Gait adaptations of individuals with cerebral palsy on irregular surfaces: A Scoping Review

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Abstract

Background: Individuals with cerebral palsy (CP) have a reduced ability to perform motor tasks such as walking. During daily walking, they are confronted with environmental constraints such as irregular surfaces (e.g., relief and uneven surfaces) which may require adaptations to maintain stability and avoid falls. Laboratory gait assessments are conventionally conducted under ideal conditions (e.g., regular and even surfaces) and may overlook subtle problems which may only present in challenging walking environments. Increased knowledge of adaptations to successfully navigate irregular surfaces may contribute to a better understanding of everyday walking barriers.

Research question: This scoping review aims to describe gait adaptations to irregular surfaces in individuals with CP and contrast adaptations with those of healthy individuals.

Methods: This review followed the 6-stage Joanna Briggs Institute methodology and respected the recommendations of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews statement. The MEDLINE, EMBASE, CINAHL, SPORTDiscus, and Web of Science databases were searched on March 2021.

Results: The research strategy identified 1616 studies published between 2014-2020, of which 10 were included after abstract and full-text screening. This review reported on 152 individuals with CP (diplegia: n=117, hemiplegia: n=35) and 159 healthy individuals. The included studies focused on spatial-temporal, kinematic, kinetic, and muscle activity parameters over relief, inclined, and staircase surfaces. 7/10 studies were conducted in laboratories, often using surfaces that are not representative of the real-world. The results suggest that for individuals with CP, adaptations on irregular surfaces differ from flat surface walking and across CP subtype. Moreover, individuals with CP present with typical and pathology-specific adaptations to irregular surfaces compared to healthy individuals.

Significance: This review highlights the clinical and research interest of focusing future studies on more ecologically valid data collection approaches and provides important recommendations to overcome research gaps in the existing literature.

Keywords: Gait analysis, irregular surfaces, cerebral palsy

1. Introduction

Cerebral palsy (CP) is a neurodevelopmental condition characterized by permanent movement and posture problems due to a brain lesion or maldevelopment before, during, or after birth [1]. Contrary to their healthy peers, individuals with CP present with reduced ability to walk [2], ultimately reducing their autonomy [3]. Their functional limitations can be quantified by the gross motor classification system (GMFCS), ranging from level I (independent walkers with restrictions in advanced motor skills) to V (cannot walk independently with severe motor restrictions) [4]. Reduced stability during walking [5] and concomitant increased fear of falls in individuals with CP is associated with decreased participation in public spaces, compared to their healthy peers [6]. This participatory reticence could be related to, among other stressors, challenging walking environments in these settings [7]. Indeed, daily walking requires adaptations to cope with environmental constraints (e.g., relief and uneven surfaces) [8]. Increased knowledge of gait adaptations required by individuals with CP to successfully navigate irregular surfaces is warranted to better understand daily walking barriers and improve interventions.

Clinical gait analysis has contributed to the quantification of complex gait deviations in individuals with CP, allowing for comparison with normative walking data from non-pathological populations [9,10] and supporting surgical [10,11] and therapeutic decision-making; however, analyses are commonly performed under standardized conditions (e.g., flat laboratory walkways) which may not reflect real-world functional challenges. As such, assessments under ideal conditions may overlook subtle problems which may only present in challenging walking environments, such as relief and uneven surfaces [12].

The positive impact of gait analysis on research and clinical domains is well established [10] but, as aforementioned, it is crucial to recognize gait adaptations used by individuals with CP to overcome everyday barriers, such as irregular surfaces. Thus, the purpose of this scoping review is to describe gait adaptations to irregular surfaces in individuals with CP and contrast adaptations with those of healthy individuals.

2. Methods

This scoping review followed the 6-stage Joanna Briggs Institute methodology for conducting scoping reviews [13]. This framework was proposed by Arksey and O'Malley [14], with refinements provided by Levac et al. [15]. The JBI stages include: (1) identifying the research question, (2) identifying relevant studies, (3) study selection, (4) charting the data, (5) summarizing and reporting the results, and (6) consultation. The latter was not considered since it is optional, and the current research team is sufficient to provide an appropriate perspective on results. The recommendations of the Preferred Reporting Items for Systematic Reviews and Meta-Analyses Extension for Scoping Reviews (PRISMA-ScR) statement [16] were also respected.

