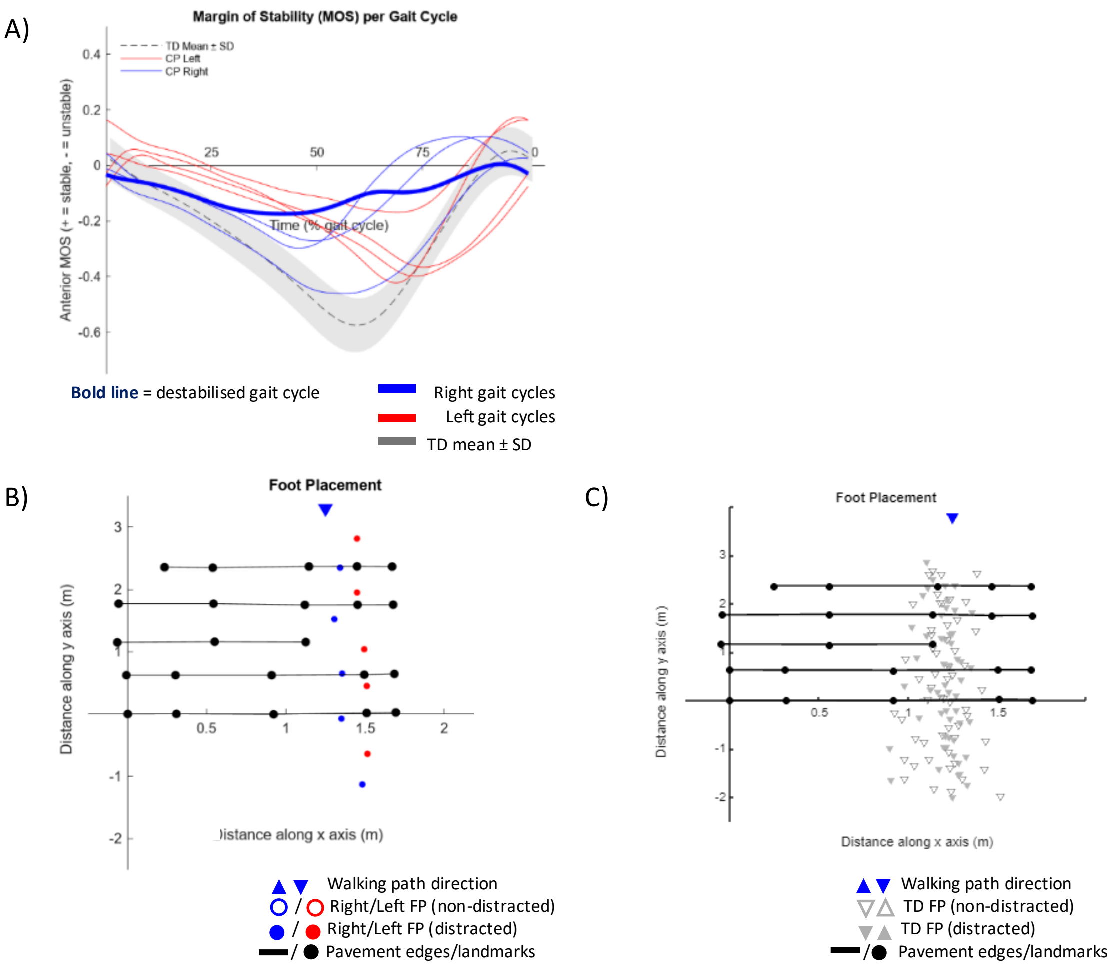


Figure 5.7. *An example trial (instability #1) where one child with CP showed stepping onto a pavement edge. A) Anterior MOS for each gait cycle during the trial, B) Foot placement stepping over pavement for the same trial C) Foot placement for TD children along the same walking path.*

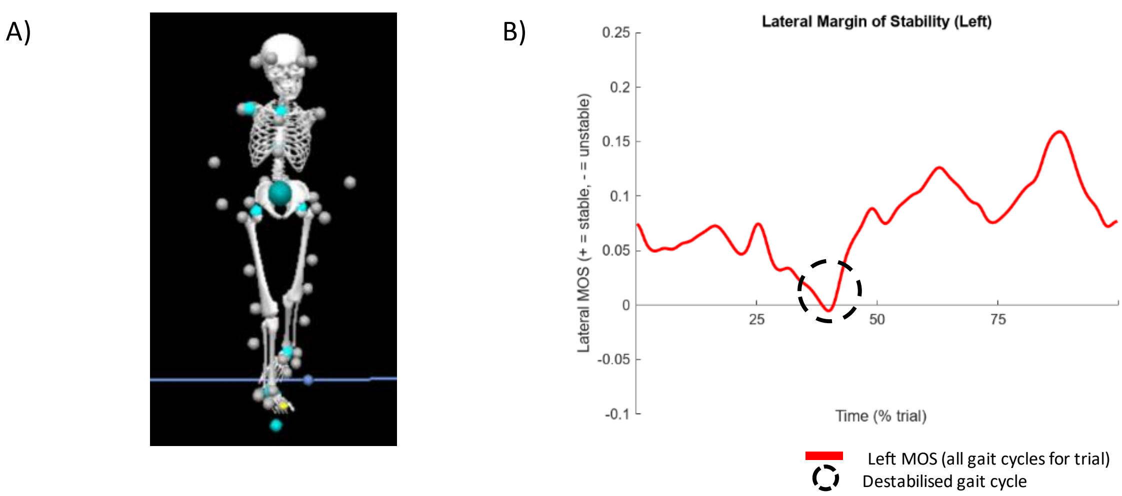


Figure 5.8. *A) Visual 3D image showing the left foot stepping onto the pavement edge (blue line), B) Left lateral MOS for the entire trial.*

5.3.2.3 Interaction 3: **Step into a pothole**

5.3.2.3.1 Summary of mechanism

Four children with CP stepped into a pothole leading to subsequent lateral instability. For two children, this also led to a decrease in anterior stability (#1, #2). For some steps into a pothole, a clear recovery strategy was evidenced e.g. a short, faster step. Although MOS was disturbed, a step into a pothole rarely caused negative MOS, suggesting successful recovery strategies. Each type of avoidance and accompanying gaze fixations are shown in Table 5.5a and Visual 3D appearances of each avoidance in Table 5.5b. An example of a change to lateral MOS can be seen in Figure 5.9, all MOS figures are shown in Appendix 9.

5.3.2.3.2 Influence of distraction

Four occurrences of instability (by stepping into a pothole) were distracted, two were non-distracted. Two of the four children that experienced instability following stepping into a pothole wore glasses, therefore fixation data was unavailable. In trial #5 the child was observed looking at the distraction and in trial #6 the child stated that they did not see the pothole they stepped into. Where data was available, eye tracking shows no fixations on the potholes causing the instability, and two children spent 72% and 70% of the time between the start of the trial and the unstable gait cycle looking at the distraction.

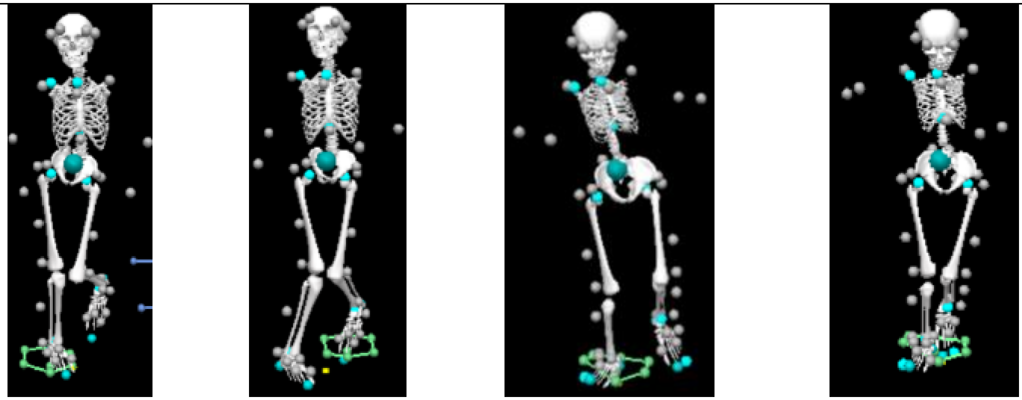
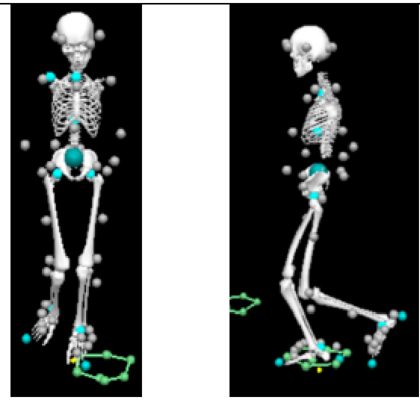
5.3.2.3.3 Typically developing children

The TD children demonstrated less variable, more stable MOS when walking on the grass surface. They stepped into a pothole during 27 out of 54 trials. Of these trials, two TD children showed lateral instability, one included anterior instability. Visual 3D appearance of the interactions and MOS are shown in Figure 5.10. One of these trials was distracted, with the child spending 6% of the time from the start of the trial to the unstable gait cycle looking at the distraction and 1% looking at the pothole, the second trial was not distracted, and the child wore glasses therefore fixation data was unavailable.

Table 5.5a. *Descriptions of each interaction with the walkway when stepping into a pothole demonstrated by children with CP. # = Occurrence of instability number*

#	Type of instability	Description	Type of trial	Fixations
1	Lateral and Anterior	The lateral edge of the left foot entered a pothole, lateral MOS remained close to zero rather than the typical increasing pattern for that gait cycle. Anterior MOS was reduced prior to contralateral heel strike.	Distracted	Fixation on distraction: 72% Fixation on pothole: 0% (0 s)
2	Lateral and Anterior	The right foot stepped into a pothole. Negative anterior MOS occurs prior to ipsilateral heel strike, step width and lateral MOS then reduced.	Non-distracted	N/A
3	Lateral	The right foot stepped into a pothole, a response with arms is seen followed by reduced lateral MOS for two full gait cycles.	Distracted	Fixation on distraction: 70% Fixation on pothole: 0% (0 s)
4	Lateral	The left foot steps into a pothole, visible instability shown and lateral MOS is reduced.	Distracted	Fixation on distraction: 0% Fixation on pothole: 25% (0.6 s) Time of first fixation on pothole: 66% (0.8 s prior to unstable gait)
5	Lateral	The right foot enters a pothole and a reduction in lateral MOS is seen but remains above zero.	Distracted	N/A
6	Lateral	The left foot steps into the pothole. Lateral MOS is reduced for a prolonged time compared to other gait cycles, and short fast recovery steps are seen.	Non-distracted	N/A

Table 5.5b. *Visual 3D appearances of interactions with the pothole demonstrated by children with CP, grouped by type of instability*

Lateral Instability	Lateral and Anterior Instability
	

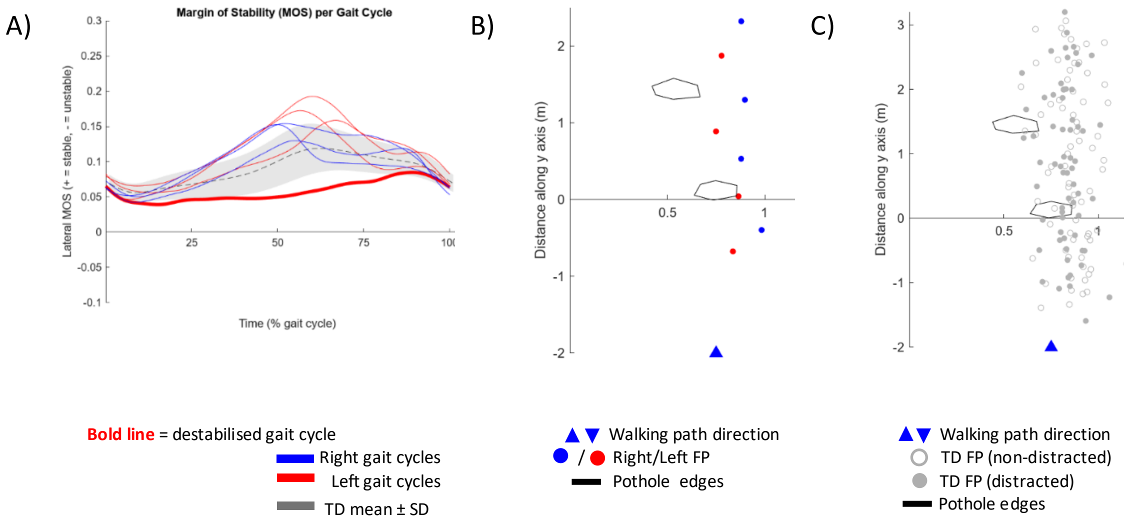


Figure 5.9. *An example trial (instability #1) where one child with CP stepped into a pothole. A) Lateral MOS for each gait cycle during the trial, B) Foot placement when stepping into the pothole for the same trial C) Foot placement for TD children along the same walking path.*

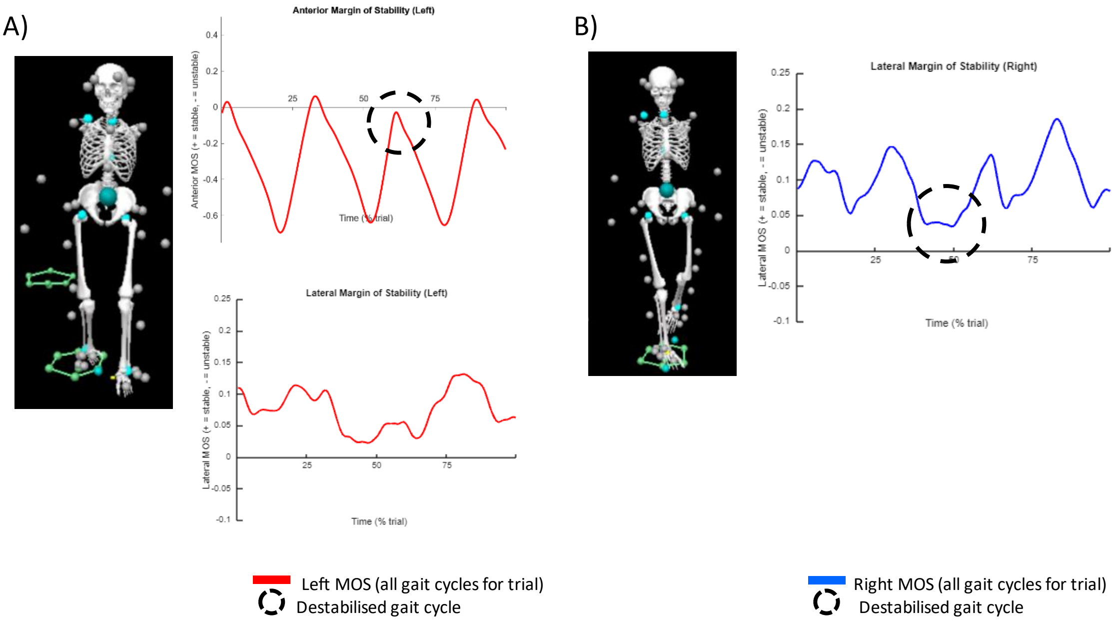


Figure 5.10. *A) First example of instability for TD child: Visual 3D image showing the right foot stepping into a pothole (green) (left) alongside left anterior and lateral MOS for the entire trial (right), B) Second example of instability for TD child: Visual 3D image showing the right foot stepping into a pothole (green) (left) alongside right lateral MOS for the entire trial (right).*

5.3.2.4 Interaction 4: **Avoiding a pothole**

5.3.2.4.1 Summary of mechanism

Avoidance of grass potholes was the most frequent cause of instability for children with CP (N = 10). This mostly occurred in a mediolateral direction and was demonstrated by seven different children. Children with CP often changed their foot placement late in the approach to a pothole either medially (crossing limbs) or laterally (increasing step width), resulting in variable, often negative, lateral MOS. On two occasions, children with CP changed their walking path to avoid a pothole with an early adjustment to foot position, which caused reduction in lateral MOS for one gait cycle. Each type of avoidance and accompanying gaze fixations are reported in Table 5.6a and Visual 3D appearances of each avoidance in Table 5.6b. An example of a change to lateral MOS can be seen in Figure 5.11. All MOS figures are shown in Appendix 9.

5.3.2.4.2 Influence of distraction

Six trials that evidenced an avoidance of a pothole leading to instability were distracted trials (#1, #2, #4, #5, #7, #10). One child opted out of eye tracking glasses (#8 and #9), one child wore glasses (#3) that caused an offset in eye tracking, therefore fixation data was unavailable. On two occasions with lateral avoidance (#6 and #7) children did not look at the pothole they avoided prior to the heel strike before the gait cycle of instability (0%). Two interactions (#5 and #10) showed 0% fixation time on the distraction and longer time during the trial (61% and 28%) looking at the pothole, while also looking at the pothole much earlier in the trial (2.1 seconds prior to unstable gait cycle) compared to other trials. Conversely interaction (#1 and #2) showed longer fixation on the distraction (21% and 22% of the trial prior to unstable gait cycle), less fixation on the pothole (19% and 19% of the trial prior to unstable gait cycle), with the first fixation on the pothole occurring much later during the trial (62% and 48%). The longest fixation on a pothole at the earliest time in the trial (#5) led to a change in walking path, that occurred earlier than the lateral or medial avoidances.

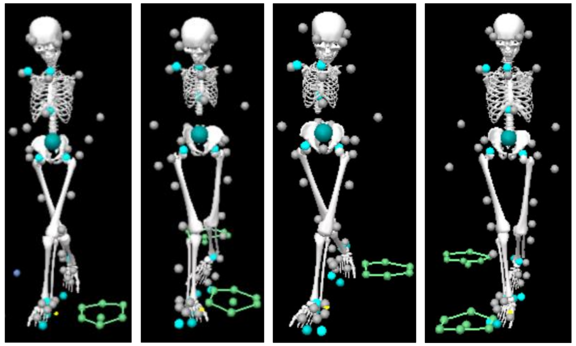
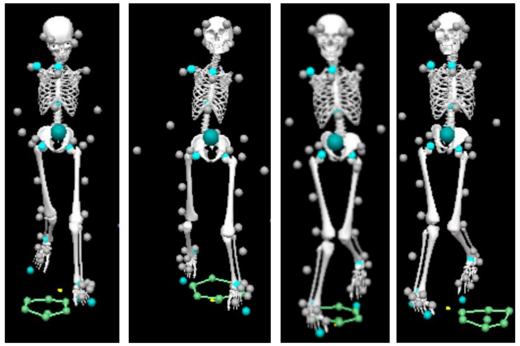
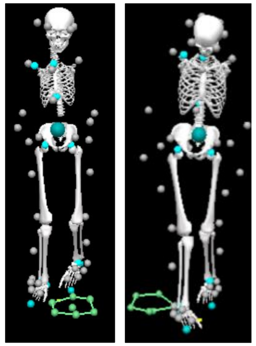
5.3.2.4.3 Typically developing children

Typically developing children demonstrated 27 trials on grass in which they did not step into a pothole. During these trials, TD children did not show any late mediolateral change in foot placement to avoid grass potholes. For most cases, TD children managed to avoid stepping in potholes through early or subtle changes to stepping patterns, that meant they would step to the side or over a pothole within their natural gait cycle (e.g. the foot moving over the pothole during swing without needing to adjust step length). Typically developing children demonstrated stable (positive) MOS on grass at times when they did not step into a pothole (Figure 5.11).

***Table 5.6a**. Descriptions of each interaction with the walkway when avoiding a pothole demonstrated by children with CP. # = Occurrence of instability number*

#	Type of avoidance	Description	Type of trial	Fixations
1	Medial Avoidance	Reduced step width causing crossing of limbs to step around pothole.	Distracted	Fixation on distraction: 21% Fixation on pothole: 19% (1 s) Time of first fixation on pothole: 62% (1.9 s prior to unstable gait)
2	Lateral Avoidance	Increased step width to avoid a pothole. Instability in steps following due to crossing limbs.	Distracted	Fixation on distraction: 22% Fixation on pothole: 19% (1s) Time of first fixation on pothole: 48% (2.7 s prior to unstable gait)
3	Change in Walking Path	Reduced step width to change walking path and move around pothole.	Non-distracted	N/A
4	Lateral Avoidance	Increased step width to step around the pothole. Instability in steps following.	Distracted	N/A
5	Change in Walking Path	Reduced step width to change walking path and move around pothole.	Distracted	Fixation on distraction: 0% Fixation on pothole: 61% (2.1 s) Time of first fixation on pothole: 39% (2.1 s prior to unstable gait)
6	Lateral and Anterior Avoidance	Increased step width and length to step around the pothole. Anterior instability in the steps following.	Non-distracted	Fixation on pothole: 0% (0 s) Time of first fixation on pothole: N/A
7	Lateral Avoidance	Increased step width and length to step around the pothole. Instability in steps following.	Distracted	Fixation on distraction: 36% Fixation on pothole: 0% (0 s) Time of first fixation on pothole: N/A
8	Medial Avoidance	Reduced step width (crossing limbs) in the step prior to the second pothole, then again in the step to avoid pothole.	Non-distracted	N/A
9	Medial Avoidance	Crossing of limbs to avoid the pothole in the step after the pothole.	Non-distracted	N/A
10	Medial Avoidance	Crossing of limbs to avoid the pothole in the step around the pothole. This follows the first pothole which is walked around without instability.	Distracted	Fixation on distraction: 0% Fixation on pothole: 28% (0.7s) Time of first fixation on pothole: 37% (1.6 s prior to unstable gait)

Table 5.6b. *Visual 3D appearances of interactions with the pothole demonstrated by children with CP, grouped by type of avoidance*

Medial Avoidance	Lateral Avoidance	Change in Walking Path
		

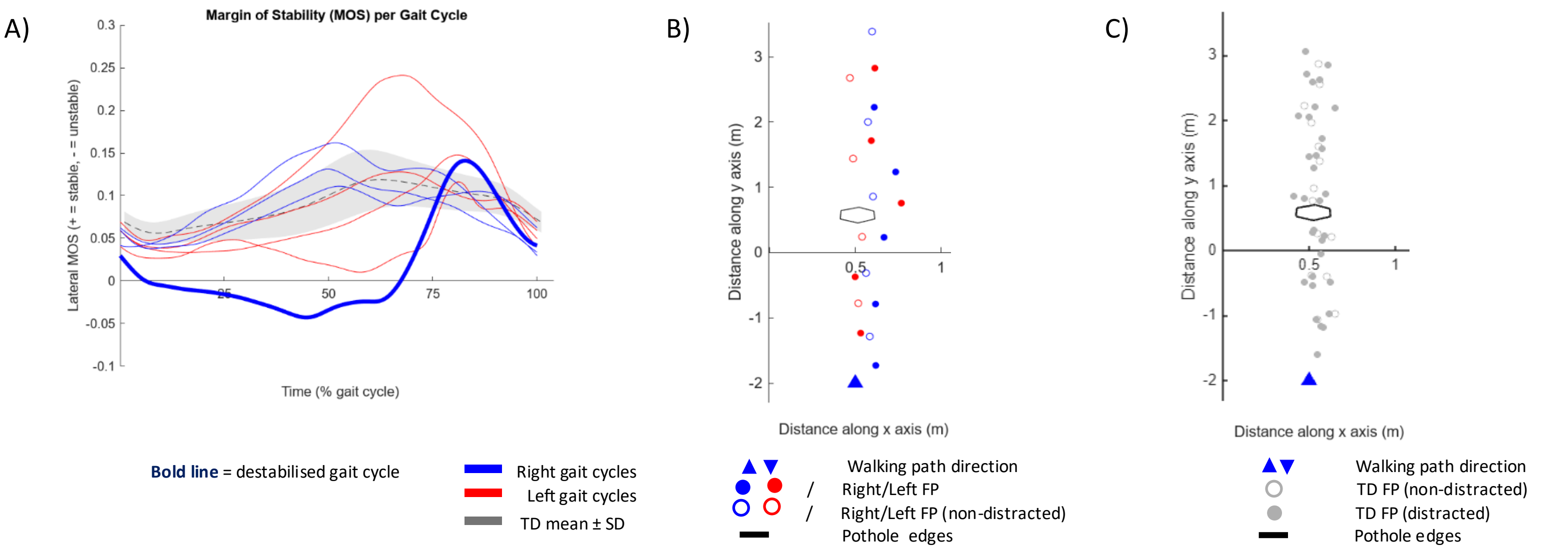


Figure 5.11. *An example trial (avoidance #1) where one child with CP showed a medial avoidance of a pothole. A) Lateral MOS for each gait cycle during the trial, B) Foot placement when avoiding the pothole for the same trial, C) Foot placement for TD children along the same walking path.*

5.3.2.5 Interaction 5: **Avoiding a pavement edge**

5.3.2.5.1 Summary of mechanism

Children with CP showed instability when they avoided edges of the pavement surface. This occurred nine times and was demonstrated by six different children. Eight out of nine avoidances were achieved through children taking a larger step in an anterior direction compared to other steps in that trial. This allowed children to avoid stepping onto a pavement edge and maintain foot placement on a level surface. There were no consistencies regarding which pavement edge was avoided (children showed instabilities over all five pavement edges at various times). One child experienced instability when stepping down from a pavement edge and another experienced lateral instability from leaning to one side while standing on one limb to step over a pavement edge, then crossing limbs on the subsequent step. Each type of avoidance and accompanying gaze fixations are shown in Table 5.7a and Visual 3D appearances of each avoidance in Table 5.7b. Avoiding pavement edges had consequences for both anterior and lateral MOS, though the largest changes to MOS were seen in the lateral direction, usually 1-2 steps after the initial avoidance of a pavement edge. An example of a change to anterior and lateral MOS can be seen in Figure 5.12, all MOS figures are shown in Appendix 9.

5.3.2.5.2 Influence of distraction

Three trials were distracted, one had a visual distraction only (no audio) and one had 0% fixation on the distraction. The one trial that showed a lateral instability had distraction with sound, however eye tracking glasses could not determine percentage fixation on the distraction.

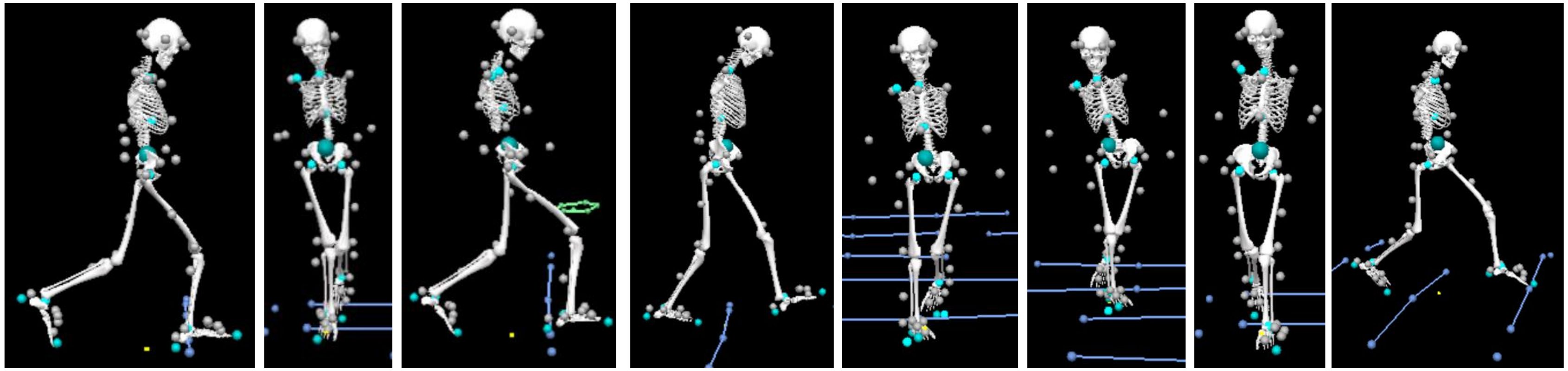
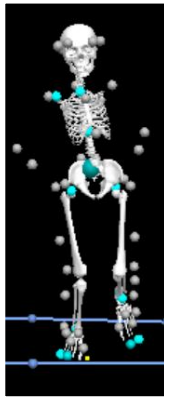
5.3.2.5.3 Typically developing children

The TD children demonstrated stable MOS more often when walking on the pavement surface (Figure 5.12). Out of 54 walks across pavement, 25 showed TD children not stepping onto a pavement edge, across all nine children. Fifteen of these trials were under non-distracted conditions, 10 distracted.

Table 5.7a. *Descriptions of each interaction with the walkway when avoiding a pavement edge demonstrated by children with CP. # = Occurrence of instability number*

#	Type of avoidance	Description	Type of trial	Fixations
1	Anterior	Increase in step length causing anterior instability.	Non-distracted	Fixation on edge: 21% (0.3 s) Time of first fixation on edge: 55% (0.7 s prior to unstable gait)
2	Anterior	Increase in step length, reduction in step width follows causing crossing limbs and lateral instability.	Non-distracted	Fixation on edge: 16% (0.7 s) Time of first fixation on edge: 50% (2.1 s prior to unstable gait)
3	Anterior	Increase in step length on two occasions, causing anterior instability, then lateral instability.	Distracted (no noise)	N/A
4	Anterior	Increase in step length causing anterior instability.	Non-distracted	Fixation on edge: 24% (1.1 s) Time of first fixation on edge: 22% (3.4 s prior to unstable gait)
5	Anterior	Stepping down from the pavement edge, participant experiences reduction in step width and therefore lateral instability.	Distracted	Fixation on distraction: 0% Fixation on edge: 1% (0.04 s) Time of first fixation on edge: 74% (1.8 s prior to unstable gait)
6	Anterior	Short step prior to edge followed by increase in step length over edge, following this crossing legs occurs causing lateral instability.	Non-distracted	Fixation on edge: 20% (1.2 s) Time of first fixation on edge: 33% (4 s prior to unstable gait)
7	Anterior	High first step over the pavement, then longer second step to avoid edge, causing anterior instability.	Non-distracted	N/A
8	Anterior	Increase in step length to step over an edge, followed by anterior and lateral instability.	Non-distracted	N/A
9	Lateral	Stepping over edge causes lateral instability on supporting limb, then step width is reduced causing lateral and anterior instability.	Distracted	N/A

Table 5.7b. *Visual 3D appearances of interactions with the pavement edges demonstrated by children with CP, grouped by type of avoidance*

Anterior Avoidance	Lateral Avoidance
	

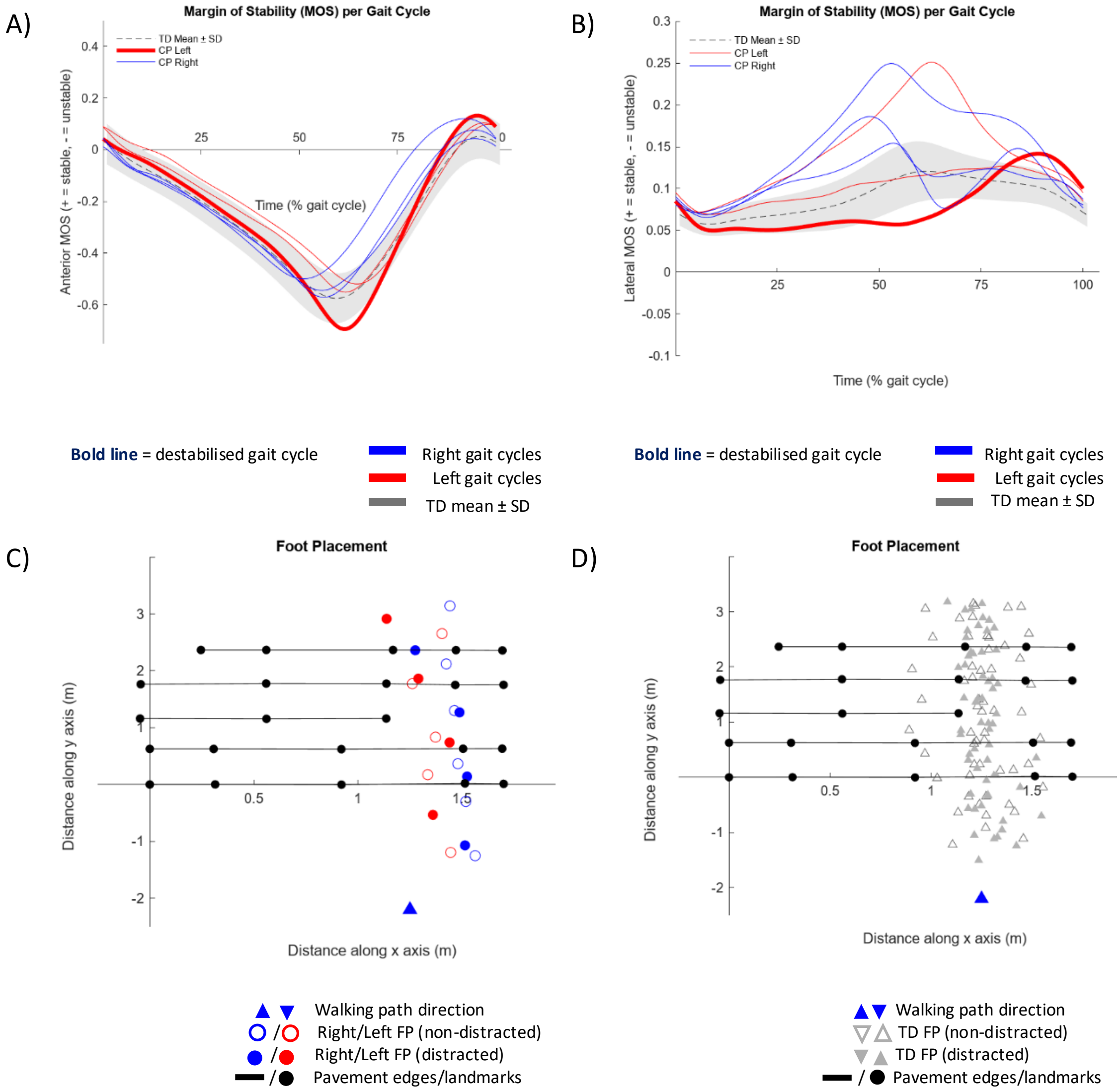


Figure 5.12*. An example trial (avoidance #3) where one child with CP showed anterior avoidance of pavement edges. A) Anterior MOS for each gait cycle during the trial, B) Lateral MOS for each gait cycle during the trial. For A) and B) bold = gait cycle following avoidance of a pavement edge, non-bold = all other left (red) and right (blue) gait cycles during the trial, grey = mean of all TD trials on pavement ± SD, C) Foot placement stepping over pavement for the same trial, D) Foot placement for typically developing children along the same walking path. bold circles = distracted, outline circles = non-distracted conditions.*

5.3.3 Responses to a challenging walkway

5.3.3.1 Spatiotemporal variables

Children with CP walked slower, had greater step width, and shorter step length on both pavement and grass for both distracted and non-distracted trials compared to TD children (Figure 5.13). Results of statistical analysis for each are reported below.