2.1. Protocol and registration

A protocol was registered with the Open Science Framework (OSF) (registration DOI 10.17605/OSF.IO/Y5VM3) before the initial research.

2.2. Search strategy:

An initial limited search of MEDLINE (Ovid) and CINAHL (Ebsco) was undertaken to analyze text words in the title, abstract, and keywords, as well as the index terms used to describe the relevant articles. Then, a second search was conducted by DA using refined key terms for each database. The following databases were searched: MEDLINE (Ovid), EMBASE (Ovid), CINAHL Plus with Full Text (Ebsco), SPORTDiscus with Full Text (Ebsco), and Web of Science Core Collection (Clarivate Analytics). The search was last conducted on March 12, 2021. The final search strategy for MEDLINE is presented in Appendix 1. The reference list of all included papers was screened by the first author (CDP) for additional sources. Following the search, all identified citations were collated and uploaded into EndNote (X9, Clarivate Analytics, USA) and duplicates were removed. Then, references were uploaded to Covidence (Cochrane, Australia) software for the process of source selection.

2.3. Study selection

Studies published in English or French were included. There was no restriction on article publication year. Studies were included if (1) results were presented for a population with CP, (2) gait analysis was performed on uneven (e.g., slopes, stairs) or relief (e.g., pebbles, bumps) surfaces, and (3) assessment of at least one quantifiable spatial-temporal (e.g., walking speed and stride length), kinematic (e.g., lower-limb joint angles), kinetic (e.g., joints moment and power), muscular (e.g., maximal activation), or energetics (e.g., energy consumption) parameter was reported. Studies were excluded if the full text was not available. Titles and abstracts were first evaluated independently by the first two authors (CDP and SGM). Then, for those identified as possibly relevant, the full texts were retrieved and assessed for inclusion in this review. Any inconsistency in the selection or elimination of studies was discussed between the two reviewers and a consensus was established by PCD if the two reviewers were not in accordance.

2.4. Data charting process

Data were extracted and table-charted according to (1) general information: year of publication, authors name, study design; (2) methodological information: participant characteristics (e.g., CP type, age, biological sex), type of motion capture (e.g., 2D measurement, optoelectronic, inertial sensors), measured parameters to assess gait adaptations, surface type, assessment environment (e.g., laboratory, outdoor); and (3) study results concerning significant gait adaptations in individuals with CP on irregular surfaces compared to level ground.

2.5. Results summary

Descriptive and numerical analyses are used to summarize the literature. Effect sizes are reported for each significant gait adaptation across surfaces (irregular vs flat) and populations (individuals with CP vs healthy controls). If the original study provided the effect size, it was cited here. Otherwise, the effect size was calculated from mean and standard deviation data. The sample mean and standard deviation were estimated using the approach of Wan et al. (2014) for the study that reported median and range data only [17].

The authors were contacted if mean and standard deviation were not available. Cohen's d effect size (*d*) was calculated if the study used parametric tests [18]; whereas Glass's delta effect size (∆) was calculated otherwise [19]. Where available, significant gait adaptation differences to irregular surfaces between CP and healthy individuals are reported. The meaning of the findings related to the overall study purpose and the implication for future research are then discussed.

3. Results

The search strategy identified 1616 studies. The selection process is illustrated with a PRISMA flowchart [20] (Figure 1). A total of 11 studies were eligible for this review [21–31]. One study [28] was excluded afterwards, with the unanimous consent of the reviewers, as it was not possible to correctly interpret the data (e.g., only means were presented in the tables (no standard deviation or range), undefined superscripts in tables, reporting of data in tables from variables that have not been addressed in the text such as 'alpha foot', and use of two-way ANOVAs to compare the kinematic data with no interaction terms, making it difficult to examine the effect of surface type on individuals with CP). Thus, a total of 10 studies were included in this review [21–27,29–31].

3.1. Data retrieved

Table 1 shows the general and experimental characteristics of the 10 studies included in this review. All studies were published between 2014-2020 and used observational cross-sectional study designs. One study included adults only [31], while others included solely children [21,25–27,29,30] or children and young adults (age ranging between 6 and 26 years) [22–24], for a total of 152 individuals with CP (diplegia: n=117, hemiplegia: n=35), and 159 healthy individuals. There is a potential overlap of participants in two studies [22,23], which may reduce the total number of unique individuals under analysis. The average sample size is 15 individuals with CP with a mean age of 13.5 ± 7.6 years and a GMFCS level of I (n=70), II (n=52), or III (n=14), with one study [24] only specifying that participants had a GMFCS of level I or II (n=16). All 14 participants with GMFCS III used assistive devices for ambulation during at least one of the walking assessments (crutches: n=2, walker: n=6, type of aid not specified: n=6). For healthy individuals, the average sample size was 16 individuals with a mean age of 14.1 ± 7.8 years. A total of 3 studies [21,24,27] focused on relief surfaces, 4 studies on inclined surfaces [25,26,29,30], 1 study on staircase surfaces [31], and 2 studies on daily walking surfaces (indoor and outdoor surface types not specified) [22,23]. These two latter studies did not specify the surface types since data were extracted from unsupervised real-world walking using inertial measurement unit sensors. For 7 of the 10 studies [21,22,24,27,29–31], the experimentation was entirely conducted in laboratory environments. For 5 studies, all participants walked barefoot [21,24,26,27,29], whereas 2 studies solely implemented shod walking [30,31], and 3 studies combined barefoot (inside) and shod (outside) gait [22,23,25]. All studies reported adaptations in spatial-temporal adaptations, 9 studies reported kinematic adaptations [21,23–27,29–31], 2 studies reported kinetic adaptations [26,30], and 2 studies reported muscle activity adaptations [29,31]. None reported energetics-related variables. All studies used 3D motion capture systems (Vicon, UK [24,26,27,29–31]; Codamotion, UK [21]; Qualisys, Switzerland [22]) or inertial sensors (Gait Up, Switzerland [22,23]), except for one study, which used 2D motion capture (Siliconcoach Pro, New Zealand [25]).

3.2. Relief surfaces

Among the 3 relief surface studies, two [24,27] were conducted on relief floor panels (Terrasensa, Germany), while the other constructed a customized surface (bags of pebbles covered with a mat) [21]. All three studies were conducted in a laboratory.

For the spatial-temporal parameters (Table 2), the 3 studies reported a decreased cadence when walking on a relief compared to level surface [21,24,27] (106.0 vs 118.2 steps/min, not available (n/a), and 5.5 vs 5.1 a.u., respectively). Romkes et al. [27] also showed increased stride width (16.0 vs 13.0 cm), double support time (1.0 vs 0.8 s), and toe clearance height (13.7 vs 8.6 cm), as well as a later toe-off (61.6 vs 59.4 % of gait cycle) when walking on relief compared to level surface. Increased stride width and toe clearance height were also found using the same surface by Böhm et al. [24] (change: 26.0 %, 3.9 cm). Malone et al. [21] did not find a statistical difference in double support time when walking on a relief surface but observed a decreased step length (44.0 vs 47.0 cm) which was not supported by Romkes et al. [27] and Böhm et al. [24]. Malone et al. [21]

and Böhm et al. [24] identified decreased walking speed on relief compared to level surfaces (0.8 vs 1.0 m/s and 0.9 vs 1.0 m/s, respectively). This result was not supported by Romkes et al. [27].

Concerning kinematic parameters, the 3 studies observed increased knee flexion, either during swing [21,24,27] (71.2 vs 62.7º, change: 12.4º and change: 8.9º, respectively), at initial contact [21] (20.6 vs 17.9º), or during the entire gait cycle [21] (65.1 vs 55.5º) when children with CP walked on a relief surface compared to level ground (Table 2). Romkes et al. [27] and Böhm et al. [24] also reported increased hip flexion during swing (change: 12º). Böhm et al. [24] observed a complete disappearance of inward foot progression angle at initial swing and increased pelvic anterior tilt during the swing phase (change: 1.9º). Malone et al. [21] reported a decreased lateral trunk lean (15.3 vs 17.7º), pelvic lateral tilt (11.0 vs 13.3º), subtalar/midfoot range of motion (9.6 vs 10.9º), center of mass peak velocity (0.9 m/s vs 1.1 m/s), and an increased gait profile score (i.e. increased difference from normal gait) (9.6 vs 8.9º) and hip peak extension (6.1 vs 2.6º).