5.3.3.1.1 Walking Speed

There was no significant interaction between walkway condition and group ($F_{3\ 51}$ = 0.82, P = 0.490), for walking speed. There was a significant main effect of group on walking speed (F = 12.50, P = 0.0025, η^2 = 0.955), where children with CP walked significantly slower than TD children. There was also a significant main effect of walkway condition on walking speed (F = 3.65, P = 0.018, η^2 = 0.045). Post-hoc analysis revealed that children walked significantly slower (difference = 0.076 m/s) during distracted trials on pavement compared to non-distracted trials on pavement (P = 0.047).

5.3.3.1.2 Step Width

There was no significant interaction between walkway condition and group ($F_{3\ 51}$ = 0.14, P = 0.935), for step width. There was a significant main effect of group on walking speed (F = 13.99, P = 0.0016, η^2 = 0.009), where children with CP had significantly greater step width than TD children (Figure 5.13B). There was no significant main effect of walkway condition on step width (F = 0.15, P = 0.931, η^2 = 0.991).

5.3.3.1.3 Step Length

There was no significant interaction between walkway condition and group ($F_{2.25\ 38.22}$ = 0.84, P = 0.450), for step length. There was a significant main effect of group on step length (F = 8.28, P = 0.010, η^2 = 0.926), where children with CP had significantly shorter step length than TD children. There was also a significant main effect of walkway condition on step length (F = 4.75, P = 0.012, η^2 = 0.074). Post-hoc analysis revealed that children walked with significantly larger step width (difference = 0.032 m) during grass non-distracted trials, compared to pavement distracted trials (P = 0.045).

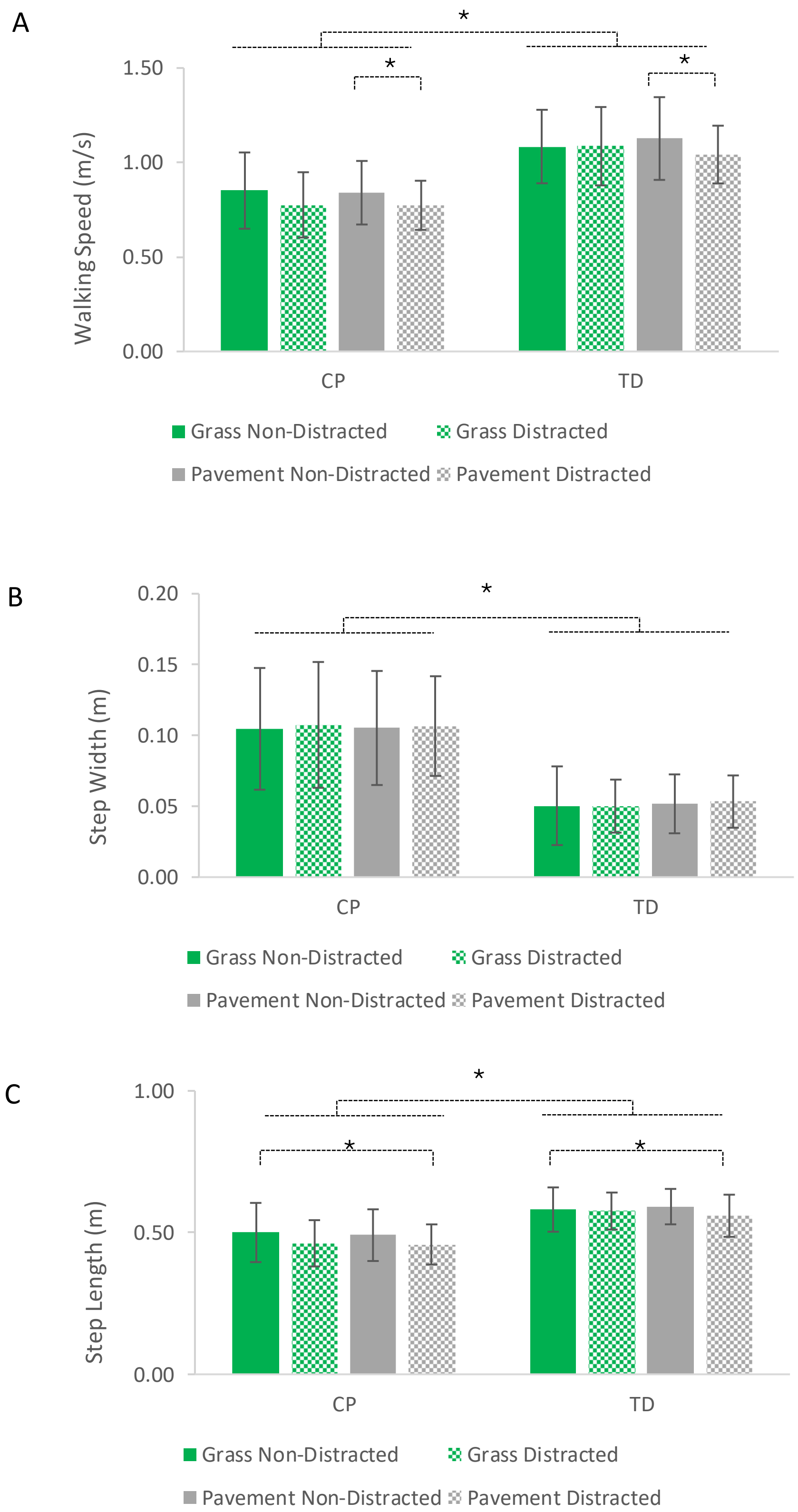


***Figure 5.13**. A) Walking speed, B) Step width and C) Step length for children with CP and TD children during challenging environment conditions. * = between group statistical significance.*

5.3.3.2 Balance confidence and fear

There were no significant differences between children with CP and TD children for balance confidence ($\chi2(1) = 0.51$, $P = 0.476$), feelings of fear ($\chi2(1) = 0.65$, $P = 0.421$) or feelings of stability ($\chi2(1) = 2.12$, $P = 0.145$). For both children with CP and TD children, there were also no significant differences between walkway conditions (grass and pavement) for balance confidence (CP: $\chi2(1) = 1$, $P = 0.317$, TD: $\chi2(1) = 0.33$, $P = 0.564$) and no significant difference between walkway conditions (grass distracted, grass non-distracted, pavement distracted and pavement non-distracted) for feelings of fear (CP: $\chi2(3) = 3.71$, $P = 0.294$, TD: $\chi2(3) = 1.15$, $P = 0.764$) or feelings of stability (CP: $\chi2(3) = 2.25$, $P = 0.522$, TD: $\chi2(3) = 6.2$, $P = 0.102$).

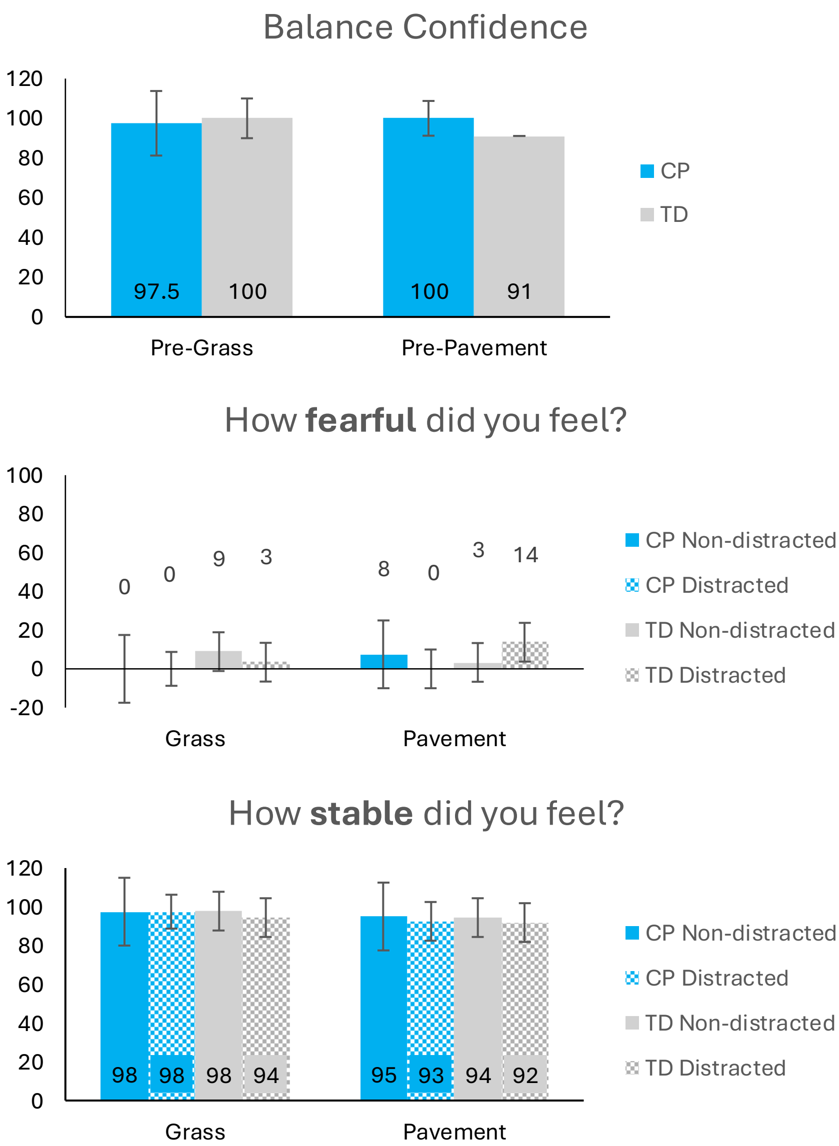


Figure 5.14. *Median and Interquartile ranges for A) Balance confidence, B) Feelings of fear and C) Feelings of stability for children with CP and TD children during challenging environment conditions.*

5.4 Discussion

The primary objective of this study was to establish the mechanisms that contribute to falls and high fall risk in replica real-world uneven surfaces with distractions, suggested by children with CP as challenging. The primary finding of this study is the novel detail into the potential mechanisms of falls including interaction with a challenging feature (e.g. trip over a pavement edge) or late avoidance of a challenging feature (e.g. a late medial change in foot placement to avoid a pothole) that were not previously gathered from laboratory-based challenging environments (Chapter 2). Secondary to this, is that in creating a bespoke walkway from the lived experiences of children with CP (Chapter 4), a high number of incidents of instability were captured, which offers novel insight into how children with CP negotiate challenging environments in their day-to-day lives.

5.4.1 Occurrences of instability on the walkway

Children with CP demonstrated several mechanisms of instability when walking on uneven surfaces with and without distractions that TD children did not. Instabilities occurred despite a reduction in walking speed, increased step width and reduced step length. Changes in gait characteristics to compensate for reduced stability are evidenced in previous work over challenging environments (Böhm et al., 2014; Stott et al., 2014; Malone et al., 2016; Romkes et al., 2020), however, there is still a lack of understanding of the mechanisms that may contribute to a near-fall or fall in the real-world (Chapter 2). The study presented in this chapter provides novel evidence to show that instabilities occur whilst implementing compensatory gait characteristics either through direct interaction with uneven walkway features (e.g. stepping onto a pavement edge) or through inadequate avoidance strategies (e.g. a late medial step around a pothole). One reason that the current study may have been able to reveal this over previous laboratory work is because the design of the bespoke walkway is informed by children's lived experiences and moves closer toward replicating the day-to-day environments that cause falls in the real-world.

Moreover, as discussed in Chapter 2, the closest research has come to understanding whether real-world fall occurrence is linked to challenging environments in laboratory settings was through reports that children with CP stumble once in every four attempts at the standardised walking obstacle course (SWOC), without providing detail into the portion of the course (e.g. stepping over, change in direction) that caused the stumbles or the mechanism (e.g. stepping behaviours, gaze behaviours) with which those stumbles occurred over the challenging environments (Kott and Held, 2002; Zipp and Winning, 2012; Bailes et al., 2017). The current study now extends understanding of the type of challenging environments that increase fall risk and exactly how fall risk is increased; this has not been addressed in previous SWOC studies.

5.4.2 Avoidance strategies

Children with CP demonstrated avoidance behaviours late in approach to walkway features. The walkway features avoided by children with CP were either a grass pothole or a raised pavement edge. Typically, an avoidance included a late change in foot placement either anteriorly or laterally, leading to instability. Avoidance behaviours were not observed in TD children, which implies any changes to stepping strategy to avoid a challenging feature were likely early and subtle enough to show little changes in stability.

When approaching a pothole, children with CP most often demonstrated a late change in foot placement resulting in a medial or lateral avoidance, where children with CP would increase step width to step around a pothole or cross limbs to step beside a pothole, rather than stepping into a pothole. A possible reason children with CP are shown to use this avoidance strategy when avoiding potholes is that medial or lateral avoidance might be perceived as a better option to maintain stability compared to the consequence of stepping into a pothole. A medial or lateral avoidance might be easier to achieve than an anterior step over a pothole for children with CP who experience different gait patterns such as stiff-knee gait, or characteristics such as reduced range of motion, contractures or selective motor control impairment that makes it more difficult to achieve full knee extension and hip flexion for increased step length (Armand et al., 2016; Zhou et al., 2019).

When approaching a pavement edge, children with CP often demonstrated an anterior avoidance, where children would increase step length to step over a pavement edge. This anterior avoidance would then result in either lateral or anterior instability in subsequent steps. This avoidance strategy might be used by children with CP due to more limited options for safe foot placement that is not on the edge itself. For example, a medial or lateral step will likely result in stepping on the same or another pavement edge and lead to further instability.

Reasons for choice of avoidance strategy around either a pothole or a pavement edge (e.g. change in foot placement medially or anteriorly) ought to be further investigated. The changes in foot placement to avoid either a pothole and pavement edge demonstrated by children with CP, suggest that perceived danger plays a part in choice of avoidance strategy. Evidence suggests that making contact with an uneven feature (e.g. pothole or pavement edge) holds the highest danger, and where there is choice, the most achievable change in foot placement to avoid the uneven feature, within the limits of mobility, are prioritised (e.g. stepping medially as opposed to anteriorly). This agrees with previous work that suggests children with stiff knee gait will increase knee flexion at the detriment of energy conservation in order to prioritise stability on uneven surfaces (Böhm et al., 2014).

For both avoidance of a pothole or pavement edge, a change in foot placement (either laterally or anteriorly) was late in approach to the feature and caused instability. This might imply a lack of preplanning in the lead up to the feature and suboptimal avoidance strategies when faced with a challenging feature. Children with CP have shown less efficient preplanning strategies in reaching tasks in the upper limbs (Aboelnasr et al., 2017) compared to TD children, which may be reflected here in a dynamic walking task. To add to this, in a previous study that explored lived experiences, a young adult, aged 24 years, with CP expressed that they needed a good awareness of their own capabilities and of how to preplan in order to avoid a fall (Brunton and Bartlett, 2013). This might imply that it takes a longer time for children with CP to be able to develop an efficient knowledge of their own capabilities and preplanning in the environments around them. Similar findings were discussed in Chapter 4, where in walk-along interviews, older children generally were able to express that they thought they had greater awareness of their surroundings and where to 'be careful'. Perhaps for children with CP the ability to plan an appropriate foot path in challenging environments, even if they know they are to be more cautious, has not fully developed, therefore errors in preplanning occur, leading to inadequate foot placement. Furthermore, sensory deficits (e.g. reduced visual acuity demonstrated by children with CP in this work and previous (Fazzi et al., 2012)) or distractions (e.g. moving attention away from planning an appropriate avoidance strategy), as discussed later in section 5.4.4, may make preplanning even more difficult in an already challenging walking environment. Focus on improving avoidance strategies is key when planning future fall prevention.

5.4.3 Recovery strategies

In many cases of instability, a recovery strategy was required in order to negotiate the walkway safely. Some examples included 1) taking an additional short, fast step laterally to increase step width following a step into a pothole that moved extrapolated centre of mass (COM) outside of the base of support momentarily, 2) reduced step length to control an increased forward acceleration of COM following a step onto a pavement edge or 3) a rapid increase in foot clearance over a pavement edge having contacted it with the foot during swing. In the real-world, where challenging environments are navigated continually by children with CP, it is plausible that some children do not make the necessary adjustments to recover from an interaction with the environment, meaning they result in a fall. This may be especially true for those with difficulty implementing specific recovery strategies. For example, a child with hip abductor weakness, a common impairment for children with CP (Metaxiotis et al., 2000; Krautwurst et al., 2013) may find it more difficult to rapidly increase step width following a step into a pothole. This might explain why in the current study, children with CP showed instability and greater risk of falling even when exhibiting the compensatory gait characteristics. This is likely reflected in the real-world, where compensatory characteristics are not adequate enough on uneven surfaces, with and without distractions to prevent a fall, contributing to high fall occurrence. Recovery strategies specific to an individual's capabilities are important to be considered for effective fall prevention or potential training programmes to reduce risk of falls. Future work could consider using similar methods to those used in this study (e.g. an uneven walkway), as applicable routine fall prevention training and understand whether recovery strategies can be improved through these methods to reduce fall occurrence in similar real-world environments.

5.4.4 Distractions

The current study extends evidence from The Walk-Along Project (Chapter 4), whereby children and parents expressed that distractions were a likely cause of trips and falls. This study documented that distractions increased near-fall occurrences, in replica real-world challenging environments. Within the available data, some differences were seen in gaze behaviour between the type of challenging surface (grass or pavement) and the interaction with that surface for children with CP. During distracted trials, children with CP showed limited fixation on either the pavement edge or pothole prior to experiencing instability (1% or less fixation on a challenging feature on four occasions when distracted, 0% fixation on one occasion when not distracted) and on average, fixated on challenging features 8.5% later through the trial prior to unstable gait cycle. Additionally, some children suggested they did not see the pothole when walking over the grass surface. When children fixated on the distraction, this may have interrupted visual processing of the environment in the steps ahead that would typically be used to plan an optimal or safe walking path (Patla and Vickers, 2003).

Although evidence exists here that distractions increase near-fall risk, 20 out of 37 interactions leading to instability also occurred with no distraction present. This suggests a wider issue regarding visual processing of the environment for children with CP. Children with CP showed significantly slower times compared to TD children during the Trail Making Test-A, which could be an indicator of impaired visual processing. Children with CP also show longer mean executive function time compared to TD children and although non-significant, a longer executive function time has been a suggested factor for increased fall risk in older adults in the past (Mirelman et al., 2012). Despite this, one TD child showed instability from stepping into a pothole, with minimal fixation on the pothole. This suggests similar effects on visual processing when walking with a distraction for TD children and children with CP. More investigation is required here, using a larger sample with eye tracking analysis that is adapted for children wearing glasses, especially given the number of instabilities that took place while no distraction was present.

To current knowledge, no study has investigated the influence of distractions on fall risk in challenging walking environments with children with CP. In real-world scenarios, distractions occur more often in less controlled environments than in the current laboratory investigation. Therefore, although many occurrences of instability here were without distractions, perhaps the more likely scenario seen in the real-world is an instability with a distraction present, as described by children with CP during The Walk-Along Project. Moreover, a more uncontrolled environment with distractions might make a response to instability less effective and thus lead to an instability of greater magnitude following an interaction with an environmental feature, to result in a fall to the ground or floor. Previous work from Matthis et al. (2018), investigated gaze behaviour of adults in outdoor natural environments and noted how vision was focused on an uneven environment almost 100% of the time when walking in uneven ground, which was almost double the amount of time spent looking at the surface when walking on level ground. A similar detailed analysis into visual scanning patterns of children with CP when walking in real-world challenging environments with distractions, whilst accounting for individual differences, would provide full understanding of the influence of distractions on near-fall mechanisms in challenging environments.

5.4.5 Self-reported falls

Children with CP reported more falls compared to TD children. This finding moves the field forward from previous work suggesting that falls are common for children with CP (Boyer and Patterson, 2018), by evidencing a direct comparison to a sample of TD children and providing a better understanding of where falls happen, why falls happen and the impact falls have on psychosocial wellbeing. As in previous work (Towns et al., 2020), negative psychosocial impacts of falls were evidenced for children with CP within this study. This included feelings of embarrassment, shock, frustration, avoidance of activities and injury. Despite these negative consequences of falls, all but two of the children with CP reported thinking of falls as just a part of everyday life and having to get up and carry on when they occurred. This attitude was present in children who reported falls at least once a month, including those who reported multiple falls per day. This perhaps reflects resilience built through having regular experiences of falls in varying day-to-day situations (inside, outside and in school). Conversely, all but two children with CP reported walking more cautiously and/or avoiding places because of falls, which highlights how some children become more anxious and tentative in certain places. The falls questionnaire used in this study was adapted based on previous work (Boyer and Patterson, 2018) and questions typically asked at the start of clinical gait analysis. More information could be gathered about fall history using a validated questionnaire such as the Falls Efficacy Scale (Yardley et al., 2005) or using a longitudinal falls diary. Nevertheless, the fall history questions included in this study provided additional detail that help to identify whether or not an individual is at high fall risk. Furthermore, the evidence put forward in this study and supporting literature emphasises the complex and wide issue of falls that exists for children with CP, which highlights the need for fall prevention, to reduce fall occurrence and the negative psychosocial consequences associated with falls in the real-world.

5.4.6 Individualised responses

Children with CP showed individualised instabilities on the walkway, for example, the child who had previous history of GMFCS II/III, but could walk independently, had the highest number of incidents of instability on the walkway (eight out of 37) including four trips, compared to all other children with CP. This implies that this child is at higher risk of falls in similar environments in the real-world and could benefit from fall prevention training focused on avoiding trips and recovery strategies following a trip. In contrast, another child experienced five instabilities on the walkway, two of these were through avoidance of a pothole and two avoidance of a pavement edge and three out of five were distracted trials, suggesting this child may benefit from novel training interventions that focus on foot placement preplanning in challenging environments with sensory distractions. This individualisation provides scope for not only tailoring individualised fall prevention but also provides evidence that the walkway protocol used in this study might offer a starting point for a more widely used tool to identify children at high fall risk. The instability exhibited by both children with CP on the challenging walkway, in combination with a high incidence of falls reported, could be used as a tool to identify ambulatory children with CP at high fall risk in real-world environments, such as the two children identified from the current study. This information in future has the potential to inform how clinicians or health practitioners intervene effectively.

A possible explanation for the individualised responses is functional ability. The child with the most incidents of instability had the highest GMFCS level, meaning lowest functionality, and the majority of incidents overall occurred in children with GMFCS II and those who had diplegia, agreeing with work that suggests those of GMFCS II experience the most falls (Boyer and Patterson, 2018). Another observation is that children with hemiplegia in the current study, only experienced instability following avoidance of a pavement edge or pothole, not through directly stepping into a pothole or onto a pavement edge. As suggested earlier (5.4.2 Avoidance Strategies), it may be that in some cases the highest perceived danger of making contact with an uneven feature (e.g. step into a pothole) is more easily avoidable for those with hemiplegia, since they have a less affected side that may increase their ability to step medially or anteriorly around a feature. This may be more difficult to achieve with those with diplegia who have more restricted functionality, thus leading to contact with a challenging feature. It should be considered that there were more children with diplegia (n = 7), compared to hemiplegia (n = 3) in this work, therefore a stronger argument could be made if this were seen in a larger group of children. Nonetheless, this is an important consideration when planning individualised fall prevention programmes.

The individualised nature of the responses and interactions with the walkway should be considered in future work, especially, given the presence and individualised nature of sensory deficits in children with CP, such as visual impairments (Fazzi et al., 2012), or neurodevelopmental disorders, such as attention deficit hyperactivity disorder or autism spectrum disorder, that may impair the ability to be aware (either through concentration or visually) of the environmental surroundings and plan an optimal walking path or avoidance strategy. Individualised responses to challenging walking environments, in this way, both with and without distractions, could help inform tailored fall prevention programmes or a future tool to identify individuals with CP at high fall risk.

5.4.7 Limitations

The methodologies used in this study are closer than previous to achieving a replica of day-to-day challenging places where falls occur, given lived experiences are deep rooted in the design of this study. Despite this, the study took place in a laboratory setting, with use of reflective markers and eye tracking glasses that children would not typically wear when walking in the real-world, therefore some children may respond differently (e.g. less cautious) in their day-to-day environments compared to the challenging environment faced in this study.

Three children with hemiplegia and seven children with diplegia took part in this study. Type of gait pattern was not collected for each child, due to the nature of parent reported metrics. Despite previous literature not identifying gait patterns associated with fall frequency (Boyer and Patterson, 2018), this work is limited and requires further exploring. Gait pattern data may have provided additional insight into the types of interaction with walkway features on a group level. For example, if all children with diplegia evidenced crouch gait, this could have offered explanation for high numbers of medial and lateral avoidances of a pothole, due to restricted range of motion. Alternatively, if all children with diplegia evidenced true equinus, this may have explained the number of trips over a pavement edge due to increased plantar flexion and therefore difficulty increasing foot clearance. Although gait pattern was not documented, the children in this study were heterogeneous, and multiple sub-types were observed during data collection.

Fall history was recorded by asking parents and children to recall how often they currently experience trips and falls on a day-to-day basis. There may exist some recall bias with asking this to children and parents as they may not remember exactly how many falls or trips they have had that day, week or month. This is reflected in the ranges of fall occurrences reported (e.g. 1-2 per day or 3-4 per month). Despite this potential limitation, fall occurrence reported in this study aligns with previous reports (Boyer and Patterson, 2018) and addresses a need for an increased quantity and quality of reporting that is lacking in previous work (Chapter 2).

Eye tracking analysis in this study was incomplete as some children wore glasses and this meant no reliable data could be extracted. Despite this, preliminary evidence that visual processing of the environment is a vital for planning adequate stepping strategies to maintain stability, is provided from a small sample of children in this study, which highlights the importance for further analysis in this area.

It is possible that repeated exposure to similar features across the bespoke walkway (e.g. experiencing potholes along different walking paths) could have led to a learning effect for some children, which may change their natural responses to the challenging features. Children were additionally able to look at the walkway prior to the first trial, which may have allowed them to assess the location of specific features. This effect was reduced initially, as familiarisation took place around the perimeter of the walkway, not over challenging environments. Moreover, the protocol used randomised trials, with minimal repetition, meaning children only ever walked over the same path twice (once with a distraction and once without a distraction) and that these walking paths took place in a randomised order. Finally, a learning effect was reduced by introducing 'catch' trials after every two recorded trials, these were trials that were in a different direction to recorded trials, with no challenging features present.

Some children with CP in the current study were involved in walk-along interviews in Study 3 (Chapter 4). This involvement may have created pre-existing ideas of the purposes of the current study and the potential risks associated with falling in uneven challenging environments. This may have led to either conscious or subconscious cautious behaviours. Despite this, these children still showed instabilities on the walkway.

5.5 Conclusion

This study provides detailed insight into potential mechanisms that contribute to falls and high fall risk in replica real-world uneven surfaces with distractions. Incorporating children's lived experiences into the design of the walkway allows this study to have meaningful application to potential real-world causes and mechanisms of falls. A link is demonstrated here between near-falls and challenging environments, by evidencing that children with CP show instabilities through interaction with uneven features of the environment, both with and without distractions. A key finding of this study is that children with CP show instabilities even when avoiding uneven features of the environment, and when implementing cautious walking strategies. Moreover, causes of instabilities are likely specific to the individual, their impairments and how they interact with distractions in the environment. This work is important for informing future fall prevention, such as training programmes that are focused on preplanning strategies when negotiating challenging environments. Importantly, this work also highlights increased fall occurrence and impacts of falling such as embarrassment, injury and fear, which brings to the forefront the importance of addressing the issue of falls in children with CP, to reduce negative psychosocial and physical consequences.

Chapter 6

Critical Synthesis, Discussion and Conclusion

6.1 Aims of the research

The aim of the research was to understand why (the causes) and how (the mechanisms) falls occur in children with CP. Three study specific aims were implemented that have contributed to achieving these aims. Each stage of this PhD builds on the previous, starting with identifying a gap in knowledge, moving to exploring the lived experiences of children with CP to inform research methods and to gaining deeper insight into the mechanistic underpinnings of why falls happen in the real-world.

The systematic review (Chapter 2) identified an understudied link between challenging environments and real-world fall risk due to a lack of investigation in environments that cause falls in the real-world. PPIE sought the opinions of children with CP and their parents to help gain insight into their lived experiences of falls (Chapter 3). The Walk-Along Project used a novel application of the walk-along interview method to reveal *why* children fall over, by identifying that children perceive the most challenging places for falls are uneven surfaces with distractions (Chapter 4). Finally, the bespoke walkway protocol was created based on the places and situations that children told us were challenging. This protocol enabled data to be collected that reveal *how* falls occur, by demonstrating that children with CP show instabilities through interaction with and avoidance of uneven features of the environment. This work offers more detailed insight into how fall risk is increased in environments that replicate those that cause falls in the real-world (Chapter 5).

The series of studies in this research presents contributions of lived experiences and novel mixed methods to provide deeper understanding of causes and mechanisms of falls in children with CP. Outcomes of this research have offered deeper insight than previous stability assessments or treatment methods targeted to reduce falls, by underpinning why and how falls happen in everyday real-world environments. This knowledge has the potential to change the way we look at fall prevention techniques, to be more informed and applicable than ever before. Only by offering this novel understanding can future investigations begin to create and implement successful interventions and tailored training to reduce falls and thus begin to reduce negative psychosocial consequences of falls for children with CP.

This chapter presents a critical synthesis and discussion of the outcomes of each stage of this research. Firstly, headline findings are discussed (section 6.2 and 6.3) with context to how they contribute to novel knowledge and understanding of the causes and mechanisms of falls in children with CP. Discussion follows on the importance of lived experience into research practice (section 6.4), then a synthesis on the involvement of stakeholders (section 6.5), including the contributions of parents, community groups and clinicians. Finally, critical synthesis is had on the potential implications and future directions of this research (section 6.6), which is broken down into 1) identification of children at high fall risk, 2) fall prevention and 3) lifelong impacts.

6.2 Suboptimal stepping strategies lead to unstable avoidance behaviours

The primary outcome of this PhD is that children with CP avoid challenging features of the environment without adequate preplanning of foot placement, which necessitates a late change in stepping strategy that leads to instability. Other mechanisms identified included stepping into the pothole, tripping over or stepping onto a pavement edge. It is widely suggested that ambulatory children with CP walk with a more unstable gait than TD children. This can be seen through various measurements on level ground such as larger COM-COP inclination angle and greater differences in COM-COP trajectories in the mediolateral direction compared to TD children (Hsue et al., 2009a; Feng et al., 2014; Wallard et al., 2014; Sharifmoradi et al., 2018) and larger asymmetries in step to step COM acceleration in all three directions (Iosa et al., 2012; Saether et al., 2014). However, MOS over level ground (Tracy et al., 2019; Rethwilm et al., 2021) and assessment over uneven surfaces (Böhm et al., 2014; Malone et al., 2015; Romkes et al., 2020) suggests that children with CP implement cautious strategies to maintain dynamic stability and reduce the risk of a fall. This PhD is the first body of work to offer examples of the types of environments where these compensation strategies are not enough to prevent a near-fall (e.g. trip or stumble) and show reduced MOS in replica real-world environments.

6.3 Distractions increase fall risk for children with CP

Children with CP told us they would be more likely to experience a fall when distracted (Chapter 4). Instabilities were then evidenced when children walked over a challenging walkway with distractions. Specifically, trials with distractions showed later fixation on challenging features causing instability compared to trials without a distraction. Distractions are therefore an important factor in increased fall risk. Real-world falls might result from more challenging environments, with distractions, where preplanning and recovery strategies are interrupted. This extends work that suggests children with CP require more steps to dissipate disturbances walking over level ground (Kurz et al., 2012), suggesting that when changes to gait are encountered (e.g. a late change in foot placement to avoid a pothole), recovery strategies take longer than TD children and that is likely worsened due to presence of distractions that interrupt sensory processing of the environment. Overall, this offers a more detailed explanation than seen previously for the high number of falls in the real-world for children with CP and provides better understanding of the mechanisms that contribute to high fall risk.