3.3. Slope surfaces

A total of 4 studies focused on gait adaptations during slope-up compared to level ground in individuals with CP [25,26,29,30]. Among them, 2 studies investigated slope-down walking [25,30] (Table 2). One study, conducted by Topçuoglu et al. [30] compared two grades of slope (5° and 10°) with level ground. Here, results are presented for the greater slope only (10°), see Table 2 for more details. The other study compared a 7° slope-up and -down with level ground [25]. Topçuoglu et al. [30], Hösl et al. [29], and Ma et al. [26] conducted their study entirely in a laboratory, while the study of Stott et al. [25] was conducted outdoor (slope-up, slope-down and level) and in a laboratory (level). Hösl et al. [29] and Ma et al. [26] performed their experimentation on a treadmill. All studies included children only, with a GMFCS level of I or II, except for one study that included solely children with GMFCS level II [25].

When walking up-slope compared to level ground, Topçuoglu et al. [30] and Ma et al. [26] observed decreased stride length (98.0 vs 107.0 cm and 39.0 vs 52.0 cm, respectively) and walking speed (1.0 vs 1.1 m/s and 0.32 vs 0.42 m/s, respectively). Both studies enrolled children with similar gross motor function, equally distributed across

GMFCS levels I and II. For slope-down walking, the studies of Stott et al. [25] and Topçuoglu et al. [30], which both included children with diplegic CP, reported decreased stride length (87.0 vs 114.0 cm and 97.0 vs 107.0 cm, respectively) when walking down a slope compared to level ground. Stott et al. [25] also reported increased walking speed (1.2 vs 1.1 m/s), while Topçuoglu et al. [30] found increased cadence (138.4 vs 123.5 steps/min).

A total of 22 kinematic adaptations were found across the 4 slope-up studies (Table 2). The gait adaptations reported by more than one study are increased hip [25,30] (40.0 vs 24.0º and 60.7 vs 40.7º), knee [25,26,29] (28.0 vs 15.0º, 43.9 vs 23.5º and change: 5º, respectively), and ankle [26,29,30] (11.3 vs -1.1º, change: 2º, 9.6 vs 1.28º) flexion at initial contact, maximum hip flexion during swing [26,29] (49.6 vs 39.8º and change: 5º, respectively), ankle dorsiflexion during stance [26,29] (24.2 vs 17.5º and change: 3º, respectively), and a decreased hip extension during stance [26] (11.3 vs 6.6º) when walking up a slope compared to level ground. For slope-down walking, both studies reported decreased hip flexion at initial contact compared to level ground [25,30] (15 vs 24.0 and 26.2 vs 40.7º). Topçuoglu et al. [30] also reported decreased knee flexion at initial contact (11.3 vs 16.4º) and hip and ankle range of motion (34.9 vs 50.6º and 25.0 vs 30.9º, respectively), as well as increased plantarflexion at initial contact (-4.9 vs 1.3º) and knee range of motion (62.7 vs 51.3º). Comparisons of 5 and 10° up and downslopes by Topçuoglu et al. [30] showed increased adaptations down a steeper slope, characterized by lower stride length, hip flexion at initial contact, and hip and ankle range of motion. All other significant gait adaptations identified by only a single study and effect sizes respective to 5 and 10° slopes are shown in Table 2.

Only two studies reported kinetic adaptations during slope-up and -down walking [26,30]. During slope-up walking compared to level ground, Ma et al. [26] reported a decreased peak hip flexion and ankle dorsiflexion moment (-0.10 vs -0.17 Nm/kg and -0.02 vs -0.05 Nm/kg, respectively), and increased peak hip extension moment during stance (0.79 vs 0.54 Nm/kg). Topçuoglu et al. [30] noticed increased peak ankle power at push-off (4.9 vs 1.9 w/Kg).