6.4 Lived experiences grounded within research design

A key outcome of this body of work is what can be learned from involving lived experiences of children with CP. Children's thoughts and opinions are fundamental to informing this work, from the discussion of the concept of the walk-along interview (Chapter 3) through to sharing their lived experiences of falls (Chapter 4), informing the design of a bespoke laboratory protocol (e.g. what distractions to use), and to the insights into fall history and feedback following involvement in the laboratory-based study (Chapter 5). Earlier work in Chapter 3 highlighted that it is important to involve those whom we study, and that this involvement and engagement should be done more in research with children with disabilities (Rouncefield-Swales et al., 2021). Chapter 3 also highlights the lack of existing research that embeds the lived experiences of children with CP. The body of work undertaken in this PhD provides a foundation for how children with CP can be involved when exploring biomechanical research questions, that are typically laboratory-based and do not routinely include patient and public involvement and engagement. Using photo elicitation and interview techniques, children with CP helped contribute to a research design that generated information about their perceptions of the causes of falls in the real-world (specific uneven surfaces) and key indicators of what might put a child with CP at high fall risk (e.g. how they interact with distractions). Incorporating the lived experiences of children with CP and their parents in everyday environments has allowed this PhD to establish causes of falls in the real-world and highlights the importance of understanding the population before understanding the problem.

Future work could extend this involvement to other key populations of interest for falls research, such as older adults and how they negotiate the home environment and/or stairs (Jacobs, 2016; Gazibara et al., 2017), or those with disabilities such as cognitive impairment or Parkinson's Disease navigating the community environment (Fasano et al., 2017; Chantanachai et al., 2021). Falls specific PPIE undertaken with these populations is likely to be beneficial in informing and designing research, in a similar way to that which occurred in this body of work.

6.5 Involvement of stakeholders

The body of work for this PhD not only required involvement from children with CP, but also parents as stakeholders in the design and conduct of research. Parents were able to offer additional insights into the day-to-day lived experiences of their children with CP and offered balance to the experiences shared by their children. An example is provided during PPIE (Chapter 3), where a child mentioned that they had not fallen in a while, but their parent reminded them saying they had fallen over only that morning. As well as balance, parents were able to offer longitudinal perspectives on lived experiences throughout childhood, such as explaining how their child would fall more when younger or need less intervention as they grew older. Parents also supported the experiences of children by encouraging them to feel comfortable in talking about their experiences during walk-along interviews.

Several charity organisations were also involved in this work as stakeholders, who would assist in PPIE and participant recruitment. The involvement with Stick ‘n’ Step led to building transparent relationships with local community groups and with parents and children. This not only created trust with children and parents helping them to be comfortable in talking to the researcher but also developed the researcher’s understanding of the lives of and mobility challenges the children faced. These relationships were built throughout the PhD journey and were extended through offering volunteering opportunities to other postgraduate research students who have since worked with the same charity to conduct PPIE in their research.

Other stakeholder work included the involvement of The North West Movement Analysis Centre at Alder Hey Children’s Hospital, who offered feedback following monthly project updates. The knowledge exchange from this involvement was valued from both sides, establishing a greater recognition in clinical practice of the importance of falls. The relationships built throughout this PhD with children, parents, community organisations and clinical practitioners offers potential for outputs from this PhD beyond conference presentations and academic papers. These outputs include falls prevention training or a falls survey that have the potential to be embedded in clinical practice or community groups; these will be discussed in section 6.6.

6.6 Implications and future Directions

The outcomes of this body of research could be used to inform the design of (1) methods that identify ambulatory children with CP at high fall risk and (2) specific interventions or training programmes that could contribute to fall prevention at the community level.

6.6.1 Identifying children with CP at most risk of falls

6.6.1.1 The Walk-Along Method

The Walk-Along Project could inform a tool for identifying children at high fall risk and causes of falls specific to the individual. For example, a device that allows a walk-along interview to be conducted by a child with CP and their parent on their own or with a clinician, in their local walking places. Similar to a video diary, this could be something that explores how often, where and what causes falls in the environments they navigate day-to-day. A Walk-Along application, for example on a smartphone, could allow children to take photos and videos of the places that might cause falls, other interactive features could include red (challenging) or green (OK) stickers, similar to those used during PPIE (Chapter 2) to elicit more detailed information about challenging places (Figure 6.1).

Figure 6.1. *An example schematic of how a walk-along interview might look in a mobile phone application*

Additional information could be gathered from this method by including a falls diary and prompts based on the questions used in Chapter 4 to highlight key individualised risk factors that may not have been considered previously e.g. distractions and attention. However, it is important to consider the low uptake of video diaries in Chapter 4, that may reflect in a falls diary since participants would be required to fill this out in their own time. This might be improved with the help of a clinician or occupational therapist to lead the walk-along interview, but would require additional time from professionals.

Another consideration is recall bias as discussed in Chapter 4 and exclusion of those that may not be able to access digital tools due to high cost of devices, or lack of digital literacy. This could be made more accessible by providing alternative versions with inclusive navigation (e.g. adjustable text, high contrast colours). This method could additionally be made more accessible given this would not be limited to collection of data in North West England. In doing so, this tool has the potential to offer insight into experiences of falls based on additional factors for consideration such as socioeconomic background and local living differences (e.g. urban vs rural environments). Although more work is required to determine wider feasibility, identifying challenging places in this way, is likely to reveal the children at most risk of falls given the research undertaken in this PhD shows that walk-along interviews can reveal places that fall risk and near-fall occurrence is increased.

6.6.1.2 Informed Survey Methods

Another method for identifying children at high fall risk, might be for clinicians to use a survey at routine appointments. Numerous clinical tools have been used previously to assess gait stability, balance and falls, such as the Falls Efficacy Scale (Yardley et al., 2005) or Berg Balance Scale (Franjoine et al., 2003), both with adult populations such as those with Parkinson's (Bloem et al., 2016) and with children with CP (Jantakat et al., 2015; Kim, 2016). Similarly, there are methods for assessing functional ability such as the Gillette Functional Assessment Questionnaire (Novacheck et al., 2000) and for improving gait assessment outcomes such as the Gait Outcomes Assessment Tool (Thomason et al., 2018).

Designing something similar based on the methods and outcomes from this research, might offer clinicians more detailed insight into how and why individual children with CP are at high fall risk in their daily lives and routines. To date no falls specific survey has been developed to explicitly identify individual children with CP at high fall risk in real-world environments. The Gait Outcomes Assessment Tool includes consideration of both walking on uneven ground and consideration of child and parent priorities (e.g. how important daily tasks such as going up and down stairs are to parents and children). This could be used in conjunction with the outcomes of this PhD to help create a specific survey for identifying children with CP at high fall risk, by including items that are informed by children's lived experiences, for example, questions on attention and distractions when walking. Given children and parents attend appointments regularly as part of their routine healthcare, the use of a survey could be more easily and widely used than using a walk-along interview application.

The survey should build on questions already asked by clinicians typically at the start of an assessment. This method would unlikely provide data as rich as that generated from walk-along interviews shown in Chapter 4, however inclusion of parent and child reported priorities, such as in the Gait Outcomes Assessment Tool, would enhance understanding of each patient's experiences of falls. Clinicians would be able to use the survey data to inform patient specific recommendations for treatment plans relating to falls. For example, children who experience falls most due to avoidance of environmental features, may benefit from sports or strengthening programmes designed to improve both stability and coordination (Verschuren et al., 2007; Auld and Johnston, 2014).

6.6.1.3 Bespoke Walkway Methods

A further application from the methods in this study might be to use the bespoke walkway protocol in Chapter 5. It may be possible to create a biomechanical and behavioural profile to predict children at high fall risk depending on how they negotiate a similar walkway. For example, children who demonstrate high fall risk behaviours such as high percentage fixations on distractions, in combination with near fall experiences due to interactions with the walkway, could score highly. A similar method has been used for older adults' stair negotiation (Ackermans et al., 2021). This type of method may require more detailed statistical analysis of key fall risk predictors and would likely require a longitudinal assessment plan. Feasibility of this method would depend on keeping parents and children engaged and accounting for growth of children over a long period (several months or years).

Another adaptation of this is to create a high fall risk index for those that negotiate the bespoke walkway with specific gait characteristics that deviate from characteristics that offer stable negotiation in challenging environments. Techniques have been used previously to quantify differences in pathological gait of children with CP to normal gait on level ground (Schutte et al., 2000) and there now exists several widely used tools for profiling gait, such as the Gait Profile Score (Baker et al., 2009) or Gait Deviation Index (Schwartz and Rozumalski, 2008). This could potentially be adapted with falls specific outcome variables over a bespoke walkway, however would be more difficult with the large range of stepping strategies evidenced over uneven surfaces. Further research and funding for a programme to explore these methods may help to make this possible, however, the bespoke walkway protocol offers this opportunity given its success in isolating individual occurrences of instability and near-falls in this PhD.

A bespoke walkway similar to the one used in this research would likely only work as an identification tool if it was a permanent set-up in a laboratory. However, creating a more accessible tool by combining elements of this walkway and something smaller and easily movable, like the earlier discussed SWOC (Chapter 2) could make assessment viable. The SWOC test has been widely used as a reliable tool to assess functional ambulation (Held et al., 2006), possibly due to the ease of setup and easily interpreted metrics (e.g. number of stumbles, time to completion). An adapted SWOC including uneven surfaces that are more applicable to real-world fall occurrence, and incorporating a distraction, with metrics such as number of trips and gaze fixation on a distraction, could provide a better reflection of those children who are at highest fall risk, whilst also being more easily accessible.

Analysis of a child's gait pattern when negotiating a bespoke walkway in clinical assessment would offer more detailed insight into the benefits of surgical outcomes on fall prevention. Currently gait analysis is conducted over level ground, without accounting for the challenges identified in this research to be an indicator of near-fall risk (e.g. potholes). Boyer and Patterson (2018), noted that gait pathologies typically associated with high fall risk that are often targeted for treatment to optimise gait, e.g. in-toeing, stiff knee gait, are not linked to fall occurrence. Perhaps the use of a bespoke walkway prior to and after treatment, as is usually done with routine gait analysis following surgery, would allow better insight into the effectiveness of specific procedures in reducing fall risk in replica real-world environments.

6.6.2 Fall prevention for real-world application

The series of studies that form part of this PhD offer a more detailed understanding of the causes and mechanisms of falls that reflect day-to-day experiences, which have the potential to inform more applicable fall prevention training and intervention techniques for children with CP. Previous interventions that have established a potential for stability improvement for children with CP include exercise (Dewar et al., 2015), balance training (Bar-Haim et al., 2008; El-Shamy and Abd El Kafy, 2014; Hosseini et al., 2015), virtual reality (Ravi et al., 2017), hydrotherapy interventions (Zverev and Kurnikova, 2016), walking interventions (Elnahhas et al., 2019) or a combination of methods (Duarte et al., 2014; Araújo et al., 2020). However, the outcomes lack direct applicability to everyday fall risk. El-Shamy and Abd El Kafy (2014) calculated fall risk as an outcome post-intervention, which identified increased stability and decreased fall risk for children with CP following static balance training. Yet static interventions may not accurately represent day-to-day dynamic stability, especially with additional environmental challenges. Intervention work or training programmes based on the current research could include a smaller version of the bespoke walkway used in Chapter 5, with distractions. It could also be used as a repeated training tool for preplanning foot path and to improve recovery strategies over replica real-world challenging environments.

Another example is to use virtual reality to create real-world scenarios or an interactive game where children are able to practice preplanning their foot path with and without distractions that replicate those identified during The Walk-Along Project. Research shows that immersive virtual reality with a Computer Assisted Rehabilitation Environment (CAREN) platform and the Gait Real-Time Analysis Interactive Lab (GRAIL) system can improve functional movements in children with CP including walking and running (Gagliardi et al., 2018; Maggio et al., 2024), and even suggests that these systems can help improve spatial navigation, which requires path preplanning (Biffi et al., 2020; Nossa et al., 2022). However, similar to the typical assessments of stability addressed previously, these protocols are carried out over level treadmill walking and are not focused on fall prevention and do not involve distractions that bring attention away to the walking path ahead. Therefore, there is scope for a new protocol, informed by the bespoke walkway used in this study, to be successful in training children with CP to plan their path around challenging features of the environments that replicate those faced in the real-world with and without distractions.

Further work would be required with longitudinal studies to assess the validity and applicability of such tools over time, in combination with measurements of fall occurrence. There is potential for a well-informed training or intervention programme, created from the findings of this research, to be introduced in community groups, such as those who supported the research programme. For example, Stick ‘n’ Step, include fall specific tasks during their sessions, including how to fall safely for ambulatory children with CP. Cerebral Palsy United offer football based physiotherapy exercises for children and adolescents with CP to improve mobility. Previous work highlights the potential of successful implementation of complex care for children through community and clinical partners (Cohen et al., 2012) and the similar applies here. Community partners may welcome ideas and protocols that clinical based therapy cannot, especially given their openness to supporting the research reported in this thesis. Importantly, a well-informed training or intervention programme is likely to align with their invested interest given the functional goals they work towards with children.

6.6.3 Lifelong impacts

Training or interventions developed from the findings of this research might not only apply to children with CP, but to adults with CP, given the issue of falls exists throughout the lifespan (Morgan and McGinley, 2013). Negative psychosocial and physical consequences of falls are seen in both adults (Morgan et al., 2015; Shah et al., 2024) and children with CP (Gibson et al., 2012; Towns et al., 2020). Adults with CP particularly present reduced physical health status, including serious injury and reduced personal wellbeing, including isolation due to falls (Morgan et al., 2014, 2015; Esterley et al., 2024). Targeted fall prevention when younger may lead to improvements later in life, especially if interventions are applicable to places that people with CP of all ages encounter every day (e.g. walking to the shop over uneven pavements). Therefore, if children are supported to learn how to safely navigate challenging environments identified in this research, and carry this into adulthood, risk of falling, and the negative consequences associated with falling could be lowered in all ages of people with CP.

6.6.4 Wider application within the ICF framework

The ICF framework highlights that functioning, disability and health should consider the personal and environmental factors that impact the ability carry out daily tasks (World Health Organization, 2001). The work in this PhD suggests that children with CP (1) regularly experience falls in the real-world (2) that these falls occur more often than in children without CP, due to physiological function (e.g. inadequate avoidance of features of a challenging environment) and environmental factors (e.g. an uneven environment with distractions), and (3) that falls increase negative psychosocial consequences, leading to reduced activity participation and participation restrictions. Thus, causes and mechanisms of falls for children with CP, fit within the ICF framework and the findings offer further justification for creating individualised fall prevention programmes for children with CP.

Moreover, this PhD presents examples of the consequences of falls for children with CP and demonstrates that these consequences can be different for each child. Physical consequences of falls such as injury are inherent. However, psychological impacts of falls, such as embarrassment, fear and reduced activity participation are evident throughout this work; these appear to be dependent on the individual and situation. Literature emphasises the importance of individualised impacts of falls on daily wellbeing. The Gait Outcomes Assessment Tool has been used to understand the importance of various areas of mobility to children and parents that could improve quality of life (Thomason et al., 2018). This contains a section for gait function and mobility, which accounts for walking on uneven ground and a section for gait appearance, which accounts for walking without tripping or falling. Previous work with caregivers shows that these are important factors for daily wellbeing of children with CP (Boyer et al., 2022), and similar to the ICF, highlights how falls and fall reduction is important for the functionality, disability and health of children with CP. The ICF additionally supports the consideration of individualised activity participation and restriction, suggesting that the negative psychosocial consequences of falls should be addressed to promote overall improvements in functioning, disability and health of children with CP.

The implications of this PhD in the context of the ICF framework are important for future work, particularly work that aims to examine tailored and applicable interventions and training to reduce falls in children with CP and, thus, reduce the negative consequences of falls. Specifically, the ICF highlights that rehabilitation and environmental change are important for prevention of activity limitation and participation restriction. The work in this PhD provides a foundation for improving how a child with CP navigates challenging environments through training and improvement in ability to adapt to high fall risk environments through intervention. This has the potential to increase activity participation physically and socially (e.g. walking with friends without falling or fear of falling), that are important to overall functioning, disability and health.

6.7 Reflexivity

My primary research interests are clinical human movement analysis, particularly in children with cerebral palsy. In the early phases of this PhD, I became aware of the value of involving children and parents within the research about them. At conferences, I gained insight that PPIE was not yet a widely adopted method for investigating stability and fall risk. Child-centred methods have been core to outcomes of this body of work and have developed my belief for their use in future research. My experience volunteering allowed me to truly understand the value of investing time into community groups and working with children and their families, and develop greater appreciation for the daily experiences of falls in children with CP. It is important to acknowledge how my subjective experiences volunteering and building relationships with Stick 'n' Step may have influenced this work, however these experiences have also helped me to have a more open mind with regards to the techniques that can be used to understand complex issues.

The design and implementation of novel research methods, particularly to manage a novel application of a walk-along interview and a more uncontrolled laboratory study than seen typically (e.g. gait analysis), have expanded my view of how problems can be approached biomechanically and creatively. The methodology used in this PhD has required commitment and initiative to be able to successfully capture data that moves closer toward reflecting real-world fall experiences. An example of this during The Walk-Along Project (Chapter 4) is travelling to places local to children and parents, to allow the interview to be accessible. An example during the laboratory-based study (Chapter 5), is sourcing material and hand making a walkway of different terrains. To move the field towards successful fall prevention for children with CP, further novel methods need to be created and then tried and tested, such as a walk-along app for identifying children, or a portable challenging walkway as a training tool. These techniques are the next step for fall prevention and importantly, based on the experience and findings of this research, it is my firm belief that these techniques can be successful with the involvement of children with CP and their lived experiences.

6.8 Conclusion

This research identified causes and mechanisms of falls in children with CP by exploring their lived experiences and using a bespoke laboratory protocol that replicated environments where falls happen most in the real-world. Uneven natural or built environments are a cause of falls and near-falls in the real-world and distractions likely increase fall risk for children with CP. Mechanisms that explain instability in children with CP and could lead to a trip or fall include lack of visual preplanning for safe foot placement and motor impairments (e.g. reduced range of motion) that can lead to a destabilising interaction with the environment (e.g. trip onto a pavement edge) or a destabilising avoidance of an environmental feature (e.g. avoidance of a pothole). More work is required to fully understand distractive influences and how this changes depending on the individual. These novel insights provide a deeper insight than previous stability assessments or treatment methods targeted to reduce falls.

Although children with CP seemed resigned to falling, we now have novel evidence about why and how these falls happen in the real-world. This knowledge offers the potential to pave the way for a low-cost diagnostic tool for identifying children with CP at high fall risk and implement fall prevention training and intervention methods that are specifically tailored to real-world fall experiences. On a larger scale, the applications resulting from this new knowledge could change the way children with CP are able to move throughout their daily walking places; without the high occurrence of trips, stumbles and falls, and thus the lifelong negative psychosocial consequences such as fear, embarrassment and frustration, that are reported briefly within this thesis, but experienced daily by children with CP. Finally, to bring this child-centred work to a close, it seems fitting to turn to a summary from the voices of children and parents:

Children with CP have to know how to “*put our feet in the exact right position*” (George) to avoid a fall. In falls research, tailored fall prevention methods are vital, since “*intervention earlier on is better, and these children don’t get enough of that intervention*” (Elliot’s Dad). The novel knowledge presented in this body of work offers the opportunity to inform future investigations into falls and fall prevention and only from this we can truly “*help people who don’t have CP, understand how people who have CP…fall*” (Leo).

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8 Appendices

8.1 Appendix 1.

Search strings for each database

Database	Search String
Web of Science	TOPIC: (("cerebral palsy“ OR hemiplegi* OR diplegi* OR "spastic hemiplegi*“ OR "spastic diplegi*")) AND TOPIC: ((ground OR “land surface” OR path OR “environmental features” OR topography OR uneven OR stair* OR obstacle* OR perturbat* OR incline* OR decline* OR slope* OR ascen* OR descen* OR ramp OR hill)) AND TOPIC: ((fall* OR “fall rates” OR “fall occurrence” OR “fall risk” OR trip* OR stumble OR slip OR stability OR unstable OR balance OR control OR “postural sway” OR “trunk sway” OR “inclination angle” OR separation OR “gait stability” OR kinematics)) *(Refined to – “document types: article”)*
PubMed	("cerebral palsy“[Title/Abstract] OR hemiplegi*[Title/Abstract] OR diplegi*[Title/Abstract] OR "spastic hemiplegi*“[Title/Abstract] OR "spastic diplegi*"[Title/Abstract]) AND (ground[Title/Abstract] OR “land surface”[Title/Abstract] OR path[Title/Abstract] OR “environmental features”[Title/Abstract] OR topography[Title/Abstract] OR uneven[Title/Abstract] OR stair*[Title/Abstract] OR obstacle*[Title/Abstract] OR perturbat*[Title/Abstract] OR incline*[Title/Abstract] OR decline*[Title/Abstract] OR slope*[Title/Abstract] OR ascen*[Title/Abstract] OR descen*[Title/Abstract] OR ramp[Title/Abstract] OR hill[Title/Abstract]) AND (fall*[Title/Abstract] OR “fall rates”[Title/Abstract] OR “fall occurrence”[Title/Abstract] OR “fall risk”[Title/Abstract] OR trip*[Title/Abstract] OR stumble[Title/Abstract] OR slip[Title/Abstract] OR stability[Title/Abstract] OR unstable[Title/Abstract] OR balance[Title/Abstract] OR control[Title/Abstract] OR “postural sway”[Title/Abstract] OR “trunk sway”[Title/Abstract] OR “inclination angle”[Title/Abstract] OR separation[Title/Abstract] OR “gait stability”[Title/Abstract] OR kinematics[Title/Abstract]) *(refined to – full text, clinical trial, controlled clinical trial, observational, RCT, journal paper, English)*
Scopus	(TITLE-ABS-KEY("cerebral palsy“ OR hemiplegi* OR diplegi* OR "spastic hemiplegi*“ OR "spastic diplegi*")) AND (TITLE-ABS-KEY(ground OR “land surface” OR path OR “environmental features” OR topography OR uneven OR stair* OR obstacle* OR perturbat* OR incline* OR decline* OR slope* OR ascen* OR descen* OR ramp OR hill)) AND (TITLE-ABS-KEY(fall* OR “fall rates” OR “fall occurrence” OR “fall risk” OR trip* OR stumble OR slip OR stability OR unstable OR balance OR control OR “postural sway” OR “trunk sway” OR “inclination angle” OR separation OR “gait stability” OR kinematics)) *(refined to – “document type: article”)*
MEDLINE **CINAHL**	AB ("cerebral palsy“ OR hemiplegi* OR diplegi* OR "spastic hemiplegi*“ OR "spastic diplegi*") AND AB (ground OR “land surface” OR path OR “environmental features” OR topography OR uneven OR stair* OR obstacle* OR perturbat* OR incline* OR decline* OR slope* OR ascen* OR descen* OR ramp OR hill) AND AB (fall* OR “fall rates” OR “fall occurrence” OR “fall risk” OR trip* OR stumble OR slip OR stability OR unstable OR balance OR control OR “postural sway” OR “trunk sway” OR “inclination angle” OR separation OR “gait stability” OR kinematics) *(refined to - full text, English, journal article)*

8.2 Appendix 2.

Data extraction summary of included papers

Author	Title	Participants	Methods	Assessment Tool	Quality Score
Uneven Surfaces					
Böhm et al. 2014	Stiff-knee gait in cerebral palsy: How do patients adapt to uneven ground?	16 children with CP (14.1 ± 6.2 yrs, diplegia, GMFCS 1-2), 13 TD children (13.5 ± 4.8 yrs)	Barefoot walking over level and uneven surface (7 m walkway). Uneven surface made of polyurethane floor panels.	3D motion analysis and EMG (8-camera Vicon/Telemyo)	Good
Malone et al. 2015	Do children with cerebral palsy change their gait when walking over uneven ground?	17 children with CP (5-18 yrs, 10 with hemiplegia, 7 with diplegia, GMFCS 1 or 2, 17 TD children (5-18 yrs)	Barefoot walking over level and uneven surface over (10 m walkway). Uneven surface customised using bags of pebbles scattered at varying angles on the walkway.	3D kinematic and kinetic data (Codamotion cx1 system and Kistler Force)	Good
Romkes et al. 2020	Walking on uneven ground: How to patients with unilateral cerebral palsy adapt?	20 children with CP (8-18 yrs, hemiplegia, GMFCS 1-2), 20 TD children (8-18yrs)	Barefoot over level and uneven surfaces, (6 m walkway). Uneven surface made of polyurethane floor panels.	3D motion analysis (12-camera Vicon)	Fair
Inclines and Declines					
Stott et al. 2014	Level versus inclined walking: Ambulatory compensations in children with cerebral palsy under outdoor conditions	10 CP (5-14 yrs, diplegia, GMFCS 2), 10 TD children (5-14 years)	Indoor conditions: barefoot level gait analysis over 7 m. Outdoor conditions: level walking and 7° incline on concrete with shoes over 7 m.	2D motion analysis and timing gates (Sony MVC digital camera perpendicular to plane on left and right sides).	Fair
Hösl et al. 2016	Contractile behaviour of the medial gastrocnemius in cwCP during forward, uphill and backward-downhill gait	15 children with CP (7-16 yrs, diplegia, GMFCS 1 or 2), 17 TD children (7-16 yrs)	Barefoot 3D gait analysis on a treadmill over 10 seconds: level, inclined (+12%) and backward declined (-12%).	3D motion analysis (8-camera Vicon), EMG, ultrasound and physical exam	Fair

Mélo et al. 2017	Spastic diparetic does not directly affect the capacity to ascend and descend access ramps: three-dimensional analysis	10 children with CP (7 to 13 yrs, diplegia, GMFCS 1 or 2), 10 TD children (7-13 yrs)	Barefoot walking over 10m, level, inclined (7°) or declined (7°).	3D motion analysis (6-camera Vicon)	Poor
Topçuoğlu et al. 2018	How do children with bilateral spastic cerebral palsy manage walking on inclines?	18 children with CP (6-10yrs, diplegia, GMFCS 1 or 2), 19 TD children	Walking with shoes indoors on level, incline (5° and 10°) and decline (5° and 10°) surfaces.	3D gait analysis, (12 camera Vicon). Forces for level and 10° ramp	Good
Ma et al. 2019	Gait characteristics of children with spastic cerebral palsy during inclined treadmill walking under a virtual reality environment.	10 children with CP (6-12 yrs, hemiplegia and diplegia, GMFCS 1-2), 10 TD children	Walking in virtual environment on treadmill level and inclined for 1 minute each.	3D motion analysis with CAREN system (12 camera Vicon, split belt treadmill).	Fair
Choi et al. 2022	Gait Adaptation Is Different between the Affected and Unaffected Legs in Children with Spastic Hemiplegic Cerebral Palsy While Walking on a Changing Slope	17 children with CP (6-18 yrs, hemiplegia, GMFCS 1-2)	Treadmill walking uphill and downhill (0°, then 5°, then 10°).	10 camera Vicon system 100Hz, lower limb markers.	Good
Camuncoli et al. 2024	The Effect of a New Generation of Ankle Foot Orthoses on Sloped Walking in Children with Hemiplegia Using the Gait Real Time Analysis Interactive Lab (GRAIL)	18 children with CP (6-11 yrs, hemiplegia, GMFCS 1-2)	Walking on treadmill inclined and declined (-10°, 10° and 0°), with two different types of AFO.	Gait Real Time Interactive Lab, 3D motion analysis (10 camera Vicon and dual-belt instrumented treadmill).	Good
Obstacles					
Bailes et al. 2016	An exploratory study of gait and functional outcomes after neuroprosthesis use in cwCP	11 Children with CP (6-17 yrs, GMFCS 1 or 2)	Gait assessment (level), 6MWT, SWOC. Tested pre and post FET neuroprosthesis intervention.	SWOC with hands free test	Good
Law et al. 2005	Gait adaptation of children with cerebral palsy compared with control	12 children with CP (mean 13 yrs, diplegia, GMFCS unknown) 12 TD children (mean 10 yrs)	Barefoot walking over 8 m with or without an obstacle (1.47 m long cylindrical stick, 11 mm diameter). Obstacle was adjusted to flat, low and high - 0, 10 and 20% leg length.	2D and 3D motion analysis (Vicon system and 2D video from 6 cameras)	Poor

	children when stepping over an obstacle				
Malone et al. 2016	Obstacle Crossing During Gait in cwCP: Cross-Sectional Study With Kinematic Analysis of Dynamic Balance and Trunk Control	34 Children 17 CP, 17 TD	Barefoot walking with an obstacle crossing. Obstacle was 10 cm hurdle	3D kinematic and kinetic data (Codamotion cx1 system and Kistler Force)	Good
Treadmill Perturbations					
Flux et al. 2021	Functional assessment of stretch hyperreflexia in children with cerebral palsy using treadmill perturbations	38 children 24 CP 14 TD	Children walked in shoes on split belt treadmill under VR environment. Short belt accelerations were applied (perturbations) at three different intensities while children walked at comfortable speed.	3D motion analysis (Vicon system)	Fair
Stairs					
Sienko Thomas et al. 2002	Stair locomotion in children with spastic hemiplegia: the impact of three different ankle foot orthosis (AFOs) configurations	19 children with CP	Walking up and down stairs with barefoot, hinged AFO's, posterior leaf spring AFO's or solid AFO's. Stairs had 15.2 cm rise and 24.1 cm run, 32° slope.	3D motion analysis (6 camera Vicon)	Good
Uneven Surfaces and Obstacle Crossing					
Coman et al. 2022	Pilates-based exercises for gait and balance in ambulant children with cerebral palsy: feasibility and clinical outcomes of a randomised controlled trial	46 children with CP	Baseline and follow up walking before and after 4-weeks pilates exercise intervention. Walking barefoot on uneven surface and walking over obstacle (23 cm hurdle).	3D motion analysis (Codamotion cx1 motion capture)	Fair

8.3 Appendix 3.

Guidance for Reporting Involvement of Patients and the Public (GRIPP) 2 checklist, long form (Staniszewska et al., 2017)

Section and topic	Item	Reported on page No
Section 1: Abstract of paper		
1a: Aim	Report the aim of the study	53
1b: Methods	Describe the methods used by which patients and the public were involved	53
1c: Results	Report the impacts and outcomes of PPI in the study	53
1d:Conclusions	Summarise the main conclusions of the study	53
1e: Keywords	Include PPI, "patient and public involvement," or alternative terms as keywords	53
Section 2: Background to paper		
2a: Definition	Report the definition of PPI used in the study and how it links to comparable studies	55-57
2b: Theoretical underpinnings	Report the theoretical rationale and any theoretical influences relating to PPI in the study	55-57
2c: Concepts and theory development	Report any conceptual models or influences used in the study	55-57
Section 3: Aims of paper		
3: Aim	Report the aim of the study	59-60
Section 4: Methods of paper		
4a: Design	Provide a clear description of methods by which patients and the public were involved	60
4b: People involved	Provide a description of patients, carers, and the public involved with the PPI activity in the study	61
4c: Stages of involvement	Report on how PPI is used at different stages of the study	61-62
4d: Level or nature of involvement	Report the level or nature of PPI used at various stages of the study	61-62
Section 5: Capture or measurement of PPI impact		
5a: Qualitative evidence of impact	If applicable, report the methods used to qualitatively explore the impact of PPI in the study	n/a
5b: Quantitative evidence of impact	If applicable, report the methods used to quantitatively measure or assess the impact of PPI	n/a
5c: Robustness of measure	If applicable, report the rigour of the method used to capture or measure the impact of PPI	n/a
Section 6: Economic assessment		
6: Economic assessment	If applicable, report the method used for an economic assessment of PPI	n/a
Section 7: Study results		

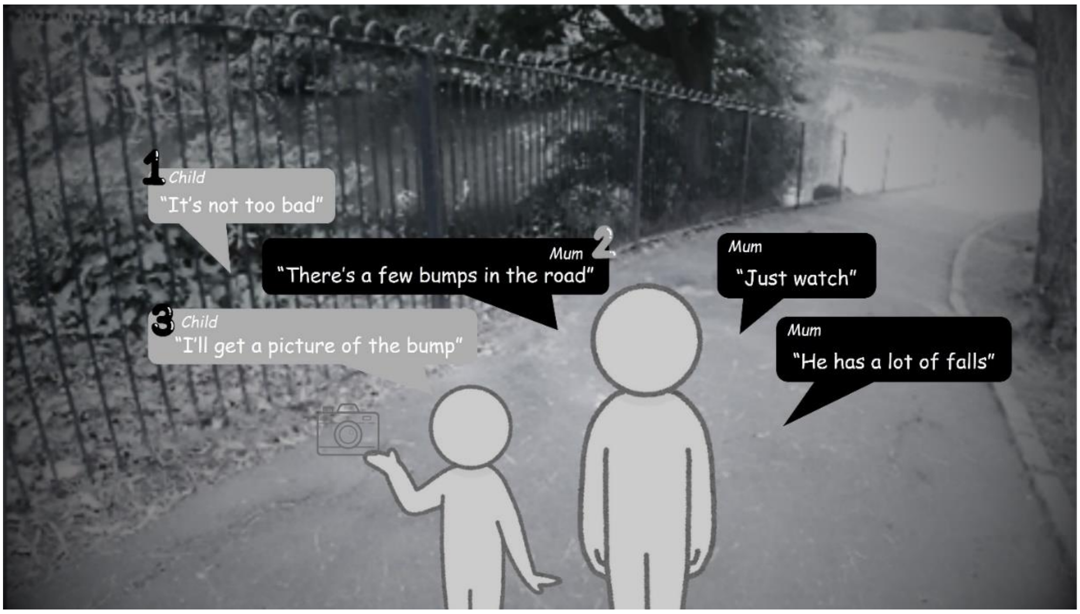
Section and topic	Item	Reported on page No
7a: Outcomes of PPI	Report the results of PPI in the study, including both positive and negative outcomes	68-71
7b: Impacts of PPI	Report the positive and negative impacts that PPI has had on the research, the individuals involved (including patients and researchers), and wider impacts	68-71
7c: Context of PPI	Report the influence of any contextual factors that enabled or hindered the process or impact of PPI	68-71
7d: Process of PPI	Report the influence of any process factors, that enabled or hindered the impact of PPI	68-71
7ei: Theory development	Report any conceptual or theoretical development in PPI that have emerged	n/a
7eii: Theory development	Report evaluation of theoretical models, if any	n/a
7f: Measurement	If applicable, report all aspects of instrument development and testing (eg, validity, reliability, feasibility, acceptability, responsiveness, interpretability, appropriateness, precision)	n/a
7g: Economic assessment	Report any information on the costs or benefit of PPI	n/a
Section 8: Discussion and conclusions		
8a: Outcomes	Comment on how PPI influenced the study overall. Describe positive and negative effects	73-75
8b: Impacts	Comment on the different impacts of PPI identified in this study and how they contribute to new knowledge	75-77
8c: Definition	Comment on the definition of PPI used (reported in the Background section) and whether or not you would suggest any changes	76
8d: Theoretical underpinnings	Comment on any way your study adds to the theoretical development of PPI	75-77
8e: Context	Comment on how context factors influenced PPI in the study	77-78
8f: Process	Comment on how process factors influenced PPI in the study	77-78
8g: Measurement and capture of PPI impact	If applicable, comment on how well PPI impact was evaluated or measured in the study	n/a
8h: Economic assessment	If applicable, discuss any aspects of the economic cost or benefit of PPI, particularly any suggestions for future economic modelling.	n/a
8i: Reflections/critical perspective	Comment critically on the study, reflecting on the things that went well and those that did not, so that others can learn from this study	78-79

PPI=patient and public involvement

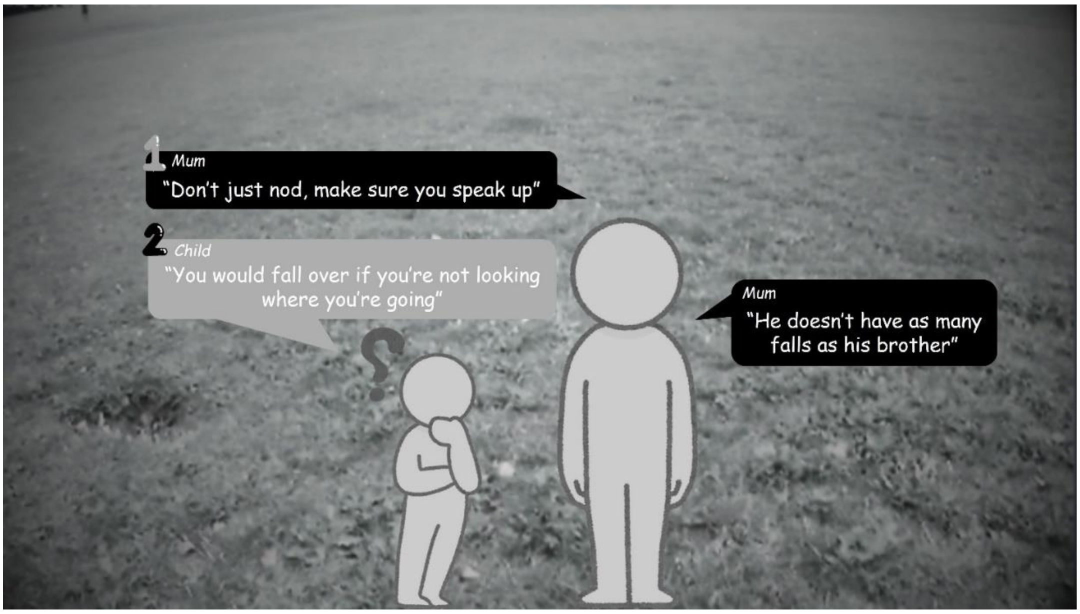
8.4 Appendix 4.

Vignettes showing conversations between each child and parent in settings identified as presenting a challenge. Speech from children is indicated in grey speech bubbles and parents in black speech bubbles. Where conversation was consecutive between parent and child, numbers indicate the order in which conversations were had. (Note: Background photographs taken by participants during the walk-along interviews. All photographs used with full consent/assent. Canva (online graphic design tool) used to add figures and speech bubbles (all graphics freely available under Canva's Content License Agreement).

1.



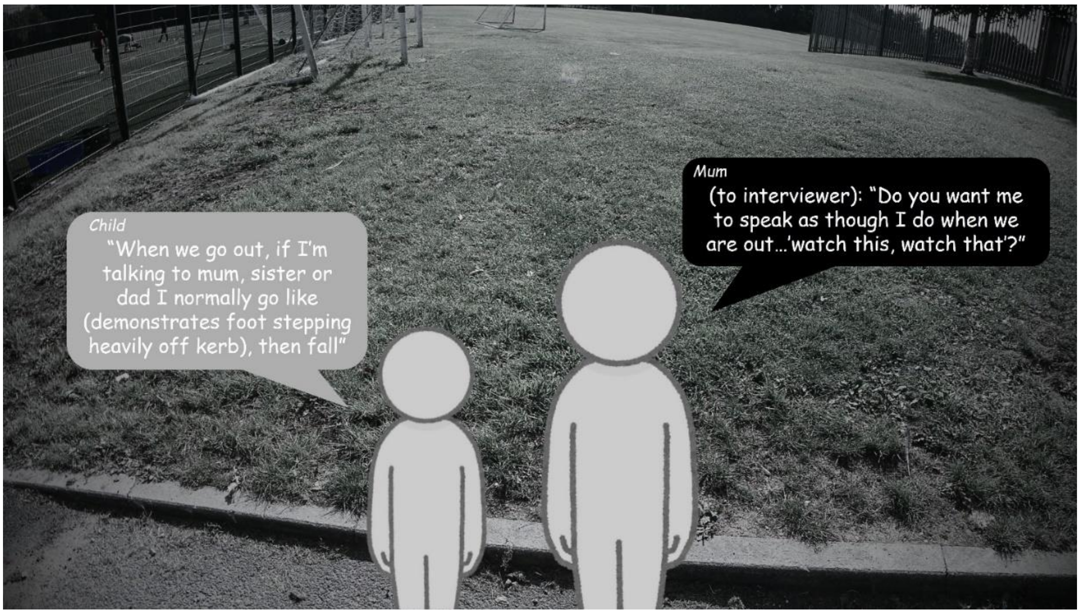
2.



3.


1
Child
"I've tripped over that pothole"
Mum
2
"Yes, you have, we've been here before"
Child
"There's another dog!"
Mum
"Watch where you are going"

4.


Mum
(to interviewer): "Do you want me to speak as though I do when we are out…'watch this, watch that'?"
Child
"When we go out, if I'm talking to mum, sister or dad I normally go like (demonstrates foot stepping heavily off kerb), then fall"

5.

1 Dad
"That one (grid) could catch you out"
2 Child
"There's a lot that you don't see that could trip you up"
3 Child
"Obviously you have to be careful"

6.

Child
"I'll probably trip over it because it's all like bumpy and there's different levels and my foot might get caught in one of them"
Child
"If I'm dragging my foot like when I'm tired then I'll probably trip over it"

7.


Interviewer: Did you get any photos?
Child: Er, no I couldn't find anything
Photos from video of potholes child stepped in on purpose but did not take photos of
Child
"I don't fall very often"
Child
"The only thing that I can potentially fall into, I think it gets loads of people, is potholes because it just catches you by surprise"

8.


Mum
"The main thing I remember being a problem that I used to have to watch out for was when the pavements aren't level with each other"
Mum
"He would trip but that was a long time ago"
Child
"The little ridge thing I might have tripped over that when I was younger"
Child
"Just have to go slower and be more careful"

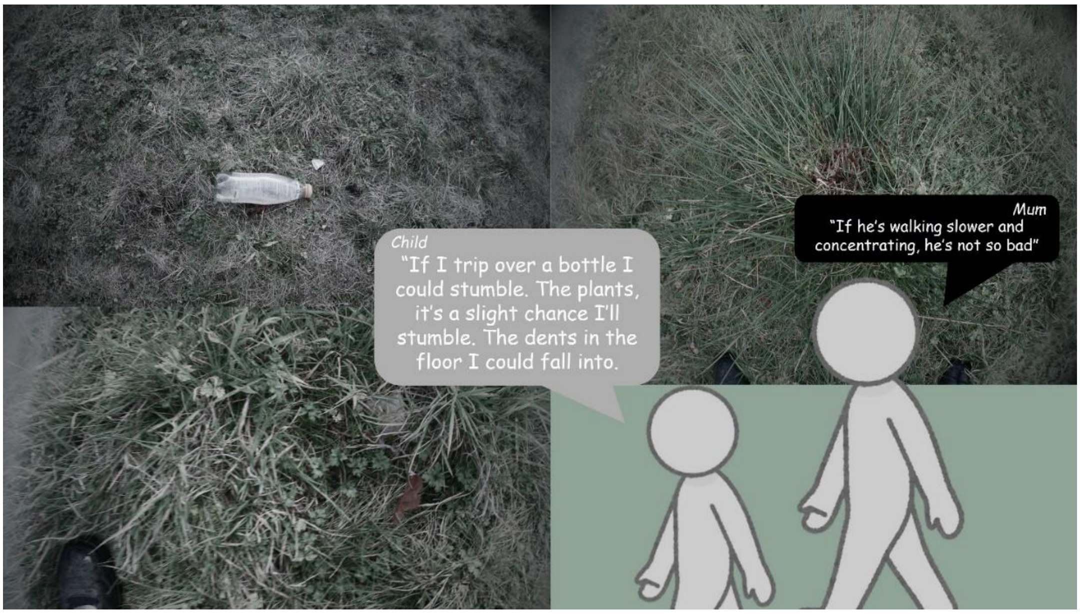
9.


1 Mum "Would that be tricky to walk on do you think?"
2 Child "Yes"
3 Mum "Do you want to try?"
4 Child "Yeah"
5 Mum "Does that feel okay or difficult?"
6 Child "Difficult"
7 Mum "Why?"
8 Child "Cause my balance"
Mum "Mostly your falls are from when you're tired aren't they, or because you can't see properly"

10.


1 Dad "What things make you trip over most?"
2 Child "Mostly bumpy and unstable ground"
Child "There is kind of some hazards around here… Can I take a picture of all this ground?"

11.

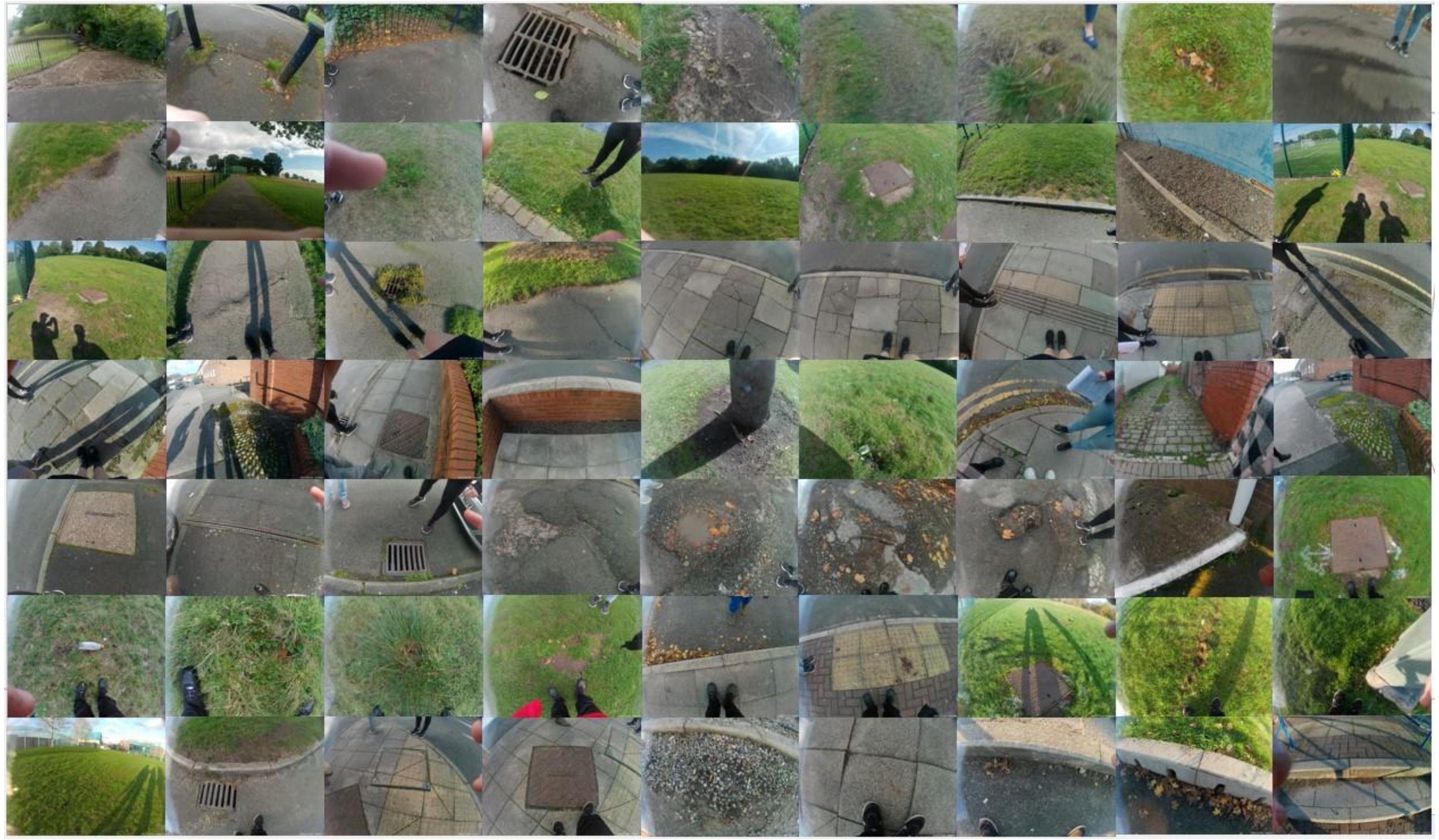

Child
"If I trip over a bottle I could stumble. The plants, it's a slight chance I'll stumble. The dents in the floor I could fall into.
Mum
"If he's walking slower and concentrating, he's not so bad"

12.


Child
"You could put your foot in and it would probably hurt you"
"Also probably the grid"
Child
"You could fall on where we started from on that hill slope, but not really over here"
Child
"If you've cerebral palsy, I would recommend having the operation as it could probably help you"

8.5 Appendix 5.

All photographs taken by children with CP during walk-along interviews.



8.6 Appendix 6.

Interview schedule and discussion guide

Interview Schedule

All the statements and questions during the interview will be tailored in a language appropriate for the age of each child participant (ages 7-16 years) and parent/guardian participants.

Introduction and gaining consent

- Interviewer and child and parent/guardian participants meet in pre-arranged location.
- Saying hello and re-introducing (if necessary).
- Summary of study, using Participant Information Sheets (given to participants again) as a guide and opportunity for children and parents/guardians to ask questions, specific focus on:
    - Brief overview of the walk and walk-along interview process (and data handling)
    - Explain we want both children's and parent's/guardian's views but we will firstly direct questions to children for parents/guardians to follow up after.
    - Google map and mud map of route given to parent/guardian and child.
    - Pre-walk statement (directed to child but involving parent/guardian):

"This is the walk we are planning to do (refer to map provided and any known landmarks). The reason we want to take a walk today is to talk about the places where you find it easy to walk and the places that might make you worried about tripping or falling. You are the expert so anything you tell me will help me learn more about how falls happen and how that makes you feel.

I may ask us to stop occasionally and talk about where we are on our walk. You can stop any time too.

Your (parent/guardian) will be with us the whole time. We can take rests during the walk whenever you want, if you feel tired just let me or (parent/guardian) know. We can also make the walk shorter if that's helpful.

- Show child and parent/guardian camera and recording equipment

"If you consent, we would also like to record the walks with cameras and microphones. I will be wearing one (show camera) and if you (child) would like to wear one too that would be great. If not, we will ask (parent/guardian) to wear one. The microphones will be attached with a clip (show microphones), and you will have a couple of minutes to get used to the equipment before we get going. The recording will continue until otherwise said after the walk."

- Introduction of video diaries and video diary sharing platform

"We would also like to capture home video diaries about trips or falls that you may encounter day-to-day that we may not come across during our walk today. This is completely optional and additional to the walk-along interview. It would require you taking pictures or videos during your day-to-day life and uploading them to a secure University OneDrive folder"

- Offer option of multiple walks if necessary - ask parent/guardian
- No right or wrong answers, no need to participate, just want to learn from their thoughts
- Confidentiality, anonymity, withdrawal from study and withdrawal of data

"Any information on cameras, paper and recorders will be confidential and only used for research. Whatever you say along the walk will be anonymised, which means no one will know it is you, even if names are mentioned during the walk."

- Any questions?

Informed consent and assent obtained from parent/guardian and child

Collection of child demographics (Age, GMFCS and/or CP diagnosis)

Set up recording equipment

- Cameras on interviewer using chest strap
- Children given the option to wear chest strap video
- If child doesn't want to, parent/guardian will be asked to wear the camera
- Children given a third camera during the interview to take pictures at stop points
- Microphones set up and attached to children and parents/guardians where possible
- Provide 2-minute familiarisation for cameras and microphones
  - "Are you OK to wear the camera and start the walk?"

Start recording

Start walk (with stops and checks as necessary)

Adjust map where necessary (and note down any reasons for changes)

Follow interview discussion guide

Stop Recording

Post-walk reminders

- Offer the option of another walk if necessary
- Reminder of video diaries and how to take part and upload to OneDrive (direct to instructions on participant information sheet previously given out)

Final thanks and summary

- Thank child and parent/guardian for their involvement
- Child offered certificate and/or sticker
-

Interview Discussion Guide

Language will be tailored for the age of each participant and guided by environmental cues and responses, using this guide as a reference. All questions may not necessarily be asked from this discussion guide or in the order as specified. Questions will firstly direct towards children with opportunity throughout the interview for parents/guardians to follow up on answers given by children.

How do you feel about where we are walking today?

1. Have you taken walks like this before?
    a. Do you feel okay about taking this walk today?
    b. How much energy do you have?
    c. Do you feel like you may lose your balance or fall on this walk/in this place?
2. Have you ever fallen here before?
    a. What might make you fall/not fall here?
        i. Prompts: functional, environmental, sensory, intrinsic (next page)

Have you ever tripped or fallen in a place like this?

1. If **NO**:
    a. Do you often fall or lose your balance balance/feel wobbly when you are walking?
    b. What places where you usually walk might cause a fall?
        i. How is that different to where we are walking now?
2. If **YES**:
    a. Did you trip or fall?
    b. Where did you fall/trip?
    c. What made you lose your balance and trip/fall over?
        i. Prompts: functional, environmental, sensory, intrinsic (next page)
    d. Would you ever not go somewhere because you may fall over? – Why?
        i. What makes you decide to not go somewhere?
        ii. What would you normally do if you wanted to avoid somewhere?
        iii. Would this change if you were with different people?
    e. How do you feel if you fall over?
    f. Do you think about falling a lot when you are walking outside?
    g. How often do you trip and not fall over?
    h. If talking about a trip, restart question: Have you ever **fallen**?

Are there any things that you can see and hear now that might make you fall?

i. Cars, playing, dogs, football etc.

Are there things that you do that make you fall or lose balance more often?

ii. What activities?
i. Why? - Prompts: functional, environmental, sensory, intrinsic (next page)

Stop Point

Take a look around, is there anything that makes you feel at risk of a fall?

2. If **<u>NO</u>**:
    a. Keep referring back to this
3. If **<u>YES</u>**:
    a. "Take a picture of what you can see around us that could make you fall"
    b. Discuss these pictures
    c. Why would this make you fall?
        i. Prompts: functional, environmental, sensory, intrinsic (see below)
    d. Would you experience this day-to-day?
        i. Has anything like this [whatever they identify] made you fall before?
        ii. Tell me about these

Prompts for why trips or falls occur:

1. Why?
2. Prompts:
    a. *Environmental* (Others, surface, obstacles, foot placement, step up/down, inclines, weather)
    b. *Functional* (Holding on, running, picking up feet, footwear/AFO's, fatigue)
    c. *Sensory* (Spatial awareness, noises, vision, vestibular)
    d. *Intrinsic* (Distractions, confidence, concentration)
3. Why would/wouldn't any of these make you fall?

Final reflective questions

(asked at the end of the walk outside with appropriate resting place e.g. bench)

How did you feel about the walk we took today?

1. Was there anywhere you thought was particularly tricky to walk?
2. Was there anywhere you felt you were more likely to trip or fall?
3. Do you feel okay now that we have taken the walk?
4. How much energy would you say you have now?
5. Do you feel like you are likely to fall now?
6. Has this changed since the start of the walk?

Is there anything else that you think would cause a fall that we haven't talked about?

Anything else you want to say about falls or the walk?

8.7 Appendix 7.

MATLAB Script used for randomising walking path directions for each participant.

Randomisation of Walkway Trials

****

NOTE: The random output is the same every time MATLAB is closed and reopened - so for each participant run the script as many number of times as the participant number for consistency (e.g. Participant 3 - run the script 3 times to get the third random output) - otherwise will be the same set of random numbers for each participant.

****

TRIAL NAMES

`P(participant number)_T(trial number)_(TrialName)_Path(number)(Distracted/Non-Distracted)`
`e.g. P1_T1_WalkPavement_Path7D`

****

Measured trials (6 grass and 6 pavement) in any *different* directions (3 distracted and 3 non distracted) with catch trials only grass to pavement or pavement to grass (unused directions), non-distracted without obstacles.

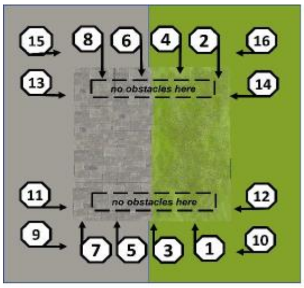
Works for 3 different grass paths with corresponding path distracted AND any 3 different pavement paths with corresponding path distracted AND a catch trial after two measured trials from either pavement to grass or grass to pavement, non-distracted, not over obstacles - so either 9, 10, 11, 12, 13, 14, 15 or 16.

Trial Labels

GRASS				PAVEMENT			
Path	Distracted (Y/N)	Code	PathName	Path	Distracted (Y/N)	Code	PathName
1	N	1	P1ND	5	N	9	P5ND
2	N	2	P2ND	6	N	10	P6ND
3	N	3	P3ND	7	N	11	P7ND
4	N	4	P4ND	8	N	12	P8ND
1	Y	5	P1D	5	Y	13	P5D
2	Y	6	P2D	6	Y	14	P6D
3	Y	7	P3D	7	Y	15	P7D
4	Y	8	P4D	8	Y	16	P8D

CATCH TRIALS

- Path 9: Non distracted = 17
- Path 10: Non distracted = 18
- Path 11: Non distracted = 19
- Path 12: Non distracted = 20
- Path 13: Non distracted = 21
- Path 14: Non distracted = 22
- Path 15: Non distracted = 23
- Path 16: Non distracted = 24



Creating a random output of 12 either grass or pavement, distracted or non distracted trials

```
% Any 3 random, grass only paths
Gra1 = randperm(4,3);
Gra2 = Gra1 + 4; % Same paths as above but to a distracted code
% Each path gets a distracted and non distracted trial added
```

```
 % e.g. if 4, 3, 1 is output from random paths we add 4 to each which provides the
code for the corresponding path with distraction (key above)

 % Any 3 random, pavement only paths
 Pav1 = randperm(4,3)+8;
 Pav2 = Pav1 + 4; % Same again for distracted trials (see key)

 % Create a row vector of random grass and pavement trials
 Trial_Code = [Gra1 Gra2 Pav1 Pav2]; % Trial number is the code from key
 % Create a string array with pathnames so can allocate pathnames to output trials
using key
 PathName = ["P1ND" "P2ND" "P3ND" "P4ND" "P1D" "P2D" "P3D" "P4D" "P5ND" "P6ND" "P7ND"
"P8ND" "P5D" "P6D" "P7D" "P8D"];
 TrialName = string(Trial_Code);
 TrialName(1:12) = PathName(Trial_Code(1:12));
 % To randomise the order in which the trials are done - shuffle the order of the 12
measured trials above
 Order = randperm(12, 12); % Create a random order array with integers - random order
of directions
 % e.g. number 9 represents the ninth trial condition from 'Trials' array

 % Assign 'Trials' numbers to new order array
 % New order array:
 Order_of_Trials = Order; % These Trial numbers are the order in which the trials
from above are carried out in - not a key to which trial it is;
 % ('Trials_in_Order' by indexing from 'order')
 % Have to make 'Trials_in_Order' a string array to index from another string array
 Order_of_Trials = string(Order_of_Trials);
 Order_of_Trials(1:12) = TrialName((Order(1:12)))
```

```
Order_of_Trials = 1×12 string
"P7D"     "P2ND"     "P2D"     "P4D"     "P4ND"     "P3ND"     ···
```

Creating randomised catch trials to add after every two measured trials

```
 % Add catch trials after every two measured trials according to random
 % order decided below:
 CatchTrials = randperm(8, 6)+16;
 PathNameCatch = ["P1ND" "P1D" "P2ND" "P2D" "P3ND" "P3D" "P4ND" "P4D" "P5ND" "P5D"
"P6ND" "P6D" "P7ND" "P7D" "P8ND" "P8D" "P9ND" "P10ND" "P11ND" "P12ND" "P13ND" "P14ND"
"P15ND" "P16ND"];
 CatchTrialName = string(CatchTrials);
 CatchTrialName(1:6) = PathNameCatch(CatchTrials(1:6))
```

```
CatchTrialName = 1×6 string
"P15ND"     "P14ND"     "P13ND"     "P11ND"     "P12ND"     "P10ND"
```

```
 % Catch trials are made up of only paths 9, 10, 11, 12, 13, 14, 15, 16 with
 % no distractions and no obstacles so as to maximise the effect of not getting used
to obstacle position
```

Final random order of trials for participant including measured trials and catch trials (run for each new particpant)

Measured, Measured, Catch, Measured, Measured, Catch, Measured, Measured, Catch, Measured, Measured, Catch, Measured, Measured, Catch, Measured, Measured, Catch.

```
Participant_Trial_Order = ["1" "2" "3" "4" "5" "6" "7" "8" "9" "10" "11" "12" "13" "14" "15" "16" "17" "18"];
Participant_Trial_Order(1:18) = [Order_of_Trials(1),Order_of_Trials(2),CatchTrialName(1),Order_of_Trials(3),Order_of_Trials(4),CatchTrialName(2),Order_of_Trials(5),Order_of_Trials(6),CatchTrialName(3),Order_of_Trials(7),Order_of_Trials(8),CatchTrialName(4),Order_of_Trials(9),Order_of_Trials(10),CatchTrialName(5),Order_of_Trials(11),Order_of_Trials(12),CatchTrialName(6)]
```

```
Participant_Trial_Order = 1×18 string
"P7D"    "P2ND"    "P15ND"    "P2D"    "P4D"    "P14ND"    ...
```

8.7 Appendix 8.

Reporting template during data collection for fall history, visual and cognitive assessment, balance confidence and anxiety questionnaire, observations during the walkway and post protocol engagement.

Participant Number:

Age: Sex: GMFCS/CP diagnosis:

Falls History

1. Is tripping or falling an issue for you?

2. How often do you experience a [trip/fall]? – Define trip/fall

   Trips Falls

   A. Never, B. Monthly, C. Weekly, D. Daily A. Never, B. Monthly, C. Weekly, D. Daily

3. How many [trips/falls] occur in that period? (if monthly, weekly or daily)

   Trips: Falls:

4. Where do these falls typically occur?

5. Why do you think that you trip and fall?

6. What impact do falls have on your daily life if any?
   a. How does that make you feel?
   b. Do you avoid any activities because of tripping or falling?

Visual and Cognitive Assessment

Acuity:

Exclusion Criteria
0.5 logMAR or greater acuity that cannot be corrected by glasses
Best for VA = -0.3 logMAR

Contrast Sensitivity:

CS: Score of 2.0 = normal contrast sensitivity. Score of 1.52 to 1.76 = normal for over 60 years of age.
1% = good

Quadrant Test (3 attempts):

1. /4 2. /4 3. /4

Trail-Making Test (time):

A:

B:

For ADULTS: After 5 minutes: test is discontinued. Average score (TMT-A) = 29 sec, deficient score = > 78 sec.

Mean Times in Seconds on Trail Making and Color Trails According to Age, IQ, and Gender

Variable	Trails A	Trails B	Color Trails 1	Color Trails 2
Age				
6–8 yrs ($n = 49$)	33.97	80.84	39.24	92.35
9–11 yrs ($n = 100$)	21.73	54.90	23.17	60.89
12+ yrs ($n = 74$)	15.94	38.17	18.17	44.56
Sex				
Female ($n = 69$)	22.68	52.52	25.13	57.89
Male ($n = 154$)	25.07	63.42	28.59	73.98

Williams et al., 1995

Physical measurements

Height: **Mass:**

Leg length: **Knee width:** **Ankle width:**

Anxiety and Balance Confidence

Condition: FIRST GRASS

1. Please use the following scale to rate <u>how confident</u> you are that you can <u>maintain your balance and avoid a fall</u> during the balance task:

0……10……20……30……40……50……60……70……80…..90……100

I do not feel confident at all	**I feel moderately confident**	**I feel completely confident**

Condition: FIRST PAVEMENT

1. Please use the following scale to rate <u>how confident</u> you are that you can <u>maintain your balance and avoid a fall</u> during the balance task:

0……10……20……30……40……50……60……70……80…..90……100

I do not feel confident at all	**I feel moderately confident**	**I feel completely confident**

Condition: GRASS Non-distracted

Using the following scale, please rate fearful of falling you felt when performing the balance task:

0.......10.......20.......30.......40.......50.......60.......70.......80.......90......100

I did not feel completely fearful at all	I felt moderately fearful	I felt fearful

Using the following scale, please rate how stable you felt when performing the balance task:

0.......10.......20.......30.......40.......50.......60.......70.......80.......90......100

I did not feel completely stable at all	I felt moderately stable	I felt stable

Condition: GRASS Distracted

Using the following scale, please rate fearful of falling you felt when performing the balance task:

0.......10.......20.......30.......40.......50.......60.......70.......80.......90......100

I did not feel completely fearful at all	I felt moderately fearful	I felt fearful

Using the following scale, please rate how stable you felt when performing the balance task:

0.......10.......20.......30.......40.......50.......60.......70.......80.......90......100

I did not feel completely stable at all	I felt moderately stable	I felt stable

Condition: PAVEMENT Non-distracted

Using the following scale, please rate fearful of falling you felt when performing the balance task:

0.......10.......20.......30.......40.......50.......60.......70….…80.......90......100

I did not feel completely fearful at all	I felt moderately fearful	I felt fearful

Using the following scale, please rate how stable you felt when performing the balance task:

0.......10.......20.......30.......40.......50.......60.......70….…80.......90......100

I did not feel completely stable at all	I felt moderately stable	I felt stable

Condition: PAVEMENT Distracted

Using the following scale, please rate fearful of falling you felt when performing the balance task:

0.......10.......20.......30.......40.......50.......60.......70….…80.......90......100

I did not feel completely fearful at all	I felt moderately fearful	I felt fearful

Using the following scale, please rate how stable you felt when performing the balance task:

0.......10.......20.......30.......40.......50.......60.......70….…80.......90......100

I did not feel completely stable at all	I felt moderately stable	I felt stable

Observations

Note any of the following here with any observed causes:

Trips/Falls Stumbles Steps off walkway Holding onto parent

*Note any influence from **distractions** – head turns or looks at screen and when*

Trial 1

Trial 2

Trial 3 ****Catch****

Trial 4

Trial 5

Trial 6 ****Catch****

Trial 7	
Trial 8	
Trial 9	****Catch****
Trial 10	
Trial 11	
Trial 12	****Catch****
Trial 13	
Trial 14	
Trial 15	****Catch****
Trial 16	
Trial 17	
Trial 18	****Catch****

Additional Notes

Any final thoughts on the protocol relative to daily fall experiences?

How did it feel?

What was most challenging?

What was the easiest?

8.8 Appendix 9.

Individual case examples of interactions with the challenging walkway leading to instability

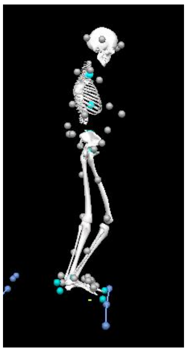
A. Trip Over Pavement Edge

Path 5, non-distracted

Trip over pavement edge

Description of Interaction

First attempt over the pavement. Participant walks slower than the previous trial on grass (0.51 m/s compared to 0.81 m/s). The participant catches the trailing (right) foot during mid swing over the third pavement edge (figure 1). This causes a quick arm movement upwards and delayed foot placement in response. Step length is also reduced on the right following the perturbation indicating a recovery step (table 1). As a result, anterior MOS before contralateral heel strike on both the right and left following the trip perturbation is reduced (table 1, figure 2 and 3).