One study focused on muscle activity adaptations [29]. During slope-up walking, Hösl et al. [29] reported for the medial gastrocnemius, increased eccentric contraction (change: 19%) and decreased maximum fascicle lengthening (change: 1%), measured with surface electromyography and an ultrasound probe, respectively. Also, more tibialis anterior activity was found with respect to flat surface (change: 33%).

3.4. Staircase surfaces

One study assessed the performance of stair negotiation compared to level ground in individuals with CP [31]. This study included 17 adults with diplegic CP (34.3 ± 9.7 years old) presenting stiff-knee gait.

Walking upstairs and downstairs, induced a 2- and 2.5-fold higher step time compared to level ground, respectively (1.2 and 1.5 vs 0.6 s, respectively).

Concerning kinematic adaptations when walking upstairs compared to level ground, Lewerenz et al. [31] observed during swing phase an increased peak hip flexion (67.3 vs 40.7º) and abduction (4.4 vs 1.6º), pelvic obliquity (5.2 vs 2.0º), peak knee flexion (74.2 vs 43.7º), and flexion velocity (171.6 vs 119.0º/s), and peak knee flexion during the entire gait cycle (74.2 vs 43.7º). When walking downstairs, individuals adopted increased hip and knee peak flexion during swing (45.3 vs 40.7º and 76.9 vs 43.7º, respectively), and increased pelvic obliquity and knee peak flexion across the gait cycle compared to level ground (4.0 vs 2.0º and 81.9 vs 43.7º, respectively).

Upstairs walking, compared to level ground, required a decreased activation of the vastus lateralis (26 vs 34 %), while downstairs walking elicited increased activation (43 vs 34 %).

3.5. Comparison with healthy individuals

The observational cross-sectional design of the reviewed studies allows identification of significantly different surface adaptations in individuals with CP compared to healthy individuals (Table 3).

On a relief surface, Böhm et al. [32] and Romkes and al. [27] reported that only children with CP increased stride width (26 % and 10 %, respectively). Inversely, Malone et al. [33] reported that healthy individuals significantly change step length (change: -5.0 cm), peak hip extension (change: 3.1º), knee flexion at initial contact (change: 4.6º), and total ankle (change: -5.2º) and subtalar/midfoot range of motion (change: -2.4º), whereas individuals with CP did not. Romkes and al. [27] also reported that healthy individuals significantly reduced their walking speed (change: 5 s) and increased their ankle dorsiflexion (change: 5.0°) and external foot progression angle (change: 6.8°) during stance, while individuals with CP did not. Böhm et al.[32] also observed that individuals with CP showed a greater increase in toe clearance height (change: 3.9 vs 2.1 cm), almost twice as much increased knee flexion, and a lack of increased ankle dorsiflexion, compared to their typically developing peers. The greater increase in toe clearance (change: 5.1 vs 3.9 cm) was also reported by Romkes and al. [27]. Increased knee range of motion was also observed by Malone et al. [33] in children with CP compared to their typically developing peers (change: 9.6 vs 2.8º).

On slope-up surface, Topçuoglu et al. [30] and Ma et al. [26] reported a greater decrease in step length (change: -9.0 vs 1.0 cm and -13.0 vs -3.0 cm, respectively) on a 10º incline. Topçuoglu et al. [30] also observed a greater decrease in walking speed in individuals with CP (change: 0.2 vs 0.1 m/s) as well as less increased hip (change: 12.8 vs 21.3º) and ankle (change: 5.8 vs 8.2º) range of motion, and decreased knee range of motion (change: 3.0 vs 5.1º), compared to healthy controls. Ma et al. [26] reported in a CP group less increased trunk peak rotation (change: -2.0 vs 4.2º) and a greater increase in ankle dorsiflexion at initial contact (change: 12.4 vs 6.9º), compared to a control group. Also, more increased forward lean at initial contact (change: 11.3 vs 4.2º) and mid-stance (change: 16.0 vs 7.0º) in individuals with CP compared to their healthy peers was reported by Stott et al. [25]. Hösl et al. [29] found less increased minimum knee flexion during stance (change: n/a vs 4.0º) and ankle dorsiflexion during swing (change: n/a vs 2.0º), as well as less decreased maximum knee flexion during swing (change: n/a vs 3.0º) in CP compared to healthy group. Concerning muscle adaptations, Hösl et al. [29] also reported more increased eccentric excursion of the medial gastrocnemius (change: 19.0% vs n/a) and a smaller increase in activity in the medial gastrocnemius (change: n/a vs 23.0%) and soleus (change: n/a vs 29.0%) in children with CP in comparison to typically developing children.