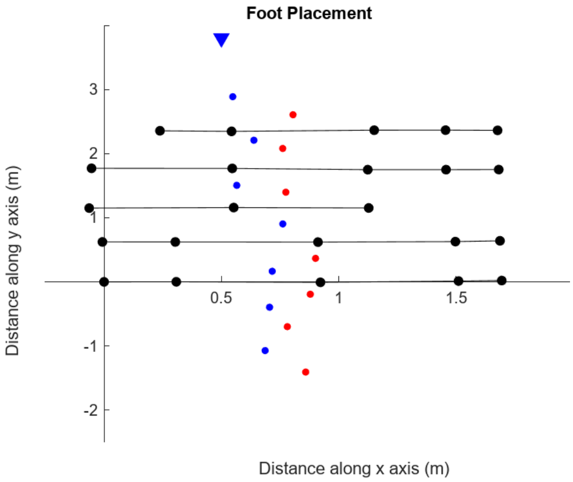


Figure 1. Foot placement of the left (red) and right (blue) foot. Blue triangle indicates walking path.

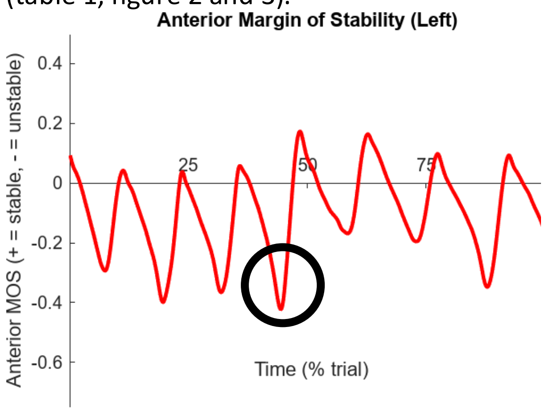


Figure 2. Left anterior margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

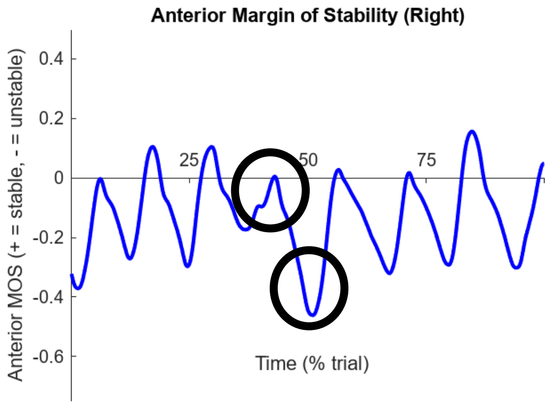


Figure 3. Right anterior margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal and Stability Metrics (* = change in response due to trip on pavement edge)

	Approach	Interaction (3^{rd} edge)	Response
Left anterior MOS before contralateral heel strike (m)	-0.26, -0.31, -0.36	-0.38*	-0.13, -0.18, -0.24
Right anterior MOS before contralateral heel strike (m)	-0.22, -0.28, -0.13	-0.34*	-0.17, -0.20, -0.24
Step width (m)	0.12, 0.18, 0.21, 0.07	0.13	0.19, 0.17, 0.18, 0.08
Step length (m)	0.40, 0.15, 0.55, 0.11	0.49	0.54, 0.20*, 0.36, 0.20

Eye tracking data (from start of trial to heel strike prior to interaction)

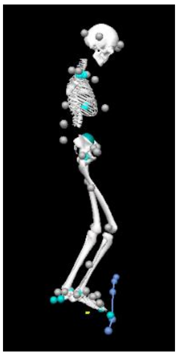
Fixation on pavement edge	Glasses offset eye tracking
Time of first fixation on edge	Glasses offset eye tracking

Path 5, distracted

Description of Interaction

No noise on distraction

Participant 2 walks over pavement and trips on first uneven edge with the trailing right leg during mid-swing. Anterior MOS on the right is delayed from entering a positive value at heel strike (figure 1). Following the trip, instability is seen as the right leg scrapes the floor before stepping over the 4th pavement edge. As a result, the foot placement of the right foot crosses the contralateral limb, reducing step width (table 1) and lateral MOS compared to other gait cycles (figure 4).



Trip over pavement edge

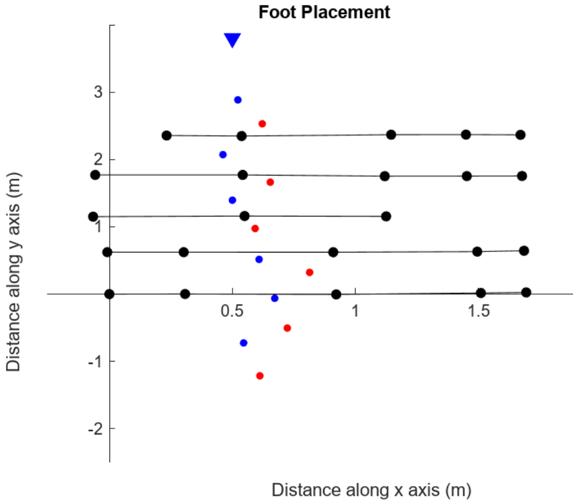


Figure 1. Foot placement of the left (red) and right (blue) foot. Blue triangle indicates walking path.

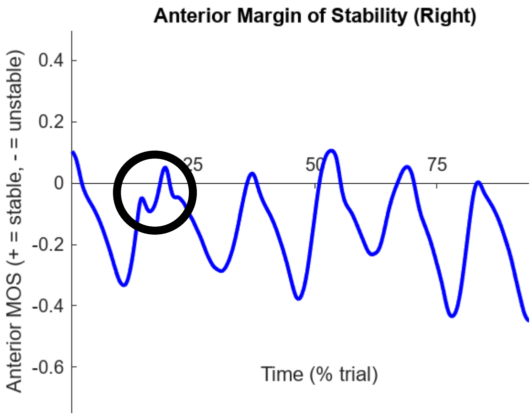


Figure 2. Right anterior margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

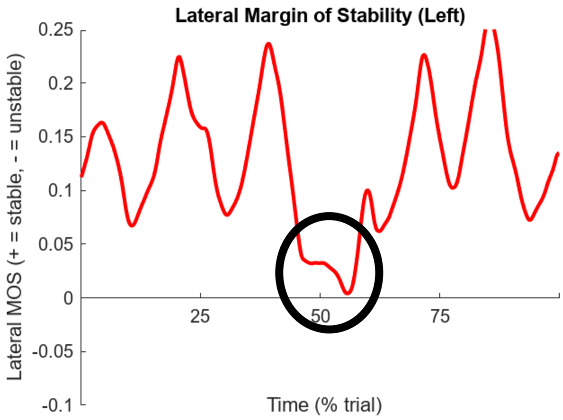


Figure 3. Left lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal Metrics (* = change in response due to trip on pavement edge)

	Approach	Interaction (3rd edge)	Response
Step width (m)	0.12, 0.18, 0.21, 0.07	0.13	0.19, 0.17, 0.18, 0.08
Step length (m)	0.40, 0.15, 0.55, 0.11	0.49	0.54, 0.20*, 0.36, 0.20

Eye tracking data (from start of trial to heel strike prior to interaction)

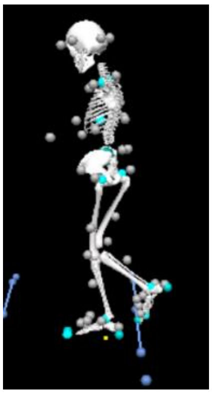
Fixation on pavement edge	Glasses offset eye tracking
Fixation on distraction	Glasses offset eye tracking
Time of first fixation on edge	Glasses offset eye tracking

Path 6, non-distracted

Trip over pavement edge

Description of Interaction

Prior to the step onto the walkway, lateral MOS reduces as participant 14 leans to their right to step their left foot over the first pavement edge (figure 2). Then, the right foot makes contact with the first pavement edge during initial swing. Following the trip, anterior MOS on the right is lower prior to ipsilateral heel strike for the following two footsteps (figure 3).



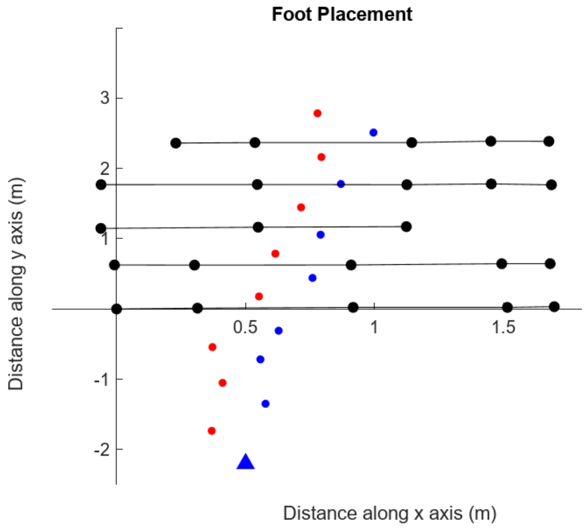


Figure 1. Foot placement of the left (red) and right (blue) foot. Blue triangle indicates walking path.

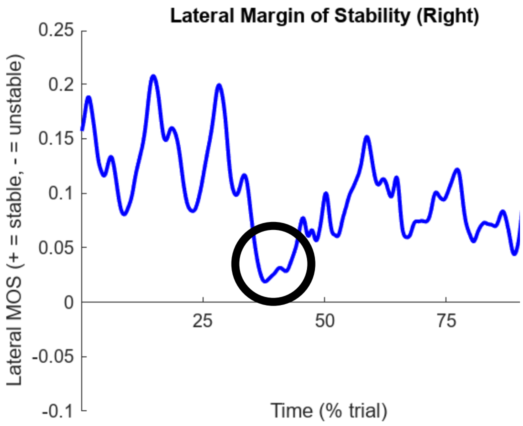


Figure 2. Right lateral margin of stability for the entire trial. Circle shows gait cycle where margin of stability is perturbed.

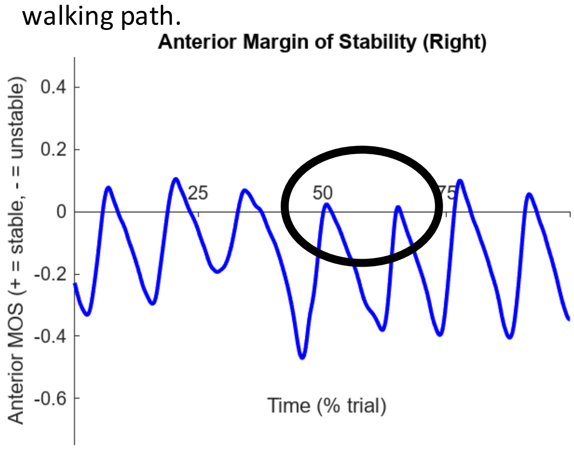


Figure 3. Right anterior margin of stability for the entire trial. Circle shows gait cycle where margin of stability is perturbed.

Spatiotemporal and Stability Metrics (* = change in response due to trip on pavement edge)

	Approach	Interaction (1st edge)	Response
Left anterior MOS before contralateral heel strike (m)	-0.27, -0.20, -0.10	-0.22	-0.23, -0.22, -0.26
Right anterior MOS at ipsilateral heel strike (m)	-0.24, -0.21, -0.14	-0.37	-0.22, -0.27, -0.27
Step width (m)	0.17, 0.14, 0.18, 0.25	0.08*	0.19, 0.14, 0.17, 0.06
Step length (m)	0.35, 0.16, 0.26, 0.48	0.29	0.32, 0.29, 0.37, 0.35

Eye tracking data (from start of trial to heel strike prior to interaction)

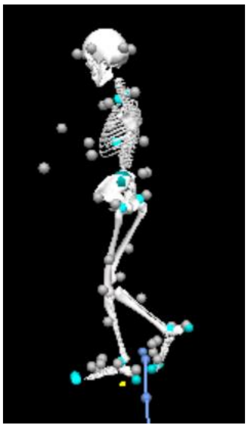
Fixation on pavement edge	Glasses offset eye tracking
Time of first fixation on edge	Glasses offset eye tracking

Path 8, non-distracted

Trip over pavement edge

Description of Interaction

Participant 14 trips their trailing (right) limb on the first pavement edge during initial-swing. Right anterior MOS at ipsilateral heel strike is reduced following this (figure 1). Left anterior MOS at contralateral heel strike is increased (figure 2).



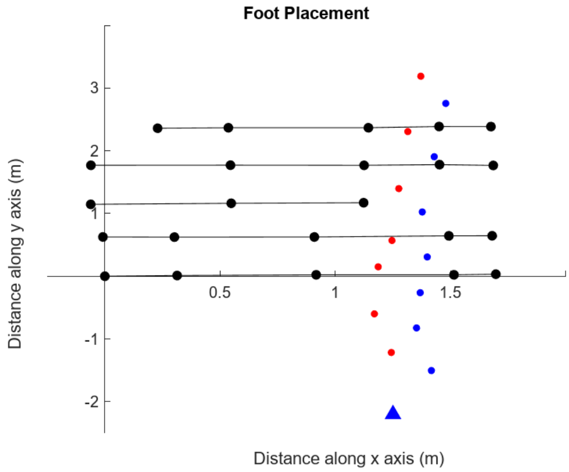


Figure 1. Foot placement of the left (red) and right (blue) foot. Blue triangle indicates walking path.

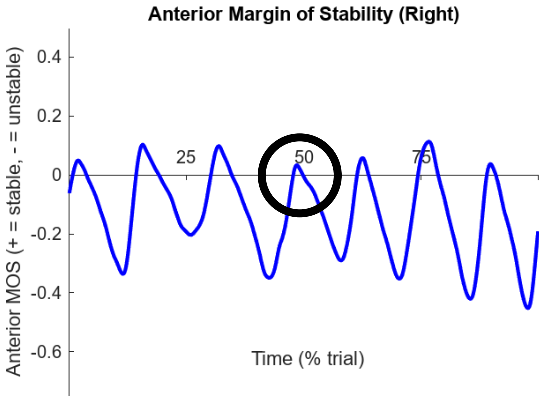


Figure 2. Right anterior margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

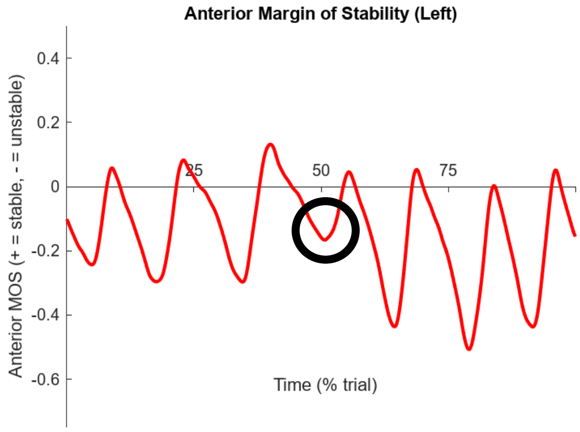


Figure 3. Left anterior margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal and Stability Metrics (* = change in response due to trip on pavement edge)

	Approach	Interaction (1st edge)	Response
Left anterior MOS before contralateral heel strike (m)	-0.17, -0.25, -0.22	-0.11*	-0.36, -0.38, -0.38
Right anterior MOS at ipsilateral heel strike (m)	-0.22, -0.13, -0.27		-0.20, -0.29, -0.37, -0.36
Step width (m)	0.10, 0.18, 0.20, 0.18	0.21	0.15, 0.12, 0.10, 0.15
Step length (m)	0.28, 0.40, 0.22, 0.34	0.41	0.17, 0.25, 0.46, 0.37

Eye tracking data (from start of trial to heel strike prior to interaction)

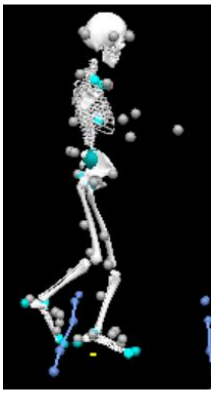
Fixation on pavement edge	Glasses offset eye tracking
Time of first fixation on edge	Glasses offset eye tracking

Path 5, non-distracted

<u>Trip over pavement edge</u>

Description of Interaction

Participant 14 steps over the first pavement edge of the walkway with much smaller step width (0.06 m) compared to other steps (table 1). They trip their left (trailing) limb in early swing when stepping across the first pavement edge. Step width is increased and no obvious perturbations in MOS are seen. At the end of the walkway the participant appears to stop before stepping down off the pavement edge, which causes changes to anterior and lateral MOS (figure 1).



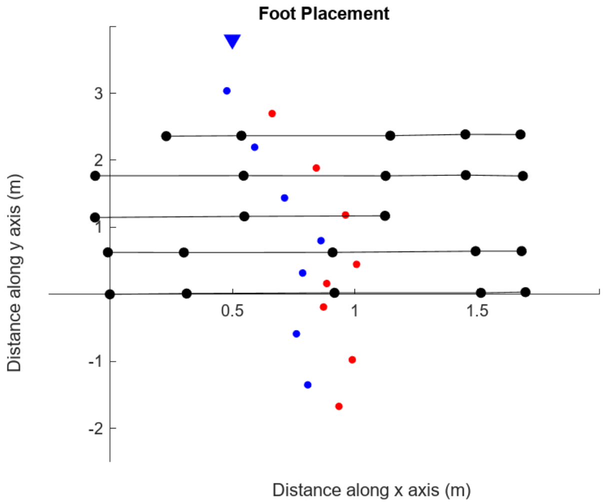


Figure 1. Foot placement of the left (red) and right (blue) foot. Blue triangle indicates walking path.

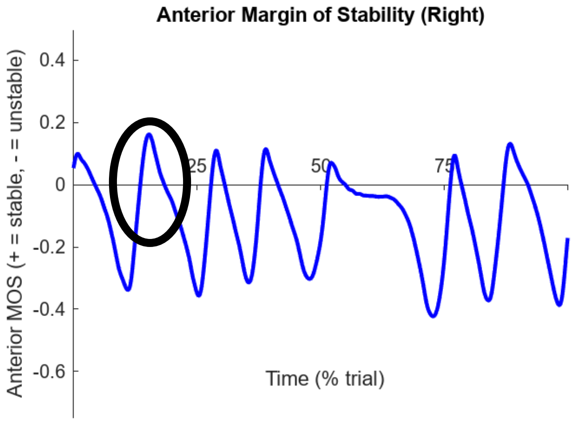


Figure 2. Right anterior margin of stability for the entire trial. Circle shows gait cycle where trip occurs.

Spatiotemporal Metrics (* = change in response due to trip on pavement edge)

	Approach	Interaction (1st edge)	Response
Step width (m)	0.22, 0.19	0.06*	0.23, 0.12, 0.24, 0.11
Step length (m)	0.35	0.50*	0.33, 0.44, 0.27, 0.37

Eye tracking data (from start of trial to heel strike prior to interaction)

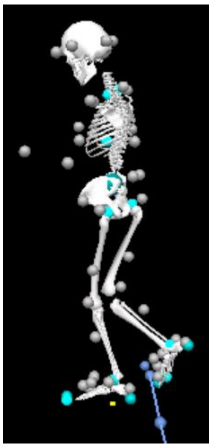
Fixation on pavement edge	Glasses offset eye tracking
Time of first fixation on edge	Glasses offset eye tracking

Path 8, non-distracted

<u>Trip over pavement edge</u>

Description of Interaction

Participant 14 trips over the first pavement edge with the right foot during early swing. Anterior MOS on the right is reduced at ipsilateral heel strike following the trip compared to other gait cycles (figure 2).



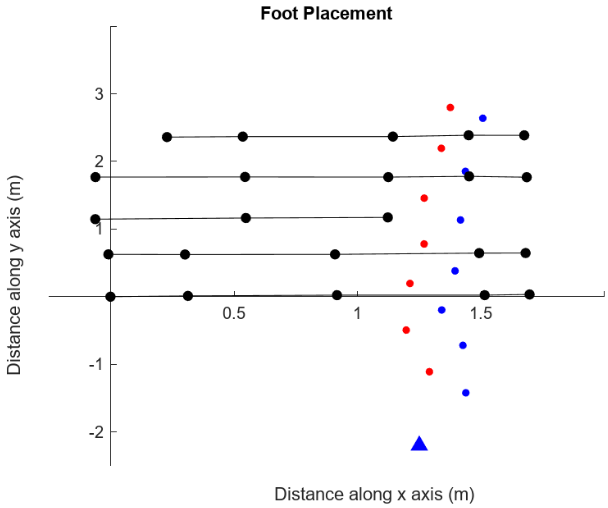


Figure 1. Foot placement of the left (red) and right (blue) foot. Blue triangle indicates walking path.

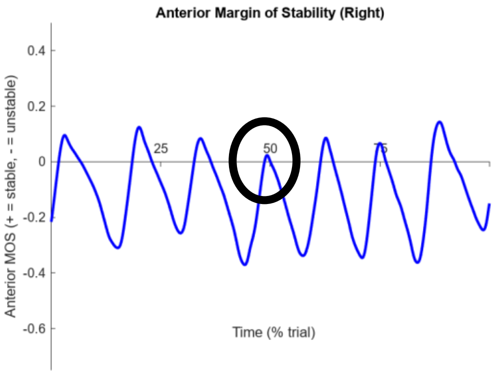


Figure 2. Right anterior margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

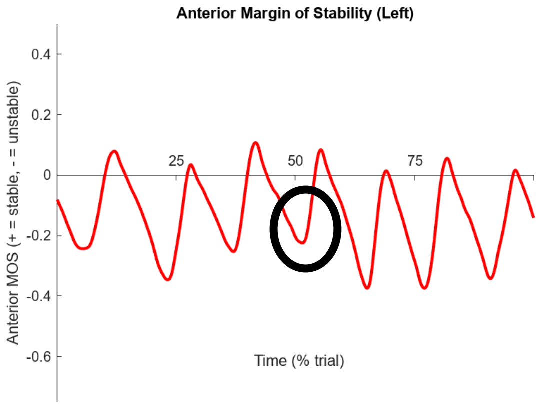


Figure 3. Left anterior margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal Metrics (* = change in response due to trip on pavement edge)

	Approach	Interaction (1st edge)	Response
Step width (m)	0.13, 0.22, 0.15, 0.12	0.18	0.11, 0.15, 0.14, 0.15
Step length (m)	0.31, 0.39, 0.22, 0.30	0.39	0.19, 0.39, 0.36, 0.32

Eye tracking data (from start of trial to heel strike prior to interaction)

Fixation on pavement edge	Glasses offset eye tracking
Fixation on distraction	Glasses offset eye tracking
Time of first fixation on edge	Glasses offset eye tracking

B. Step Onto Pavement Edge

Description of Interaction

Participant 2 steps onto the fourth pavement edge with the right foot. A short step is taken following the step on pavement edge. This causes negative MOS in the anterior direction on the left (figure 2), at ipsilateral heel strike, in comparison to other gait cycles where anterior MOS begins positive, this also causes reduced anterior MOS just before contralateral heel strike on the left compared to prior gait cycles (table 1).

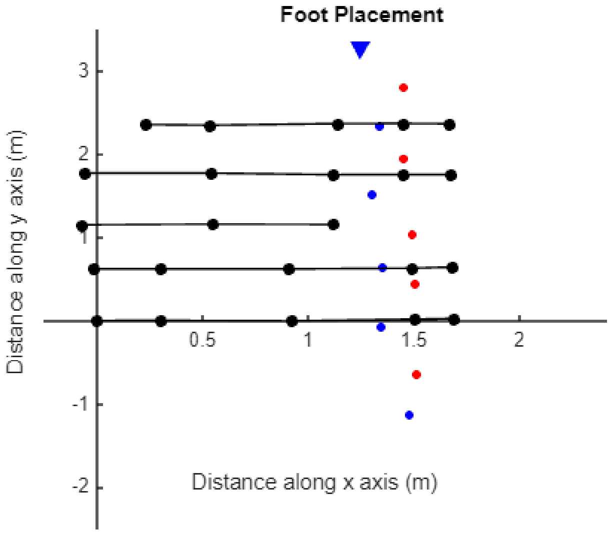


Figure 1. Foot placement of the left (red) and right (blue) foot. Blue triangle indicates walking path.

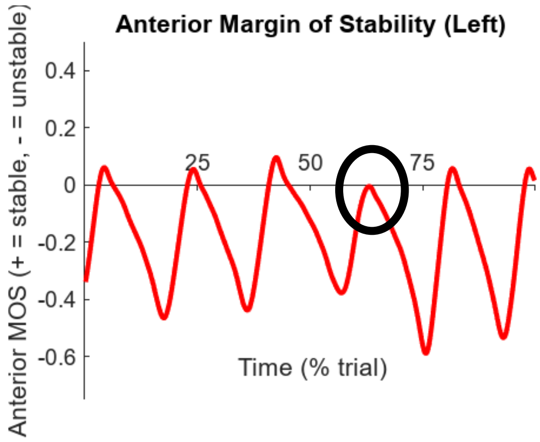


Figure 2. Left anterior margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal and stability Metrics (* = change in response to interaction)

	Approach	Interaction (4^{th} edge)	Response
Left anterior MOS before contralateral heel strike (m)	-0.35, -0.36	-0.27	-0.42*, -0.47
Right anterior MOS before contralateral heel strike (m)	-0.42, -0.31	-0.36	-0.18*, -0.48
Step width (m)	0.15, 0.19	0.15	0.16, 0.18
Step length (m)	0.42, 0.48	0.39	0.21*, 0.51

Eye tracking data (from start of trial to heel strike prior to interaction)

Fixation on pavement edge	Glasses offset eye tracking
Time of first fixation on edge	Glasses offset eye tracking

Path 7, non-distracted *__Step onto pavement edge__*

Description of Interaction

Participant 3 walks fast with forward lean and constant negative anterior MOS for every right and left gait cycle (figure 2) Anterior MOS becomes progressively more negative each gait cycle on both right and left. Lateral MOS on the right is reduced close to zero for the entire trial as soon as they step onto the walkway, then MOS increases after stepping off the walkway (figure 3). Participant steps on pavement edges during this trial.

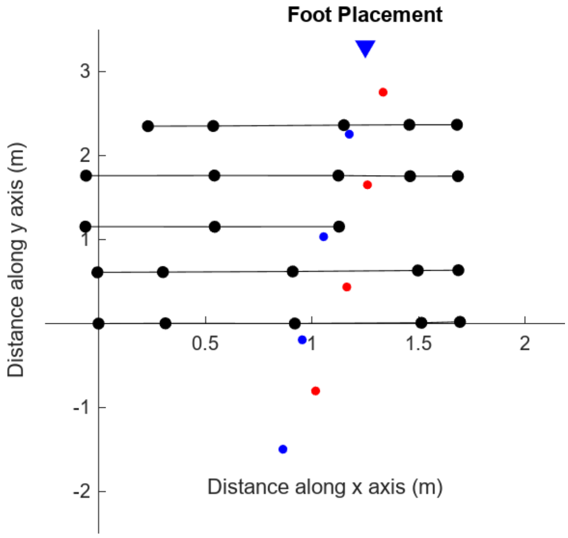


Figure 1. Foot placement of the left (red) and right (blue) foot. Blue triangle indicates walking path.

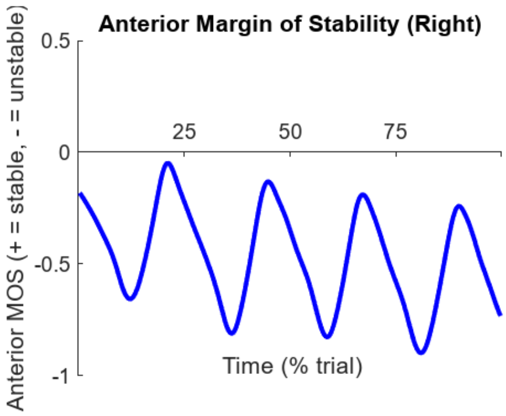


Figure 2. Right anterior margin of stability for the entire trial. Similar is shown in left anterior margin of stability.

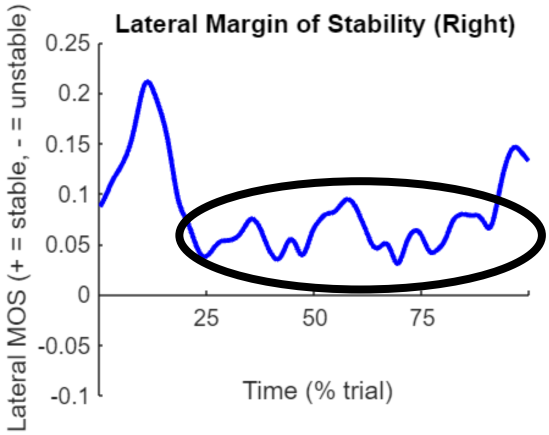


Figure 3. Right lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction

Spatiotemporal Metrics (* = change in response to interaction)

	Step 1	Step 2	Step 3	Step 4	Step 5	Step 6	Step 7	Step 8
Step width (m)	0.20	0.15	0.09	0.19	0.12	0.19	0.06	0.11
Step length (m)		0.51	0.60	0.63	0.60	0.63	0.61	0.70

Eye tracking data (from start of trial to heel strike prior to interaction)

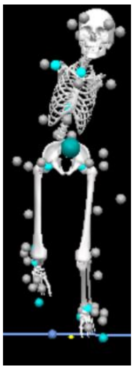
Fixation on pavement edge	Glasses offset eye tracking
Time of first fixation on edge	Glasses offset eye tracking

Path 6, distracted

<u>Step onto pavement edge</u>

Description of Interaction

Participant 3 was distracted (talking) at the beginning of the trial (noted observations). They step on the first pavement edge with the left foot causing a slight instability. During the instability, COM velocity and forward trunk lean increases. Anterior MOS on the left is reduced prior to the following contralateral heel strike (table 1). Following the instability, step width is increased, lateral MOS on the left is increased more rapidly than in other gait cycles (figure 1) and on the right has a prolonged peak (figure 2), a potential response to instability.



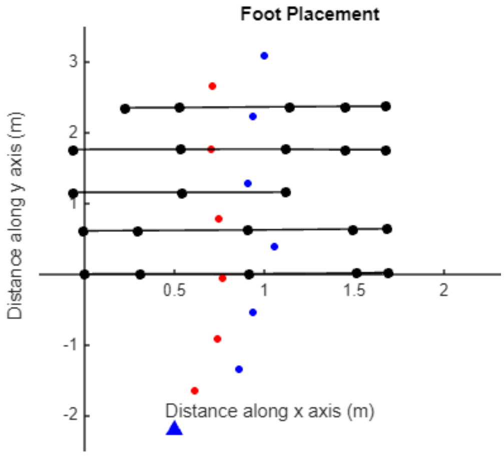


Figure 1. Foot placement of the left (red) and right (blue) foot. Blue triangle indicates walking path.

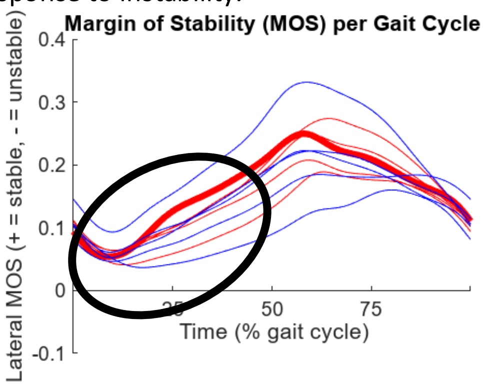


Figure 2. Lateral margin of stability for the left (red) and right (blue) sides for each gait cycle. Bold line indicates instability during gait cycle. Circle shows rapid increase in stability due to interaction.

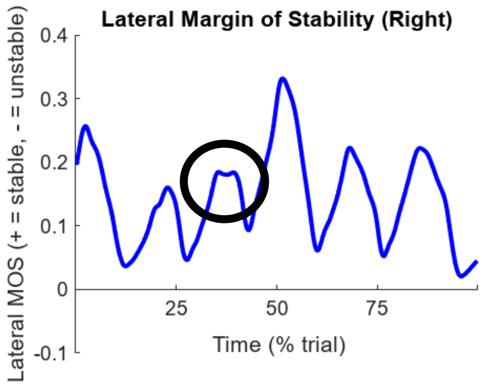


Figure 3. Right lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction

Spatiotemporal and stability Metrics (* = change in response to interaction)

	Approach	Perturbation (1st edge)	Response
Left anterior MOS before contralateral heel strike (m)	-0.27, -0.38	-0.42*	-0.48*, -0.39, -0.29
Right anterior MOS before contralateral heel strike (m)	-0.39, -0.40, -0.46	-0.32	-0.45, -0.36
Step width (m)	0.24, 0.12, 0.18	0.18	0.28*, 0.30*, 0.16
Step length (m)	0.43, 0.39	0.48	0.45, 0.38, 0.50

Eye tracking data (from start of trial to heel strike prior to interaction)

Fixation on pavement edge	Glasses offset eye tracking
Fixation on distraction	Glasses offset eye tracking (talking during trial)
Time of first fixation on edge	Glasses offset eye tracking

Path 6, non-distracted

Step onto a pavement edge

Description of Interaction

Participant 5 reaches the second pavement edge and stands on this with their right foot. Anterior MOS upon the following left heel strike is reduced and remains below zero (unstable). The following step has a much smaller length, before stepping over the third pavement edge with the right foot. During the subsequent step, the left foot contacts the pavement edge during initial swing, meaning anterior MOS on left heel strike again remains below zero (figure 2).

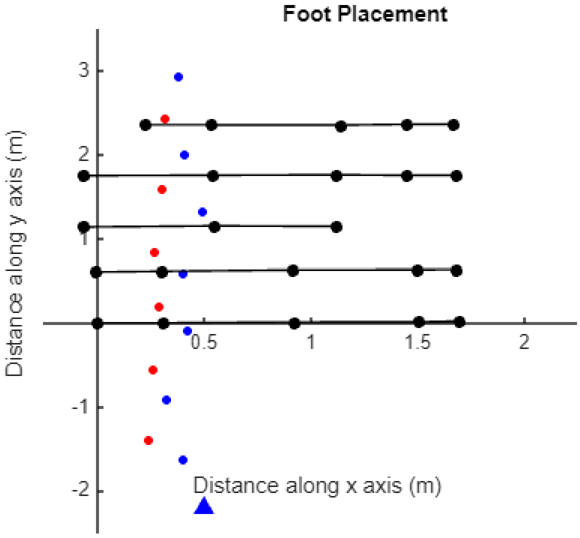


Figure 1. Foot placement of the left (red) and right (blue) foot. Blue triangle indicates walking path.

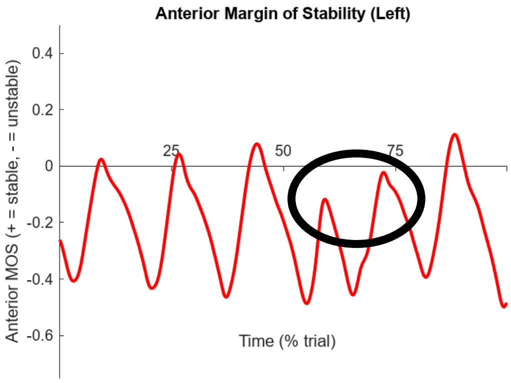


Figure 2. Left anterior margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal and Stability Metrics (* = change in response to interaction)

	Approach	Interaction (2nd edge)	Response
Left anterior MOS before contralateral heel strike (m)	-0.33, -0.37, -0.40	-0.39	-0.42*, -0.34, -0.46
Right anterior MOS before contralateral heel strike (m)	-0.20, -0.31, -0.20	-0.33	-0.27, -0.32
Step width (m)	0.12, 0.18, 0.21, 0.07	0.13	0.19, 0.17, 0.18, 0.08
Step length (m)	0.40, 0.15, 0.55, 0.11	0.49	0.54, 0.20*, 0.36, 0.20

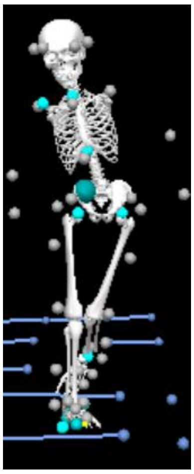
Eye tracking data (from start of trial to heel strike prior to interaction)

Fixation on pavement edge	6% (0.4 seconds)
Time of first fixation on edge	54% (2.8 seconds prior to interaction)

Path 7, non-distracted ***Step onto a pavement edge***

Description of Interaction

Participant 10 steps on the fourth pavement edge with the heel, shows crossing of limbs and reduced step width, then takes a slightly larger step forward and steps on the last pavement edge. In the gait cycle following the interaction, crossing of limbs is seen again causing reduced step width and negative lateral MOS on the left (figure 2). Left anterior MOS at contralateral and ipsilateral heel strike is also reduced in the gait cycle following the interaction (table 1).



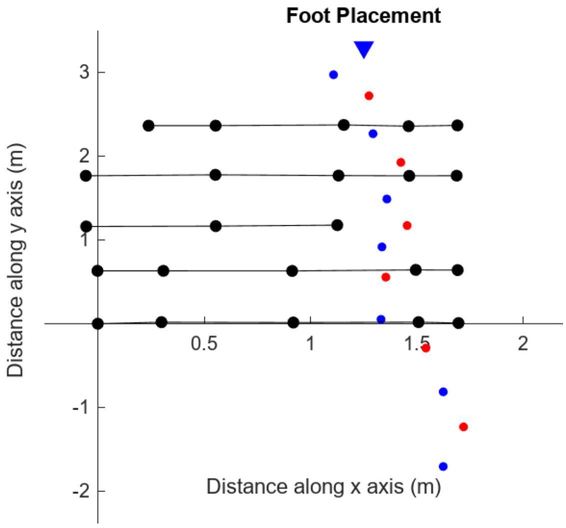


Figure 1. Foot placement of the left (red) and right (blue) foot. Blue triangle indicates walking path.

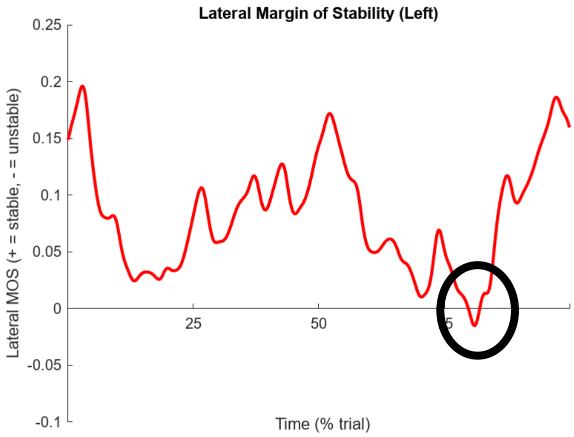


Figure 2. Left lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal and Stability Metrics (* = change in response to interaction)

	Approach	Interaction (5th edge)	Response
Left anterior MOS before contralateral heel strike (m)	-0.18, -0.30, -0.35, -0.22	-0.42*	-0.46*, -0.42
Right anterior MOS at ipsilateral heel strike (m)	0.04, 0.05, 0.05, 0.09	-0.04*	-0.02*
Step width (m)	0.05, 0.08, 0.10, 0.01*	0.00*	0.18, -0.07, 0.07, 0.09
Step length (m)	0.42, 0.33, 0.24, 0.37	0.49*	0.37, 0.53, 0.44, 0.45

Eye tracking data (from start of trial to heel strike prior to interaction)

Fixation on pavement edge	8% (0.5 seconds)
Time of first fixation on edge	61% (2.7 seconds prior to interaction)

Path 5, distracted

Step onto pavement edge

Description of Interaction

Participant 14 walks slowly (0.53 m/s). They step onto the first pavement edge and stop to retain balance. They then show a small trip with the right (trailing) limb during swing phase over the second pavement edge, however with no changes to MOS. The participant steps onto the final pavement with the right foot and lateral MOS on the right is reduced for a full gait cycle compared to others (figure 2 and 3).

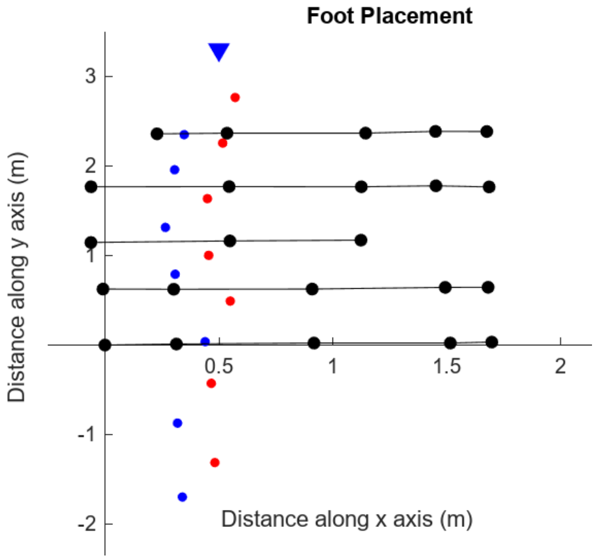


Figure 1. Foot placement of the left (red) and right (blue) foot. Blue triangle indicates walking path.

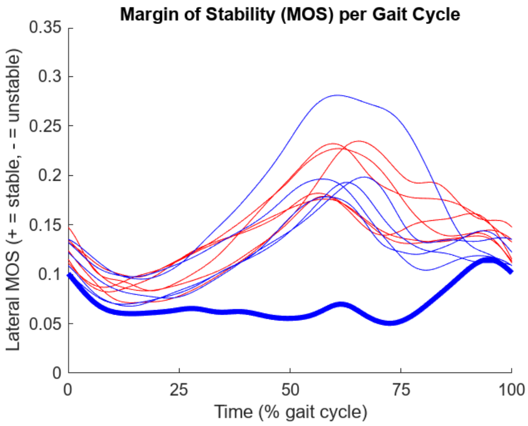


Figure 2. Lateral margin of stability for the left (red) and right (blue) sides for each gait cycle. Bold line indicates instability during gait cycle.

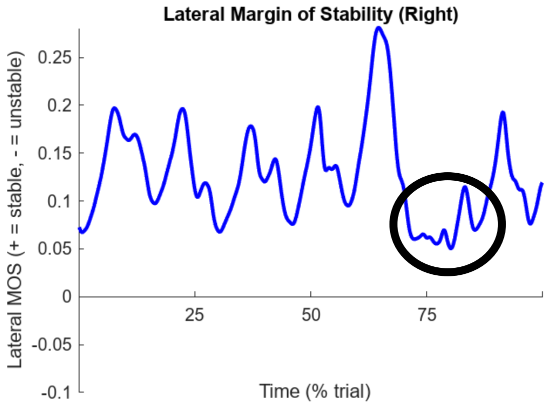


Figure 3. Right lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal Metrics (* = change in response to interaction)

	Approach	Interaction (5^{th} edge)	Response
Step width (m)	0.18, 0.18, 0.14, 0.24	0.12	0.02*, 0.12, 0.16, 0.13
Step length (m)	0.32, 0.31, 0.22, 0.29	0.46	0.46, 0.45, 0.43, 0.39

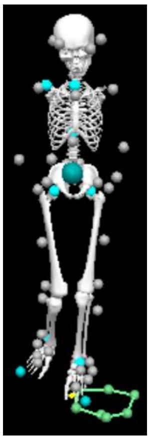
Eye tracking data (from start of trial to heel strike prior to interaction)

Fixation on pavement edge	Glasses offset eye tracking
Fixation on distraction	Glasses offset eye tracking
Time of first fixation on edge	Glasses offset eye tracking)

C. Step Into A Pothole

Description of Interaction

Participant 1 stepped their lateral part of the left foot into a pothole. When this occurs left lateral MOS remained close to zero in a full gait cycle rather than increasing as shown in other gait cycles (figure 2). Anterior MOS was reduced prior to contralateral heel strike on the left, compared to other gait cycles, after stepping into the pothole (table 1). Following the step into the pothole, step width was also reduced.



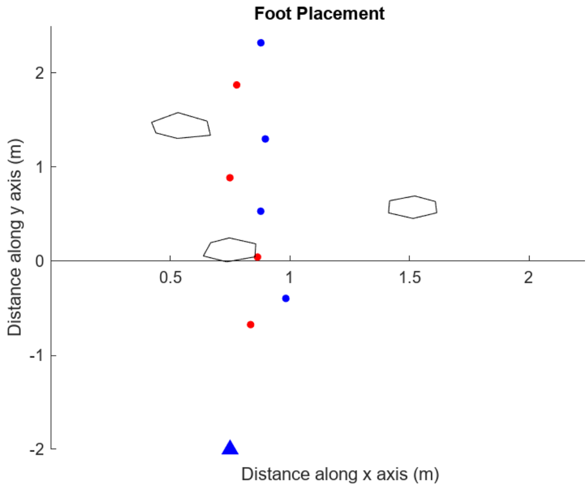


Figure 1. Foot placement of the left (red) and right (blue) foot. Blue triangle indicates walking path.

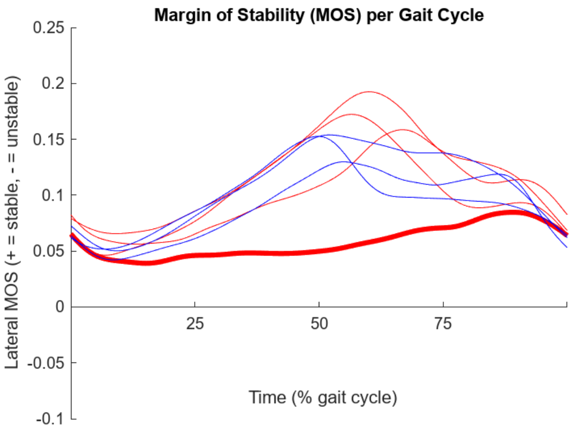


Figure 2. Lateral margin of stability for the left (red) and right (blue) sides for each gait cycle. Bold line indicates instability during gait cycle.

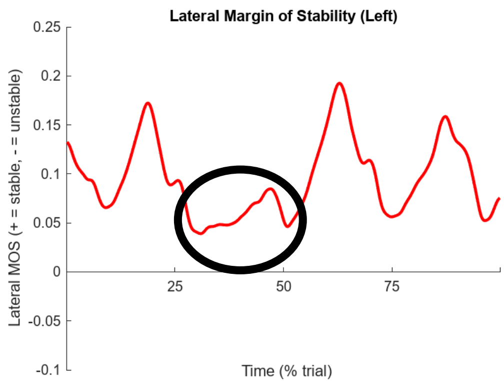


Figure 3. Left lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal and Stability Metrics (* = change in response to interaction)

	Approach	Interaction with pothole	Response
Left anterior MOS before contralateral heel strike (m)	-0.21	-0.34*	-0.29, -0.30
Right anterior MOS before contralateral heel strike (m)	-0.29, -0.31	-0.26	-0.40, -0.38
Step width (m)	0.10, 0.14	0.11	0.02, 0.11
Step length (m)	0.27	0.44	0.48, 0.36

Eye tracking data (from start of trial to heel strike prior to interaction)

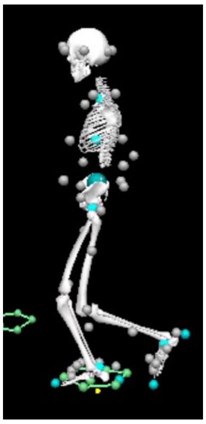
Fixation on pothole	0% (0 seconds)
Fixation on distraction	72%
Time of first fixation on pothole	Did not look at pothole

Path 3, non-distracted

Step into a pothole

Description of Interaction

Participant 2 stepped their right foot into a pothole. Causing negative anterior MOS at right heel strike as oppose to positive in other gait cycles (figure 2). Step width was reduced during and after the perturbation (table 1), which resulted in a small decrease in lateral MOS to 0.02, which was lower than other gait cycles in this trial (figure 3).



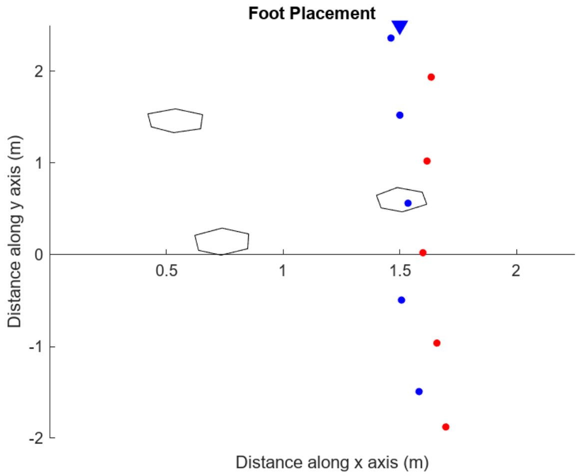


Figure 1. Foot placement of the left (red) and right (blue) foot. Blue triangle indicates walking path.

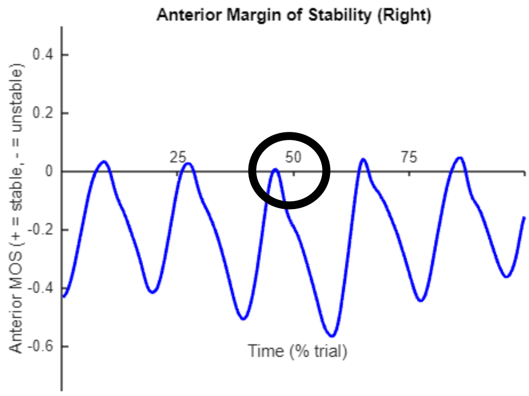


Figure 2. Right anterior margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

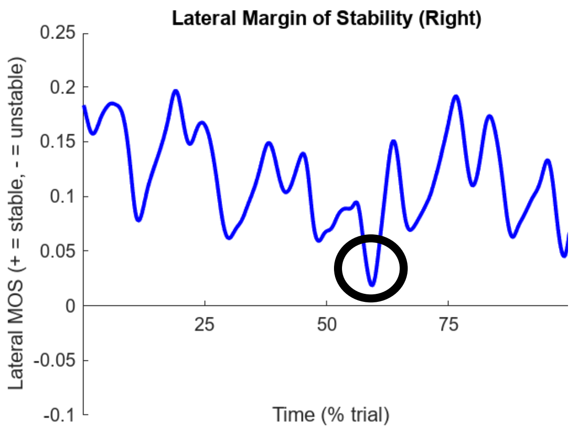


Figure 3. Right lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal and Stability Metrics (* = change in response to interaction)

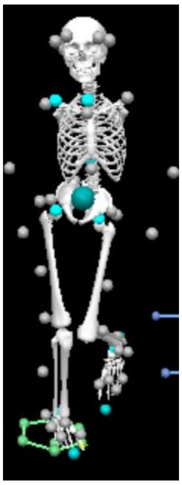
	Approach	Interaction with pothole	Response
Step width (m)	0.14, 0.11	0.08	0.05, 0.09
Step length (m)	0.41, 0.50	0.46	0.54, 0.51

Eye tracking data (from start of trial to heel strike prior to interaction)

Fixation on pothole	Glasses offset eye tracking
Time of first fixation on pothole	Glasses offset eye tracking

Description of Interaction

Participant 5 stepped into a pothole with the right foot (figure 1), showed a response to the perturbation with arms. Following the step into the pothole, right lateral MOS was reduced for two full gait cycles (figure 2).



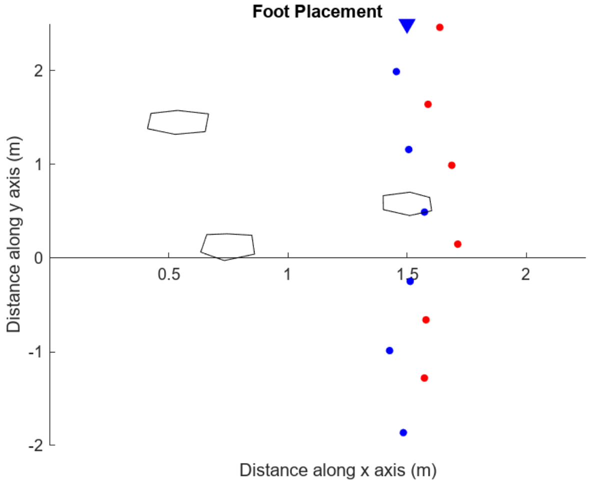


Figure 1. Foot placement of the left (red) and right (blue) foot. Blue triangle indicates walking path.

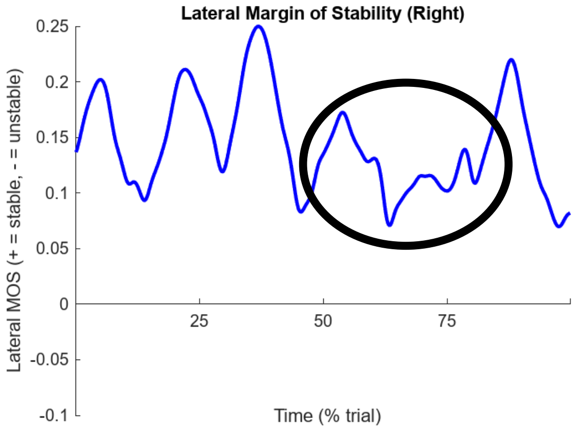


Figure 2. Right lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal Metrics (* = change in response to interaction)

	Approach	Interaction With pothole	Response
Step width (m)	0.18, 0.14, 0.09, 0.18	0.15	0.14, 0.20, 0.07, 0.14
Step length (m)	0.47, 0.35, 0.49, 0.17	0.50	0.35, 0.39, 0.42, 0.33

Eye tracking data (from start of trial to heel strike prior to interaction)

Fixation on pothole	0% (0 seconds)
Fixation on distraction	70%
Time of first fixation on pothole	Did not look at pothole

Description of Interaction

Participant 5 stepped into a pothole with the left foot. Lateral MOS on the right reduced during swing phase of the right gait cycle, and remained much lower compared to other gait cycles (figure 2). MOS moved toward the ipsilateral side during the left foot step into the pothole, causing potential instability on the following step, can also be seen observationally. Anterior MOS increased following the step (table 1).

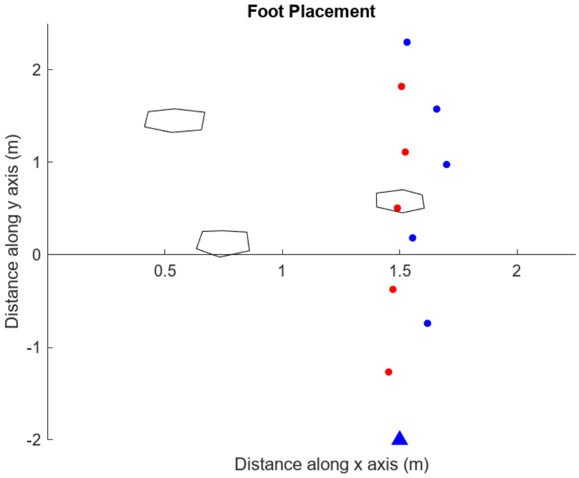


Figure 1. Foot placement of the left (red) and right (blue) foot. Blue triangle indicates walking path.

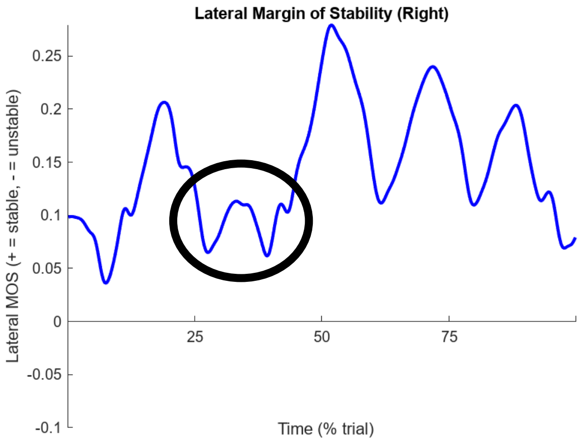


Figure 2. Right lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal and Stability Metrics (* = change in response to interaction)

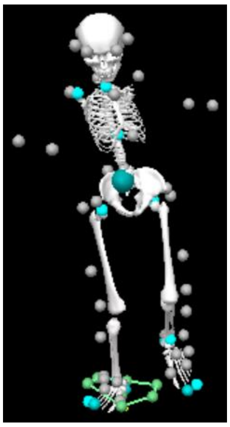
	Approach	Interaction With pothole	Response
Left anterior MOS before contralateral heel strike (m)	-0.58, -0.48	-0.44	-0.36*, -0.46, -0.44
Right anterior MOS before contralateral heel strike (m)	-0.55, -0.44		-0.29*, -0.14*, -0.24, -0.28
Step width (m)	0.15, 0.15, 0.09	0.06	0.19, 0.20, 0.15, 0.15
Step length (m)	0.52, 0.37, 0.55	0.33	0.46, 0.14, 0.46, 0.24

Eye tracking data (from start of trial to heel strike prior to interaction)

Fixation on pothole	25% (0.6 seconds)
Fixation on distraction	0%
Time of first fixation on pothole	66% (0.8 seconds prior to interaction)

Description of Interaction

Participant 14 walked slow (0.43 m/s) with large step width (mean: 0.18 m). The participant was looking at the distraction (based on real-time observations). They stepped their right foot into a pothole. Right lateral MOS was slightly reduced on this gait cycle compared to others (figure 2), but they then recovered.



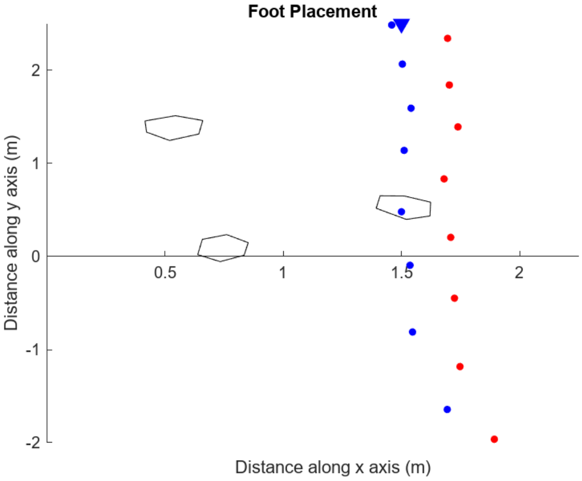


Figure 1. Foot placement of the left (red) and right (blue) foot. Blue triangle indicates walking path.

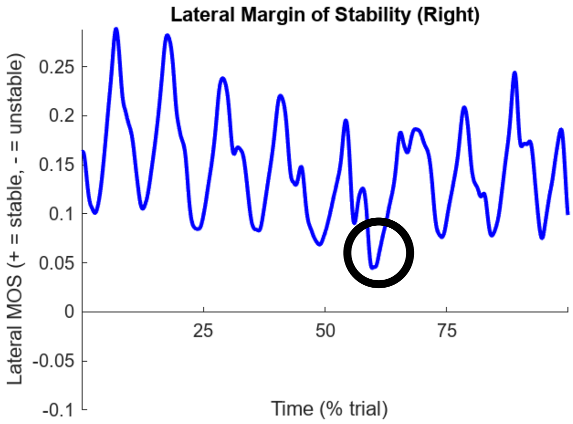


Figure 2. Right lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal Metrics (* = change in response to interaction)

	Approach	Interaction With pothole	Response
Step width (m)	0.19, 0.22, 0.17	0.16*	0.20, 0.17, 0.17
Step length (m)	0.21, 0.24, 0.32	0.34*	0.29, 0.28, 0.36

Eye tracking data (from start of trial to heel strike prior to interaction)

Fixation on pothole	Glasses offset eye tracking
Fixation on distraction	Glasses offset eye tracking
Time of first fixation on pothole	Glasses offset eye tracking

Path 3, non-distracted

Step into a pothole

Description of Interaction

Participant 14 approached the pothole faster than typical (0.55 m/s), with large step width. They stepped the left foot onto the edge of the pothole, which then moved into the pothole throughout stance. They took a shorter, narrower, faster footstep with the right leg the step following, followed by a wider step with the left (table 1). The step into the pothole caused a lateral MOS on the left to remain decreased for a full gait cycle unlike others (figure 2).

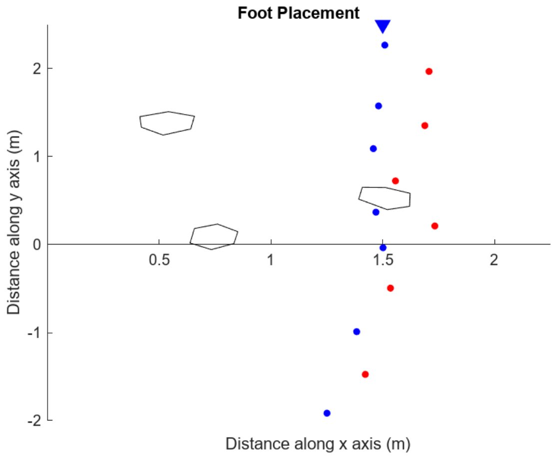
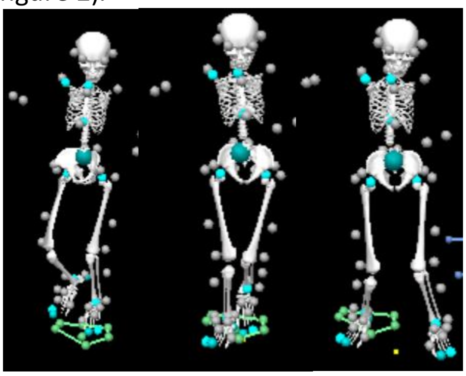


Figure 1. Foot placement of the left (red) and right (blue) foot. Blue triangle indicates walking path.



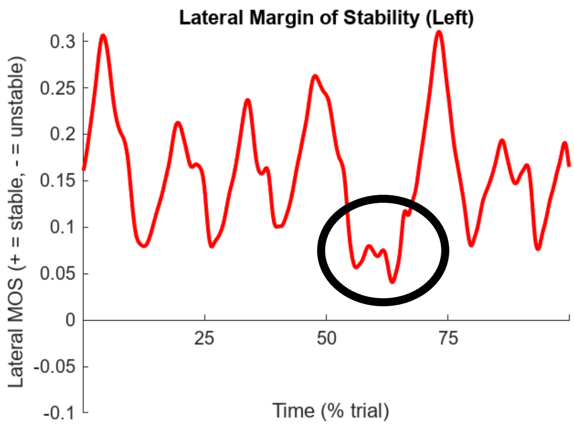


Figure 2. Left lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal Metrics (* = change in response to interaction)

	Approach	Interaction With pothole	Response
Step width (m)	0.18, 0.21. 0.20, 0.22	0.10	0.06*, 0.24*, 0.27
Step length (m)	0.29, 0.40, 0.21, 0.27	0.36	0.36, 0.15*, 0.26, 0.45

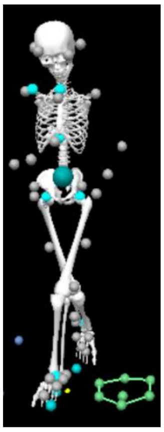
Eye tracking data (from start of trial to heel strike prior to interaction)

Fixation on pothole	Glasses offset eye tracking (child mentioned they didn't quite see the pothole)
Time of first fixation on pothole	Glasses offset eye tracking

D. Avoiding A Pothole

Description of Interaction

Participant 1, makes a late adjustment step with the right foot to increase step width around the pothole, this reduces anterior MOS on the left prior to contralateral heel strike compared to other gait cycles (table 1). The left foot then crosses the right on the step around the pothole causing a negative step width and negative lateral MOS on the right on this gait cycle (figure 2).



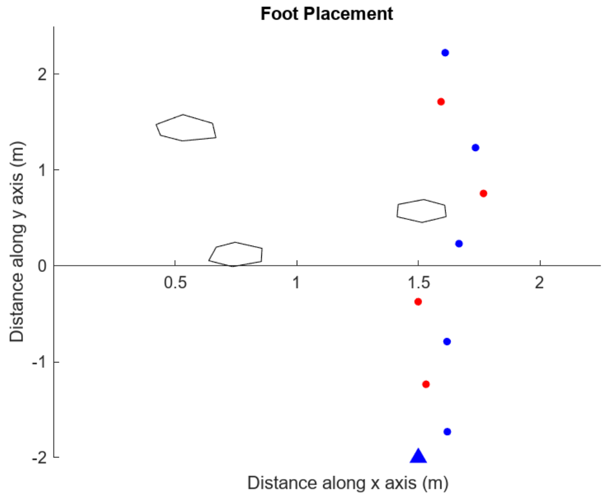


Figure 1. Foot placement of the left (red) and right (blue) foot. Blue triangle indicates walking path.

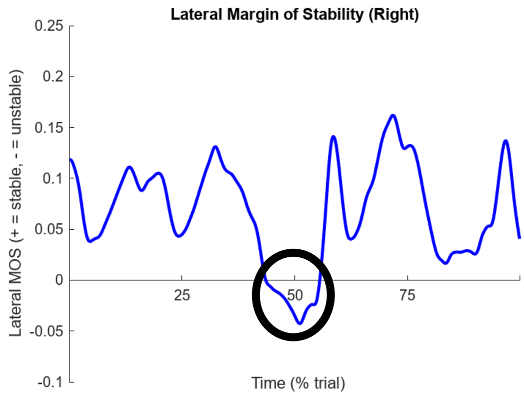


Figure 2. Right lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal and Stability Metrics (* = change in response to interaction)

	Approach	Interaction with pothole	Response
Left anterior MOS before contralateral heel strike (m)	-0.30, -0.30	-0.48*	-0.37, -0.42
Right anterior MOS before contralateral heel strike (m)	-0.34, -0.30	-0.35	-0.33, -0.44
Step width (m)	0.10 , 0.16	-0.09	-0.05, 0.13
Step length (m)	0.42, 0.61	0.53	0.48, 0.48

Eye tracking data (from start of trial to heel strike prior to interaction)

Fixation on pothole	19% (1 seconds)
Fixation on distraction	21%
Time of first fixation on pothole	62% (1.9 seconds prior to interaction)

Path 3, distracted

Avoiding a pothole

Description of Interaction

Upon approach to the pothole participant 1 increases their step width with the left foot to the side of the pothole (figure 1), then step their right foot over the pothole. In the step following the pothole, step width is reduced (table 1) and crossing of legs is seen, causing MOS to remain closer to zero on the right rather than increasing as in other gait cycles (figure 2).

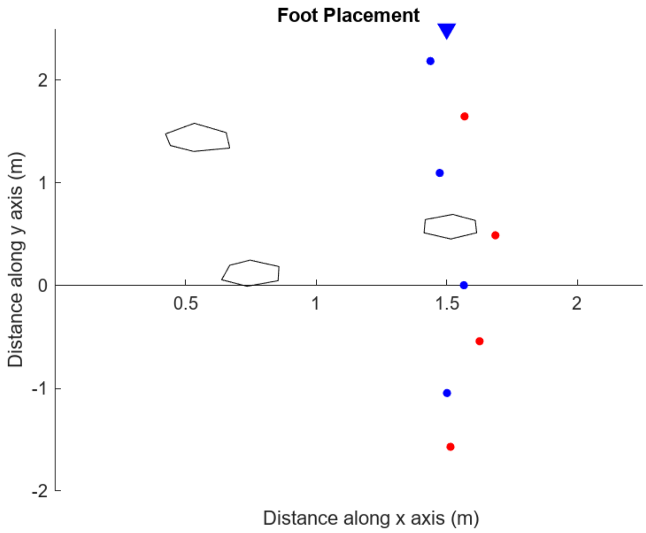


Figure 1. Foot placement of the left (red) and right (blue) foot. Blue triangle indicates walking path.

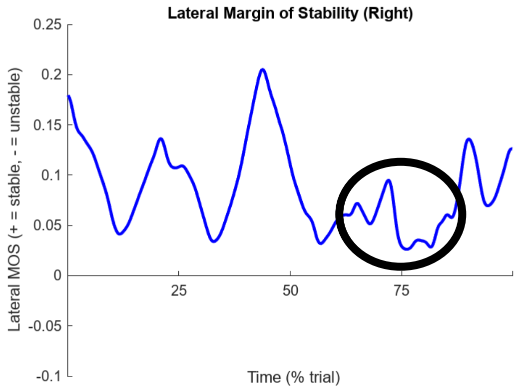


Figure 2. Right lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal Metrics (* = change in response to interaction)

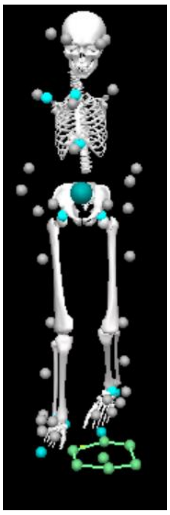
	Approach	Interaction with pothole	Response
Step width (m)	0.11, 0.12, 0.08, 0.20*	0.12	0.05, 0.10, -0.01, 0.05
Step length (m)	0.54, 0.55, 0.61*	0.48	0.55, 0.50, 0.53, 0.49

Eye tracking data (from start of trial to heel strike prior to interaction)

Fixation on pothole	19% (1 seconds)
Fixation on distraction	22%
Time of first fixation on pothole	48% (2.7 seconds prior to interaction)

Description of Interaction

Upon approach to the pothole, participant 2 decreases their step width with the left foot making them step closer to the pothole, they then step their right foot to the right of the pothole and their left foot over the pothole, step length is reduced an lateral MOS is reduced on the right compared to other gait cycles (figure 2).



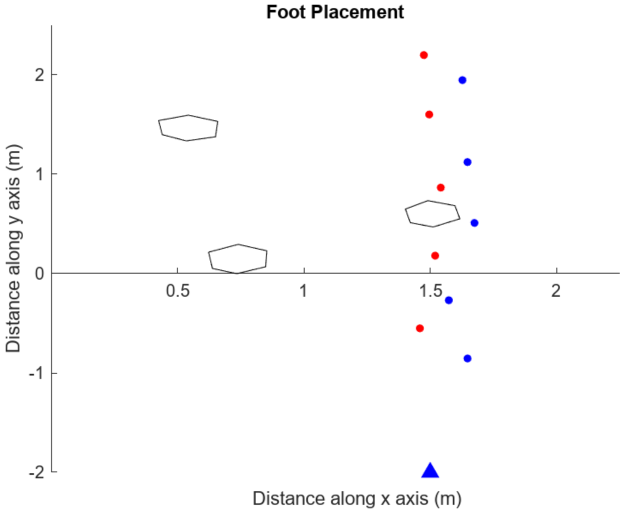


Figure 1. Foot placement of the left (red) and right (blue) foot. Blue triangle indicates walking path.

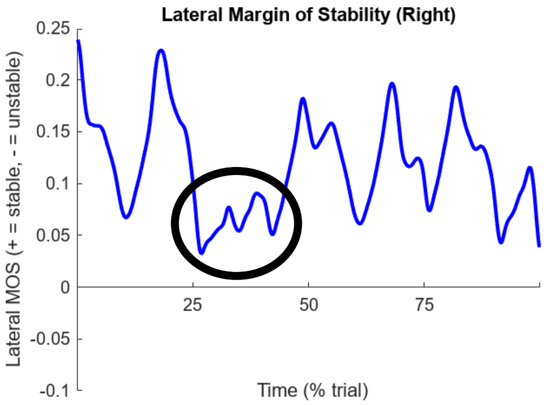


Figure 2. Right lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal Metrics (* = change in response to interaction)

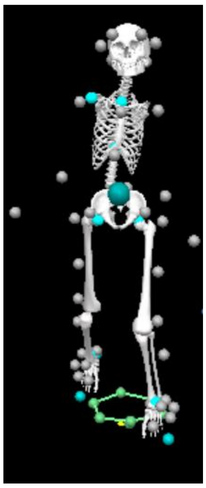
	Approach	Interaction with pothole	Response
Step width (m)	0.12, 0.18, 0.13, 0.04*	0.16*	0.14, 0.12, 0.15, 0.14
Step length (m)	0.30, 0.29, 0.45	0.32	0.35, 0.26, 0.47, 0.35

Eye tracking data (from start of trial to heel strike prior to interaction)

Fixation on pothole	Unavailable - Glasses offset eye tracking
Time of first fixation on pothole	Unavailable - Glasses offset eye tracking

Description of Interaction

Participant 3 has negative anterior MOS for majority gait cycle similar to in other trials. When they reach the pothole they take shorter wider steps to step each foot around the pothole. Following stepping around the pothole lateral MOS on the right is reduced more than other gait cycles (figure 2).



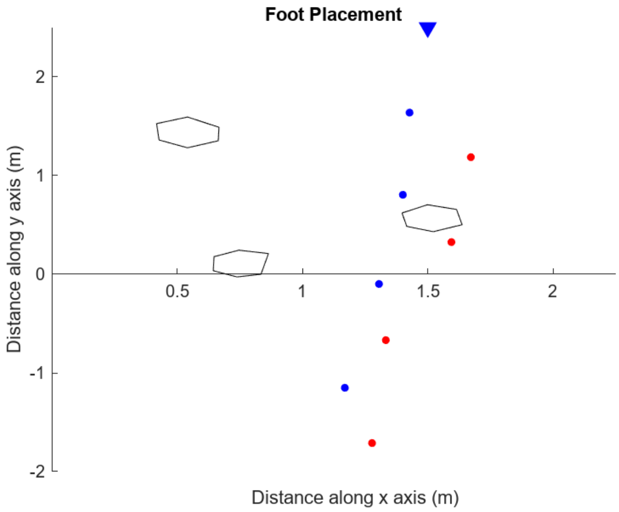


Figure 1. Foot placement of the left (red) and right (blue) foot. Blue triangle indicates walking path.

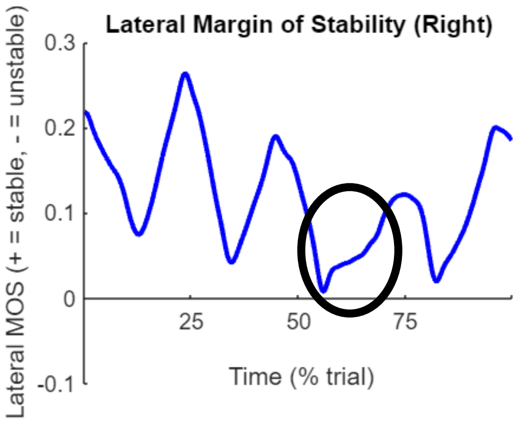


Figure 2. Right lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal Metrics (* = change in response to interaction)

	Approach	Interaction with pothole	Response
Step width (m)	0.18, 0.25, 0.28	0.22	0.30, 0.07, 0.17, 0.15
Step length (m)	0.36*, 0.41*	0.45*	0.48, 0.59, 0.47, 0.55

Eye tracking data (from start of trial to heel strike prior to interaction)

Fixation on pothole	Unavailable - Glasses offset eye tracking
Time of first fixation on pothole	Unavailable - Glasses offset eye tracking

Description of Interaction

Participant 4 avoids two potholes, the first by stepping to the side and second by stepping over with the right foot and narrowly missing the pothole (figure 1). During the first pothole avoidance, the left foot steps beside the pothole and shows very subtle lower lateral MOS on the left compared to other gait cycles. The right foot follows but step width is reduced when stepping around the pothole. This causes a slight decrease in lateral MOS on the right, below other gait cycles (figure 3), however still above 0.

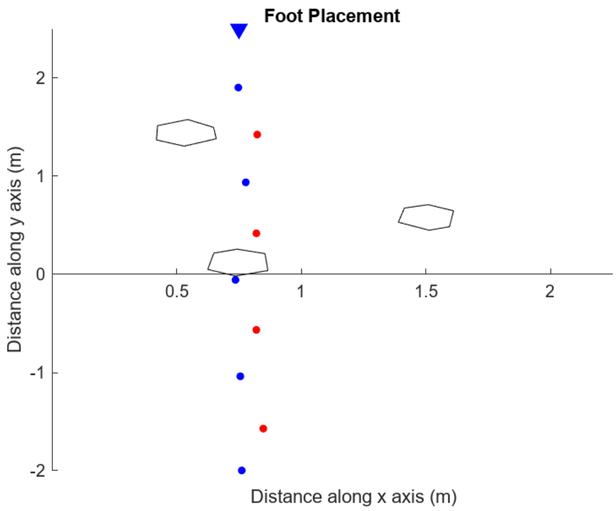


Figure 1. Foot placement of the left (red) and right (blue) foot. Blue triangle indicates walking path.

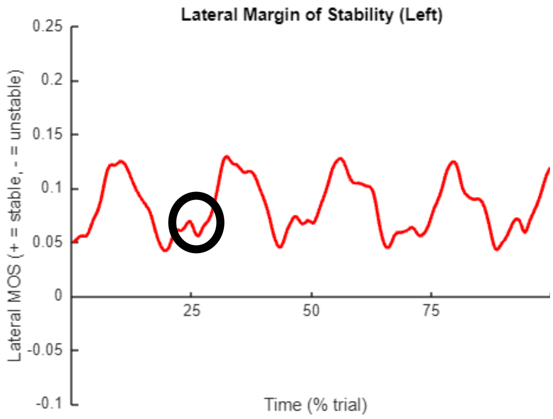


Figure 2. Left lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

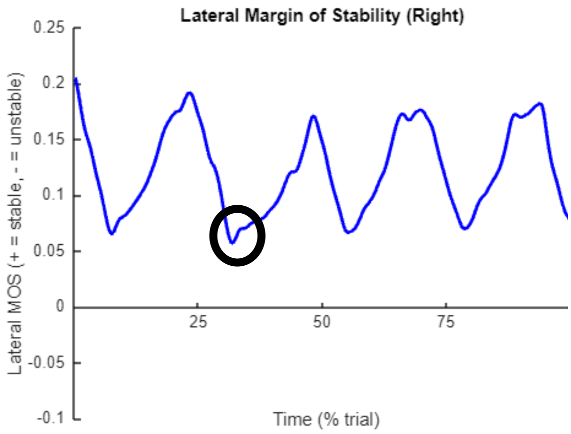


Figure 3. Right lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal Metrics (* = change in response to interaction)

	Approach	Interaction with pothole	Response
Step width (m)	0.06	0.08	0.06, 0.05*, 0.07, 0.09
Step length (m)		0.47	0.49, 0.51, 0.48, 0.48

Eye tracking data (from start of trial to heel strike prior to interaction)

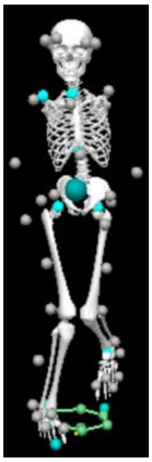
Fixation on pothole	61% (2.1 seconds)
Fixation on distraction	0%
Time of first fixation on pothole	39% (2.1 seconds prior to interaction)

Path 3, non-distracted

Avoiding a pothole

Description of Interaction

Participant 5 increases step width and length on the right to avoid a pothole. When this occurs, right anterior MOS on ipsilateral heel strike is reduced compared to other gait cycles (figure 2), right anterior MOS is also reduced on contralateral heel strike in the step following the perturbation (table 1). Left anterior MOS is reduced in the following step prior to ipsilateral heel strike (figure 3).



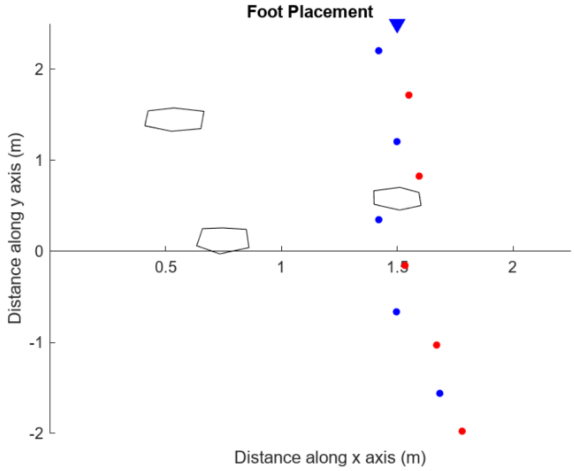


Figure 1. Foot placement of the left (red) and right (blue) foot. Blue triangle indicates walking path.

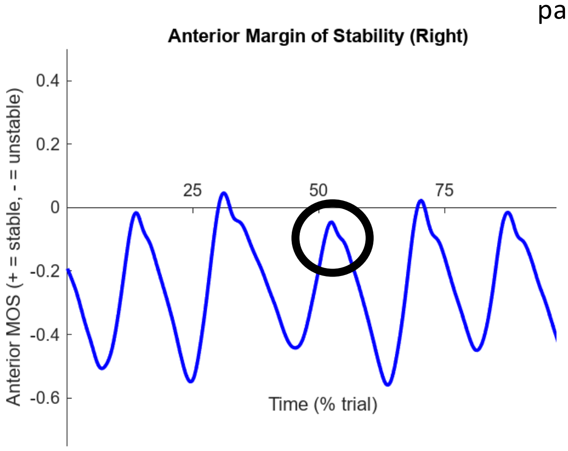


Figure 2. Right anterior margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

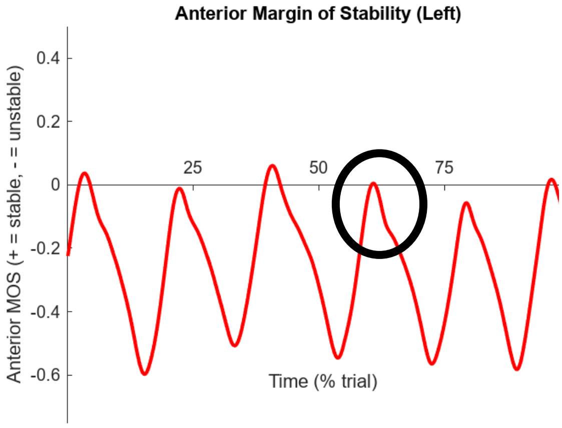


Figure 3. Left anterior margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

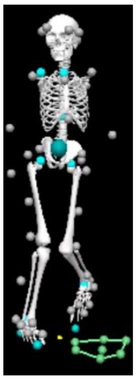
Spatiotemporal and Stability Metrics (* = change in response to interaction)

	Approach	Interaction with pothole	Response
Left anterior MOS before contralateral heel strike (m)	-0.55, -0.46	-0.51	-0.50, -0.53
Right anterior MOS before contralateral heel strike (m)	-0.39, -0.49, -0.32	-0.50*	-0.40, -0.40
Step width (m)	0.08, 0.13, 0.05, 0.09	0.17	0.12, 0.03, 0.16, -0.01
Step length (m)	0.53, 0.50, 0.50, 0.39	0.46	0.52, 0.49, 0.38, 0.53

Eye tracking data (from start of trial to heel strike prior to interaction)

Fixation on pothole	0% child: “couldn’t see potholes”
Time of first fixation on pothole	NA (seconds prior to interaction)

Description of Interaction



Participant 5 avoids two potholes, first by stepping the right foot to the side of the pothole, then stepping the left foot over. The second, they step their left foot closer to the pothole, then over with the right. After avoiding the first pothole, there is a decrease in anterior MOS on ipsilateral heel strike for both left and right compared to other gait cycles (figure 2). Left lateral MOS is remains lower during step around the pothole compared to other gait cycles (figure 3), at this time, right lateral MOS, increases, indicating a shift in MOS toward the left side.

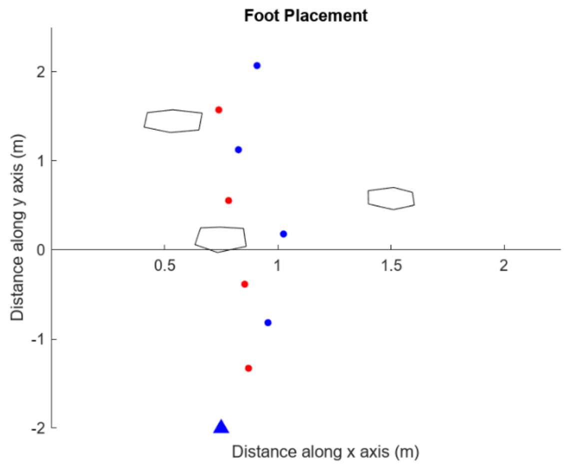


Figure 1. Foot placement of the left (red) and right (blue) foot. Blue triangle indicates walking path.

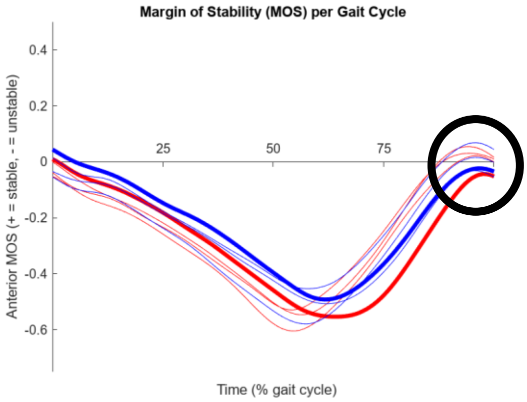


Figure 2. Anterior margin of stability for the left (red) and right (blue) sides for each gait cycle. Bold line indicates instability during gait cycle. Circle shows reduction in stability due to interaction.

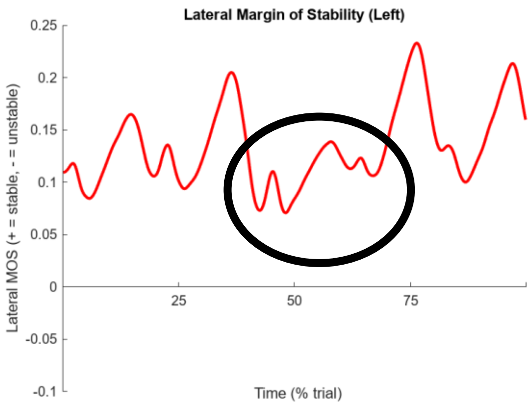


Figure 3. Left lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal Metrics (* = change in response to interaction)

	Approach	Interaction with pothole	Response
Step width (m)	0.07, 0.08, 0.09	0.16*	0.25* 0.06, 0.09
Step length (m)	0.51, 0.43	0.56	0.37, 0.57, 0.45

Eye tracking data (from start of trial to heel strike prior to interaction)

Fixation on pothole	0% (0 seconds) child: "couldn't see potholes"
Fixation on distraction	36%
Time of first fixation on pothole	N/A (seconds prior to interaction)

Description of Interaction

Participant 6 avoids two potholes. For the first pothole, the child steps their left foot on the edge of the pothole, very close to stepping in. There is little change to MOS, however lateral MOS on the right is close to zero before, during and slightly after this perturbation (figure 2). When avoiding the second pothole, there is a crossing of limbs as the left steps next to the pothole, then the right steps over, this causes a reduction in left lateral MOS (figure 3).

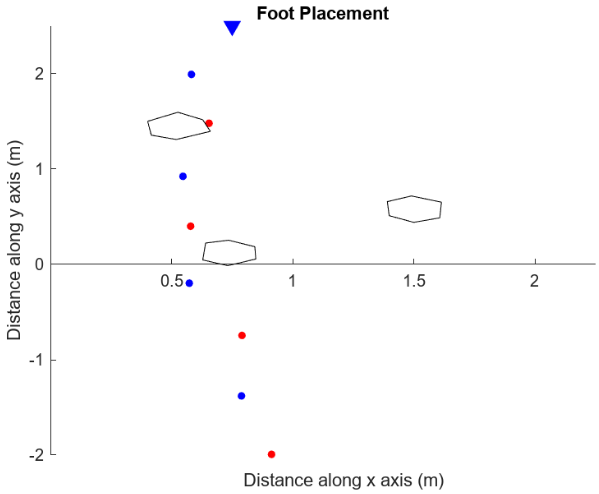


Figure 1. Foot placement of the left (red) and right (blue) foot. Blue triangle indicates walking path.

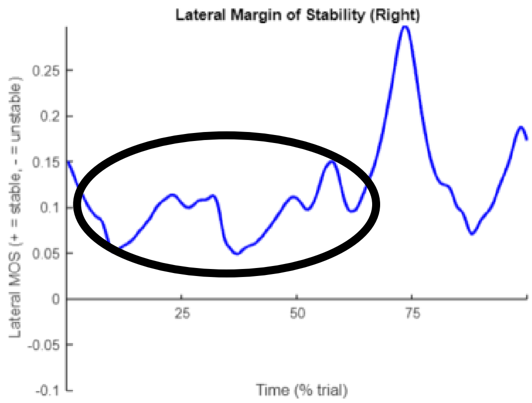


Figure 2. Right lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

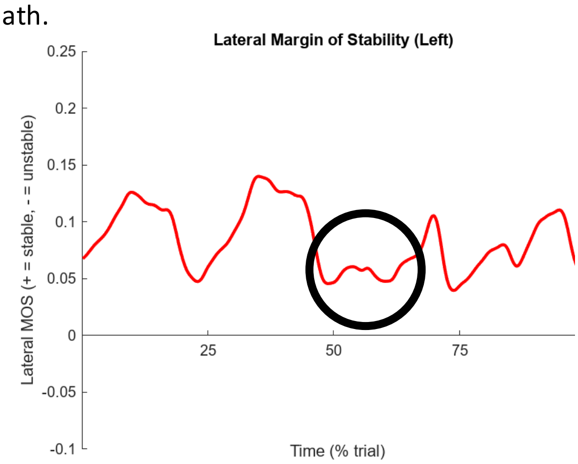


Figure 3. Left lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal Metrics (* = change in response to interaction)

	Approach	Interaction with pothole	Response
Step width (m)	0.09	0.05*	0.09, 0.03, 0.00*, 0.20
Step length (m)		0.51	0.55, 0.52, 0.60*, 0.56

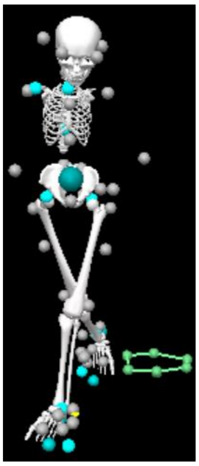
Eye tracking data (from start of trial to heel strike prior to interaction)

Fixation on pothole	Opted Out
Time of first fixation on pothole	Opted Out

Path 3, non-distracted ***Avoiding a pothole***

Description of Interaction

Participant 6 steps next to a pothole with the right foot then crosses legs and steps the left across the right to avoid the pothole. When the left crosses the right foot, there is a reduced step width (table 1) and a negative left and right lateral MOS (figure 2 and 3).



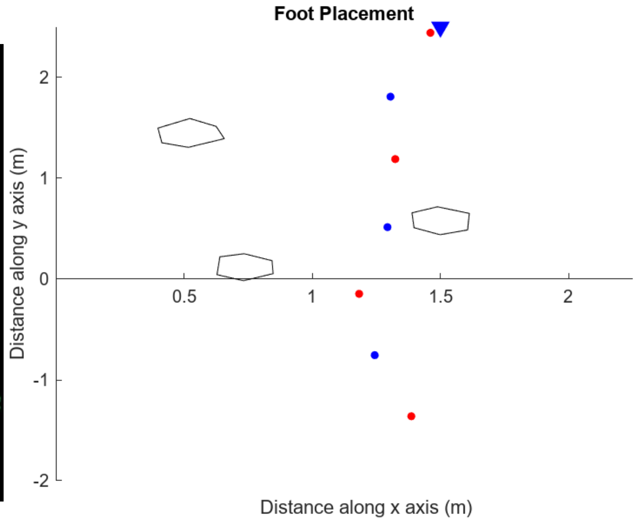


Figure 1. Foot placement of the left (red) and right (blue) foot. Blue triangle indicates walking path.

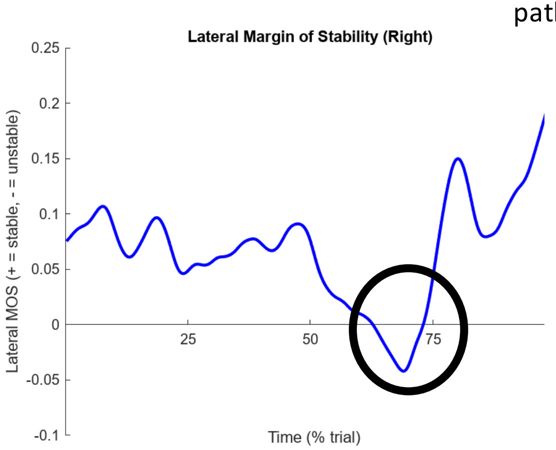


Figure 2. Right lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

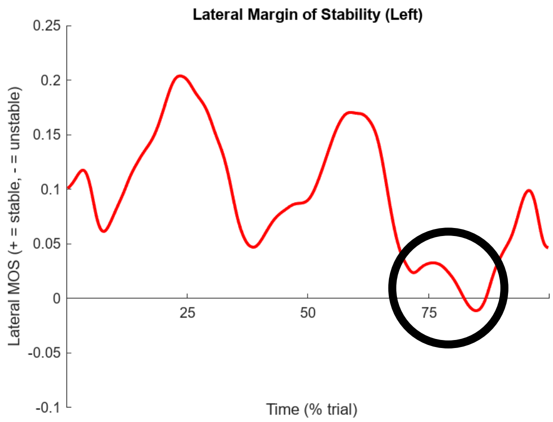


Figure 3. Left lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal Metrics (* = change in response to interaction)

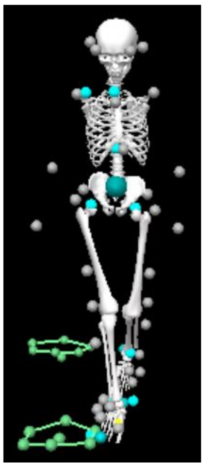
	Approach	Interaction with pothole	Response
Step width (m)	0.05, 0.15, 0.01, 0.03	-0.12*	-0.07*, 0.12
Step length (m)	0.64, 0.61, 0.68	0.66	0.61, 0.59

Eye tracking data (from start of trial to heel strike prior to interaction)

Fixation on pothole	Opted Out
Time of first fixation on pothole	Opted Out

Description of Interaction

Participant 15 shows a very subtle example of crossing limbs to avoid a pothole. They step behind the second pothole with their left foot then cross over with their right foot to step to the side of the pothole. As the right foot crosses the left, step width is reduced (table 1) and left lateral MOS is reduced and sustains a low value during stance (figure 2).



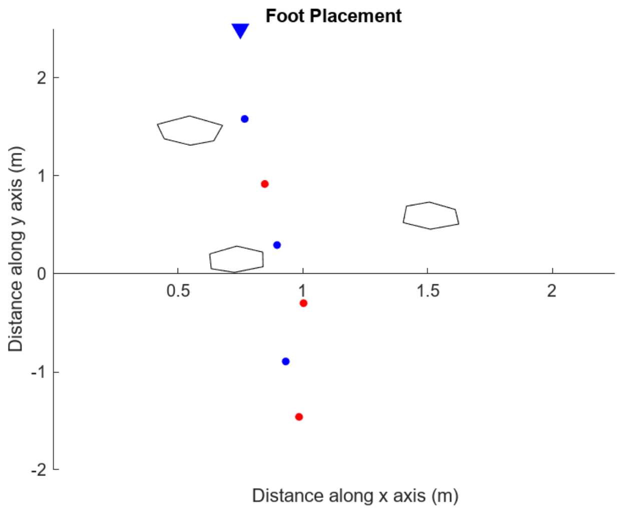


Figure 1. Foot placement of the left (red) and right (blue) foot. Blue triangle indicates walking path.

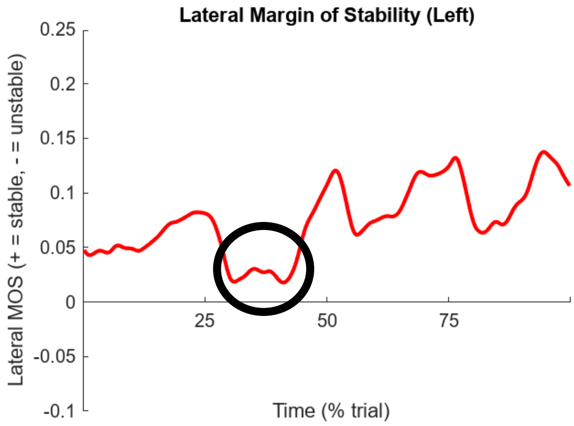


Figure 2. Left lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal Metrics (* = change in response to interaction)

	Approach	Interaction with pothole	Response
Step width (m)	0.02, 0.07	-0.04*	0.09, 0.06, 0.04
Step length (m)	0.67	0.63	0.59, 0.59, 0.57

Eye tracking data (from start of trial to heel strike prior to interaction)

Fixation on pothole	28% (0.7 seconds)
Fixation on distraction	0%
Time of first fixation on pothole	37% (1.6 seconds prior to interaction)

E. Avoiding Pavement Edges

Path 5, non-distracted

<u>Avoiding pavement edges</u>

Description of Interaction

Participant 1 shows instabilities before contralateral heel strikes on the first left and right steps onto the pavement. Participant one appears to increase step length (table 1), in order to step over the pavement edge. This causes disturbance to anterior MOS (table 1).

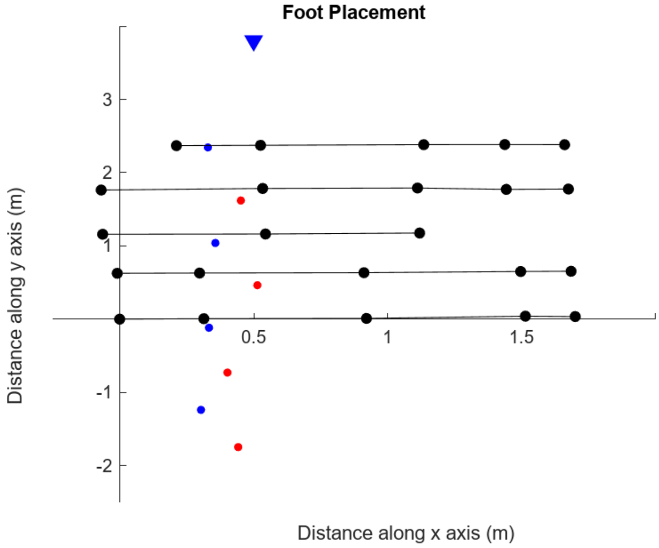


Figure 1. Foot placement of the left (red) and right (blue) foot Blue triangle indicates walking path.

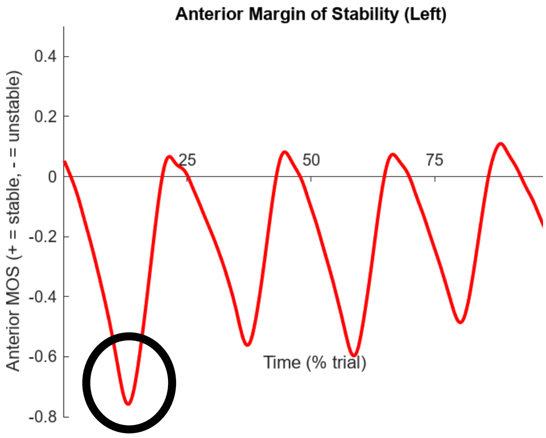


Figure 2. Left anterior margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

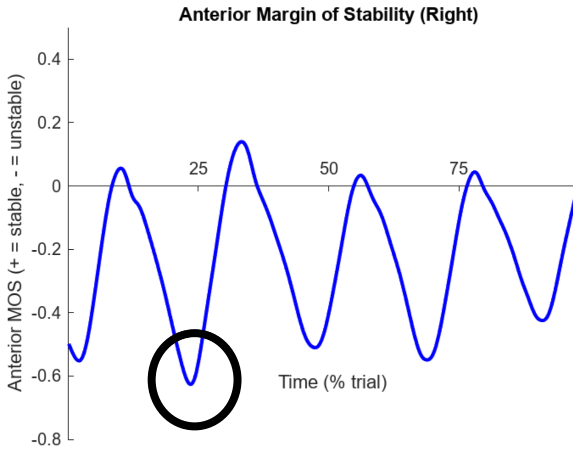


Figure 3. Right anterior margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal and Stability Metrics (* = change in response to interaction)

	Interaction (1st edge)	Response
Left anterior MOS before contralateral heel strike (m)	-0.67*	-0.46, -0.49, -0.37
Right anterior MOS before contralateral heel strike (m)	-0.58*	-0.43, -0.52, -0.43
Step width (m)	0.12	0.11, 0.08, 0.14, 0.17, 0.06, 0.08, 0.12
Step length (m)	0.72	0.58, 0.58, 0.58, 0.62, 0.51, 0.51

Eye tracking data (from start of trial to heel strike prior to interaction)

Fixation on pavement edge	21% (0.3 seconds)
Time of first fixation on edge	55% (0.7 seconds prior to interaction)

Description of Interaction

Participant increases step length during the entire trial to avoid stepping on pavement edges. However as they take a step over the second pavement edge with the right foot, step width is reduced (table 1) and the right leg begins to cross over the left therefore lateral margin of stability enters negative (figure 1). There is no disturbance or change to anterior margin of stability.

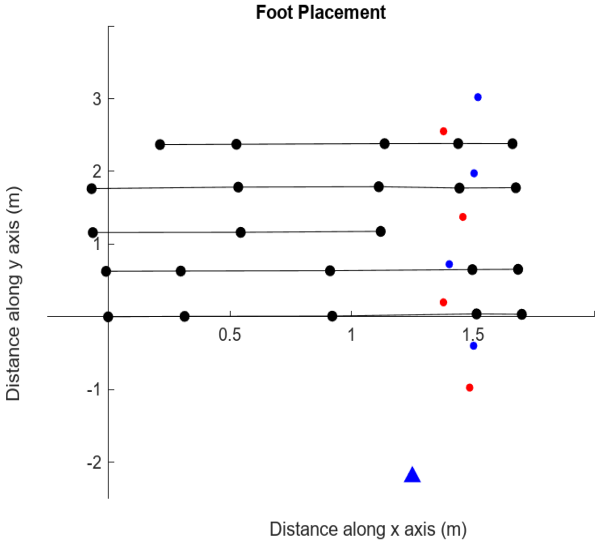


Figure 1. Foot placement of the left (red) and right (blue) foot Blue triangle indicates walking path.

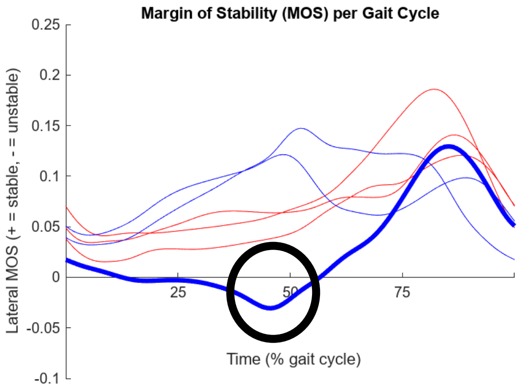


Figure 2. Lateral margin of stability for the left (red) and right (blue) sides for each gait cycle. Bold line indicates instability during gait cycle. Circle shows reduction in stability due to interaction.

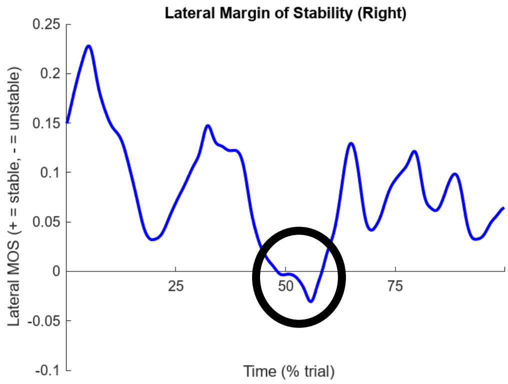


Figure 3. Right lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal Metrics (* = change in response to interaction)

	Approach	Interaction (2nd edge)	Response
Step width (m)	0.19, 0.02, 0.12	0.01*	-0.06*, 0.03, 0.11, 0.13
Step length (m)	0.57, 0.600.52	0.65*	0.60, 0.58, 0.47

Eye tracking data (from start of trial to heel strike prior to interaction)

Fixation on pavement edge	16% (0.7 seconds)
Time of first fixation on edge	50% (2.1 seconds prior to interaction)

Description of Interaction

No noise on distraction

Participant 2 increases step length to avoid pavement edges (table 1, figure 1). Over pavement edge 1 causes a reduced anterior MOS on the left before contralateral heel strike (table 1). Participant continues to avoid pavement edges, this causes lateral MOS on the left to reduce (figure 2) when stepping over the fourth pavement edge also causing a decreased step width (0 m), in response to earlier instability.

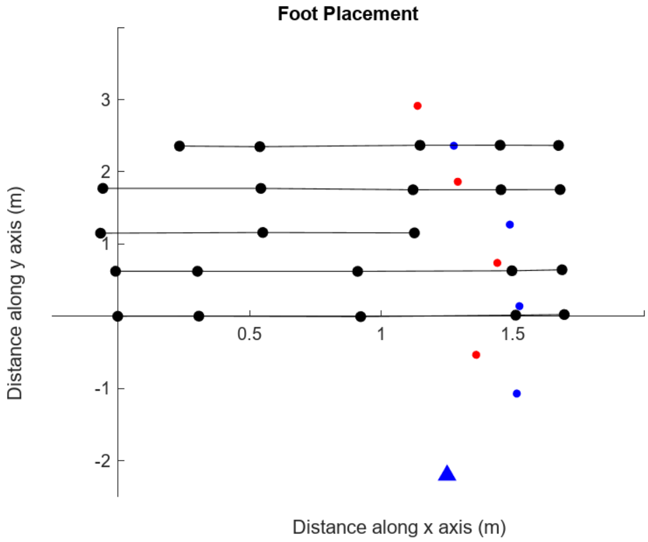


Figure 1. Foot placement of the left (red) and right (blue) foot Blue triangle indicates walking path.

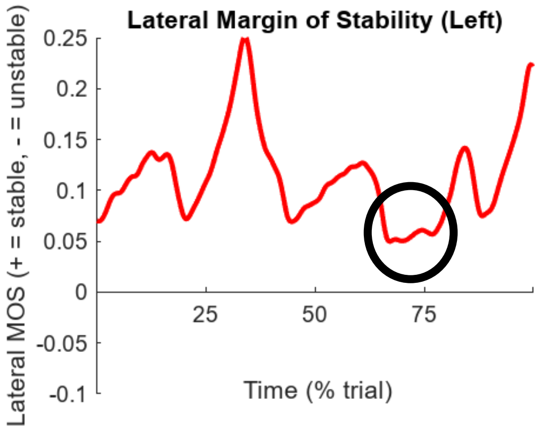


Figure 2. Left lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal and Stability Metrics (* = change in response to interaction)

	Approach	Interaction (1st edge)	Response
Left anterior MOS before contralateral heel strike (m)	-0.41	-0.57*	-0.44, -0.43
Step width (m)	0.07, 0.13	0.17*	0.09, 0.05, 0.18, 0.00*
Step length (m)	0.54	0.66*	0.60, 0.53, 0.60, 0.50

Eye tracking data (from start of trial to heel strike prior to interaction)

Fixation on pavement edge	Glasses offset eye tracking
Time of first fixation on edge	Glasses offset eye tracking

Path 7, non-distracted

Avoiding pavement edges

Description of Interaction

Participant 4 increases their step length (table 1) over the fourth pavement edge. This decreases anterior MOS on the left and right prior to contralateral heel strike (table 1, figure 1). Increased walking speed on this trial compared to others (0.85 m/s

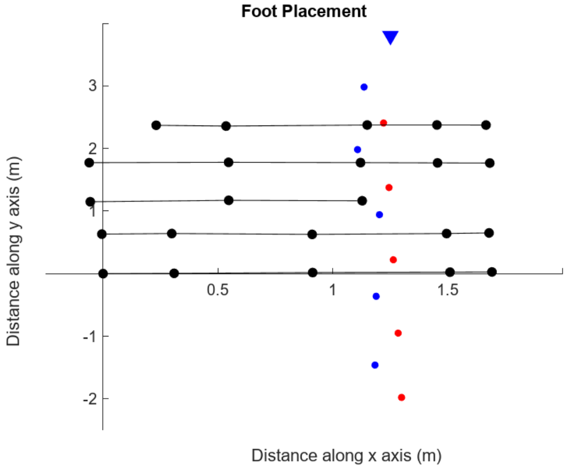


Figure 1. Foot placement of the left (red) and right (blue) foot Blue triangle indicates walking path.

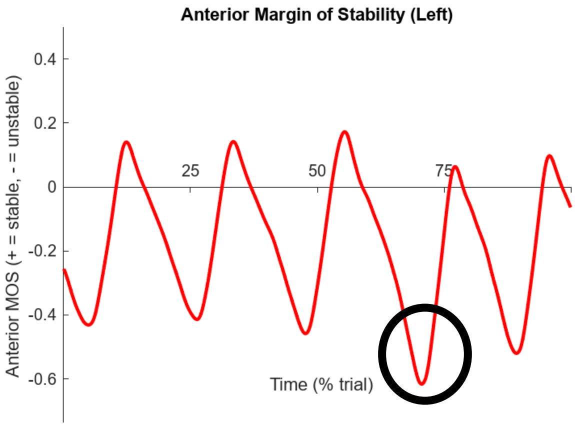


Figure 2. Left anterior margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

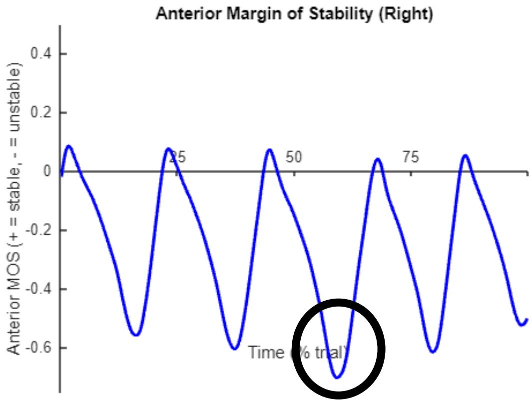


Figure 3. Right anterior margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal and Stability Metrics (* = change in response to interaction)

	Approach	Interaction (4^{th} edge)	Response
Left anterior MOS before contralateral heel strike (m)	-0.33, -0.32, -0.32	-0.51*	-0.44
Right anterior MOS before contralateral heel strike (m)	-0.45, -0.48	-0.56*	-0.54, -0.43
Step width (m)	0.08, 0.11, 0.13, 0.04	0.06	0.08, 0.08, 0.10, 0.11
Step length (m)	0.57, 0.43, 0.60, 0.44	0.71*	0.59, 0.58, 0.52, 0.51

Eye tracking data (from start of trial to heel strike prior to interaction)

Fixation on pavement edge	24% (1.1 seconds)
Time of first fixation on edge	22% (3.4 seconds prior to interaction)

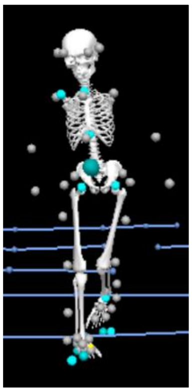
Path 5, distracted

Avoiding pavement edges

Description of Interaction

Not looking at distraction

Participant 10 does not look at the distraction during the trial. They step down from the fifth and final pavement edge, where the right limb crosses the left causing a reduction step width (table 1) and negative lateral MOS on the right (figure 2) in steps following.



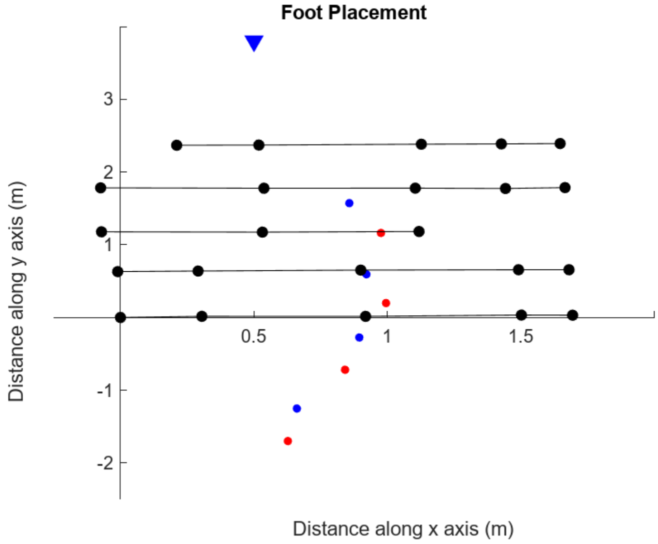


Figure 1. Foot placement of the left (red) and right (blue) foot Blue triangle indicates walking path.

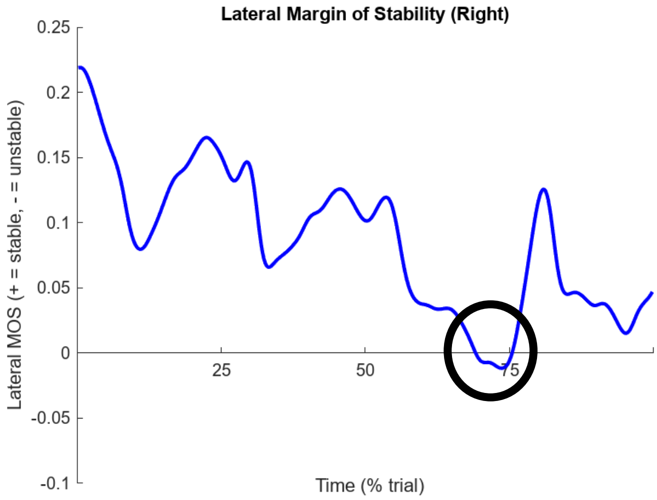


Figure 2. Right lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal Metrics (* = change in response to interaction)

	Approach	Interaction (5th edge)	Response
Step width (m)	0.10, 0.05, 0.06, 0.09	-0.06	0.15, -0.04
Step length (m)	0.40, 0.57, 0.39, 0.48	0.45	0.54, 0.45

Eye tracking data (from start of trial to heel strike prior to interaction)

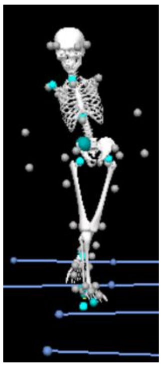
Fixation on pavement edge	1% (0.04 seconds)
Fixation on distraction	0%
Time of first fixation on edge	74% (1.8 seconds prior to interaction)

Path 8, non-distracted

Avoiding pavement edges

Description of Interaction

Participant 10 takes a small step, then a large step over the second pavement edge, they cross their right leg over the left when taking a larger step, this reduces step width (table 1), and causes a reduction in left lateral MOS to below zero (figure 1). There is also a reduction in right anterior MOS at ipsilateral heel strike in the steps following (table 1).



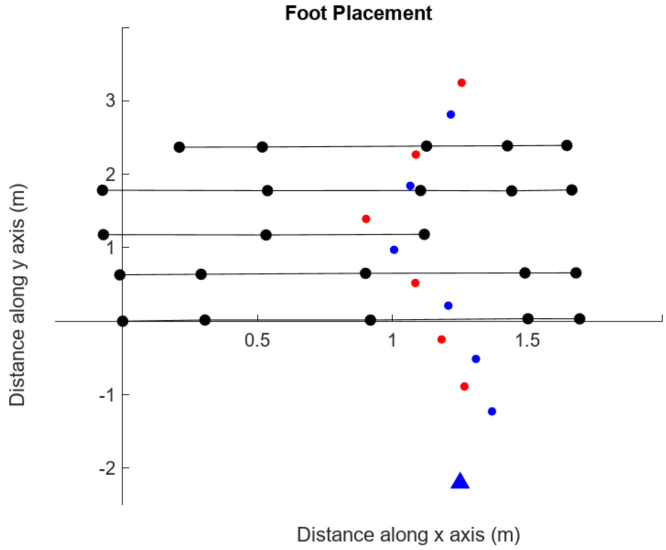


Figure 1. Foot placement of the left (red) and right (blue) foot Blue triangle indicates walking path.

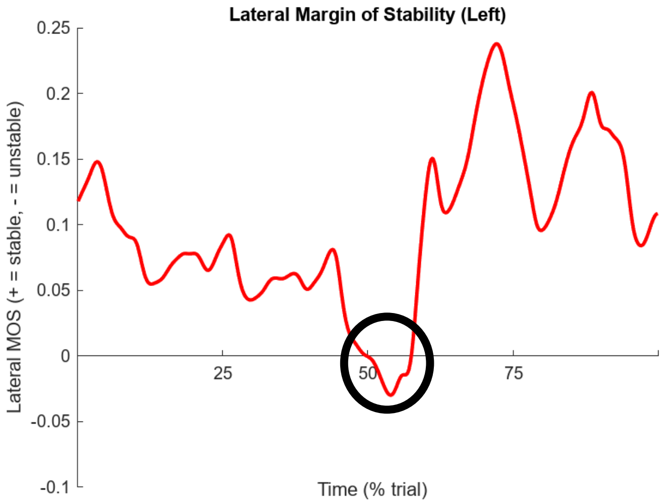


Figure 2. Left lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal and Stability Metrics (* = change in response to interaction)

	Approach	Interaction (2nd edge)	Response
Right anterior MOS at ipsilateral heel strike (m)	-0.32, -0.24, -0.29	-0.40*	-0.44*, -0.36
Step width (m)	0.04, 0.13, 0.02, 0.10	-0.08	0.07, 0.15, -0.02, 0.10
Step length (m)	0.37, 0.27, 0.46, 0.31	0.45*	0.43, 0.44, 0.43, 0.53

Eye tracking data (from start of trial to heel strike prior to interaction)

Fixation on pavement edge	20% (1.2 seconds)
Time of first fixation on edge	33% (4 seconds prior to interaction)

Path 8, non-distracted

Avoiding pavement edges

Description of Interaction
Participant 11 is cautious and walking slowly (0.61 m/s). They avoid pavement edges throughout (figure 1). They lift the foot over the first pavement edge high, then attempt to step over the second edge, which reduced right anterior MOS at contralateral heel strike compared to other gait cycles (figure 2).

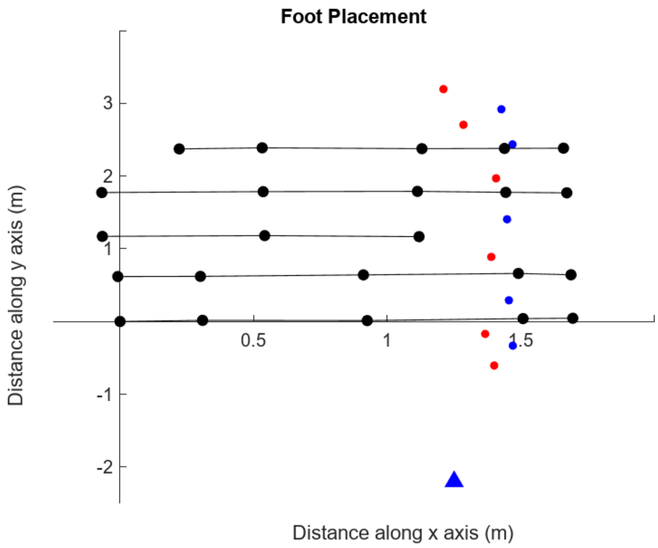


Figure 1. Foot placement of the left (red) and right (blue) foot Blue triangle indicates walking path.

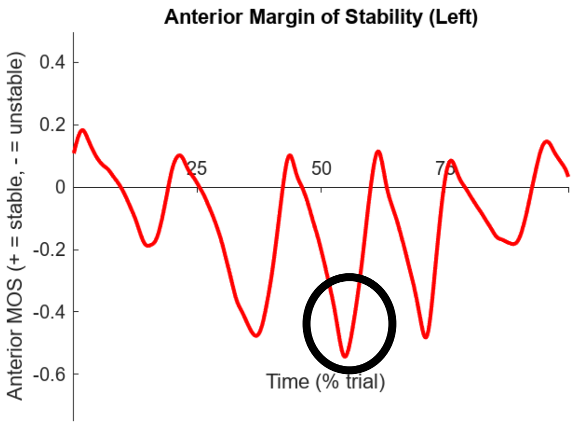


Figure 2. Left anterior margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal and Stability Metrics (* = change in response to interaction)

	Approach	Interaction (2nd edge)	Response
Left anterior MOS before contralateral heel strike (m)	-0.13, -0.27	-0.43*	-0.39*, -0.09
Right anterior MOS at ipsilateral heel strike (m)	-0.20, -0.05	-0.50*	-0.45*, -0.17, -0.14
Step width (m)	0.06, 0.07, 0.10, 0.09	0.05	0.07, 0.03, 0.06, 0.17
Step length (m)	0.28, 0.16, 0.47	0.59*	0.52, 0.56, 0.47, 0.27

Eye tracking data (from start of trial to heel strike prior to interaction)

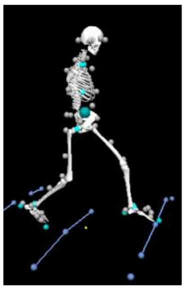
Fixation on pavement edge	Glasses offset eye tracking
Time of first fixation on edge	Glasses offset eye tracking

Path 7, non-distracted

Avoiding pavement edges

Description of Interaction

Participant 11 walks fast compared to other trials (1.03 m/s). They take one much bigger step compared to others (table 1), to step over the third pavement edge with the left foot, this causes a reduced left lateral MOS compared to other gait cycles (figure 2). An additional reduction in right anterior MOS is seen prior to contralateral heel strike (figure 3).



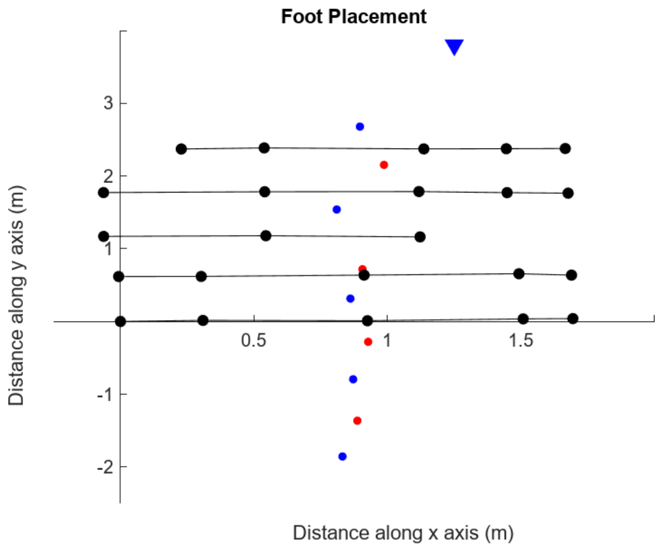


Figure 1. Foot placement of the left (red) and right (blue) foot Blue triangle indicates walking path.

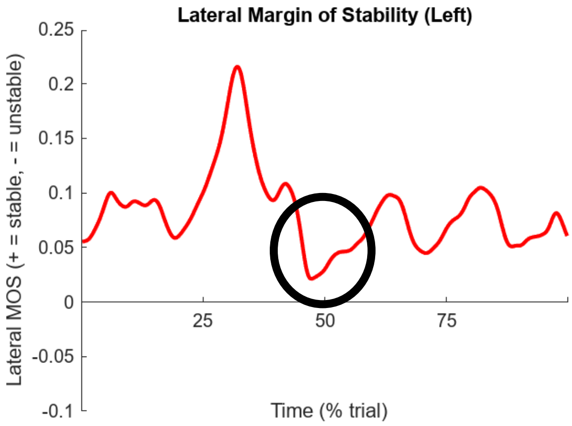


Figure 2. Left lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

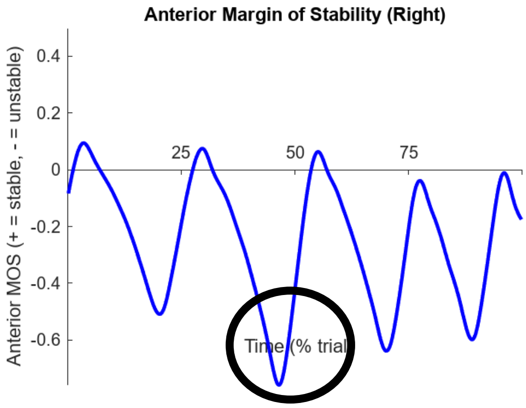


Figure 3. Right anterior margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal and Stability Metrics (* = change in response to interaction)

	Approach	Interaction (3rd edge)	Response
Left anterior MOS before contralateral heel strike (m)	-0.30	-0.53*	-0.37, -0.52, -0.47
Right anterior MOS at ipsilateral heel strike (m)	-0.39	-0.64*	-0.53, -0.53
Step width (m)	0.08, 0.07, 0.18	0.10	0.02, 0.06, 0.06, 0.01
Step length (m)	0.52, 0.62	0.82	0.40, 0.59, 0.52, 0.57

Eye tracking data (from start of trial to heel strike prior to interaction)

Fixation on pavement edge	Glasses offset eye tracking
Time of first fixation on edge	Glasses offset eye tracking

Path 6, distracted

<u>Avoiding pavement edges</u>

Description of Interaction

Participant 14 demonstrates a slight trip with the right (trailing) foot when stepping over the first pavement edge, however shows no instability. Following this, participant 14 steps over the second pavement edge and at the same time crossing limbs occurs, reducing step width (table 1) and causing negative lateral MOS (figure 2). The following right heel strike shows slightly reduced anterior MOS as (figure 3). This is followed by a shorter step compared to others (table 1).

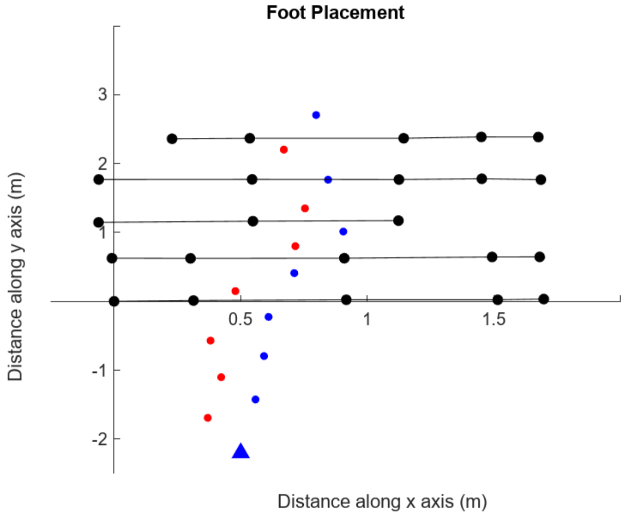


Figure 1. Foot placement of the left (red) and right (blue) foot Blue triangle indicates walking path.

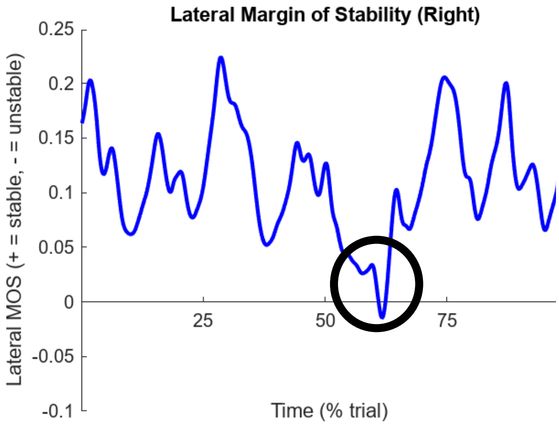


Figure 2. Right lateral margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

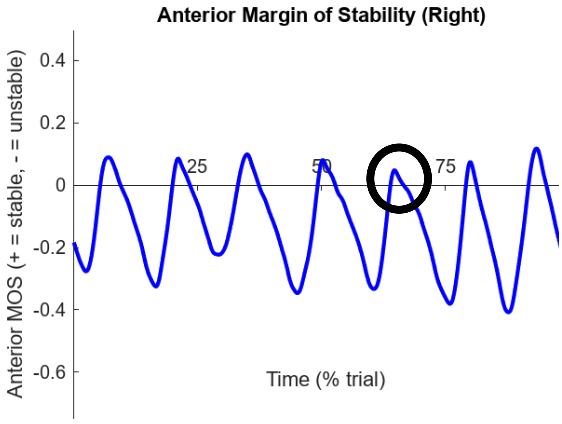


Figure 3. Right anterior margin of stability for the entire trial. Circle shows reduction in stability due to interaction.

Spatiotemporal Metrics (* = change in response to interaction)

	Approach	Interaction (2nd edge)	Response
Step width (m)	0.21, 0.23, 0.13, 0.22	0.00*	0.16, 0.15, 0.09, 0.16
Step length (m)	0.21, 0.36, 0.37, 0.28	0.39	0.23, 0.32, 0.42, 0.42

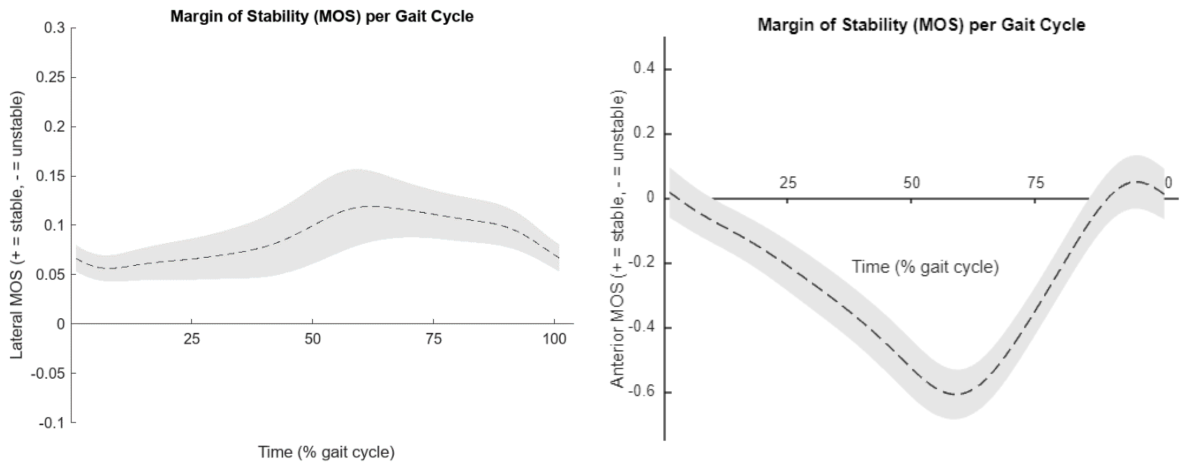
Eye tracking data (from start of trial to heel strike prior to interaction)

Fixation on pavement edge	Glasses offset eye tracking
Time of first fixation on edge	Glasses offset eye tracking

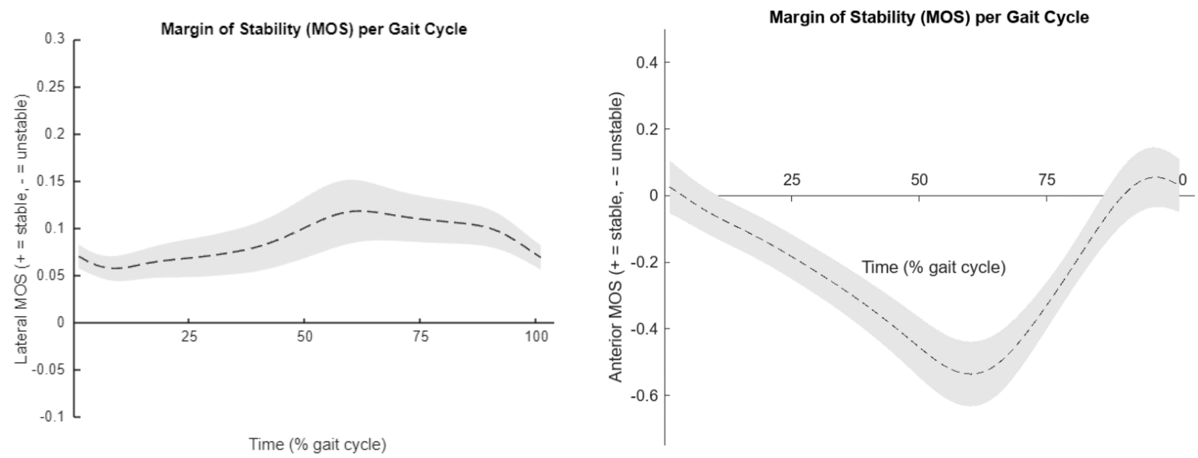
8.9 Appendix 10a.

Anterior and lateral margin of stability for typically developing children (mean ± standard deviation) on trials where children walked over pavement and demonstrated A) no steps on pavement edges and B) at least one step on a pavement edge

A



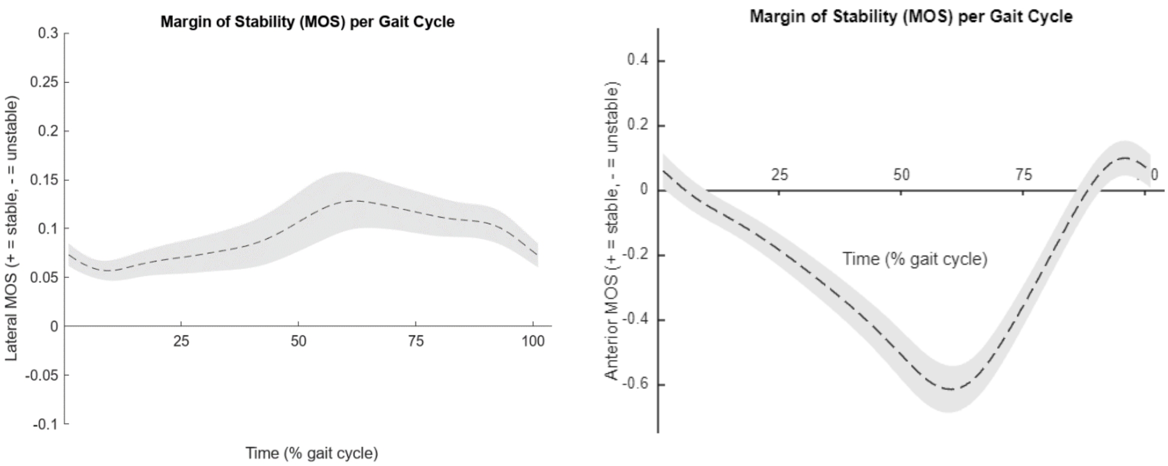
B



8.10 Appendix 10b.

Anterior and lateral margin of stability for typically developing children (mean ± standard deviation) on trials where children walked over grass and demonstrated A) no steps into a pothole and B) at least one step into a pothole

A



B