When walking down a slope, Topçuoglu et al. [30] observed that individuals with CP have greater increased cadence (change: 14.9 vs 0.1 steps/min), decreased stride length (change: 10 vs 3 cm), decreased hip range of motion (change: 15.6 vs 7.5º), increased plantar flexion at initial contact (change: 6.2 vs 0.2º), and decreased knee flexion at initial contact (change: -5.1 vs 2.1º), compared to their healthy peers. Also, greater increased hip extension at initial contact (change: 9.0 vs 6.0º) was reported by Stott et al. [25].

Regarding stair negotiation, Lewerenz et al. [31] reported less gait adaptations in individuals with CP compared to healthy when walking upstairs and downstairs, such as less decreased hip peak abduction during swing (change: 2.8 vs -1.2º, and 0 vs -3.1º, respectively) and ankle peak plantarflexion during stance (change: 1.2 vs -5.2º and 1.4 vs -3.8º), respectively). Upstairs, less increased hip peak flexion during swing (change: 26.6 vs 28.6º) was also reported in individuals with CP. Downstairs, a higher increase in step time (change: 0.9 vs 0.1 s) and pelvic obliquity (elevation) during swing (change: 2.0 vs 0.6º) was reported for individuals with CP compared to healthy individuals.

4. Discussion

4.1. Summary

This scoping review describes gait adaptations of individuals with CP on irregular, compared to even surfaces and contrasts adaptations with those of healthy individuals. A total of 10 studies were retained and the majority involved children (9/10 studies) with diplegia (127/152 individuals). For two other studies [22,23], authors reported gait adaptations between outdoor and laboratory environments, without specifying outdoor surface types. In general, this scoping review highlights that individuals with CP adapt their gait on irregular surfaces in comparison to level ground and healthy controls and that adaptations appear to be modulated by CP type and severity.

4.2. Relief surfaces

The 3 relief surface studies [21,24,27] used of surfaces with major irregularities. Böhm et al [24] and Romkes et al. [27] used a shock-absorbing relief surface developed to replicate reliefs found in nature (see figure 2) [34], while Malone et al. [21] used a custom surface comprised of bags of pebbles covered with a mat, which in this case, is not a commonly traveled surface.

The spatial-temporal gait adaptation commonly reported by the three studies is a decrease in cadence on the relief surface, compared to the level ground. This decreased cadence, in addition to reduced walking speed reported by Malone et al. [21] and Böhm et al. [24], is indicative of a greater balance challenge and a more cautious gait when walking on relief, compared to flat, surfaces. Similarly, the greater stride width reported by Böhm et al [24] and Romkes et al. [27] might represent an adaptive strategy to increase stability via a wider base of support [35]. Differences between cohorts may account for inconsistent adaptive responses on relief surfaces across studies. For instance, the absence of decreased walking speed reported only by Romkes et al. [27], whose study included solely children with hemiplegia, may be driven by compensatory adaptations from the less affected side. Indeed, a previous study has shown that the impulsive torque of a non-affected limb can provide the energy needed for gait speed maintenance [36]. Moreover, Romkes et al. [27] mainly recruited children with low functional limitations (GMFCS I = 18/20 participants), potentially limiting maladaptive behaviors on the relief surface.

Increased knee flexion during swing phase is the only kinematic adaptation reported by all the 3 studies. As suggested by Romkes et al. [27] and Böhm et al. [24] this adaptation may increase toe clearance on relief surfaces compared to level ground. Romkes et al. [27] and Böhm et al. [24] also reported increased hip flexion during swing phase, further strengthening the increased toe clearance adaptation hypothesis. Foot and ankle kinematics change when walking on relief surfaces as evidenced by the disappearance of inward foot progression (coronal plane) and reduced subtalar/midfoot (coronal plane) and ankle range of motion (sagittal plane) reported by Böhm et al. [24] and Malone et al. [21], respectively. In these two studies, however, it is important to note that a multi-segment foot model was not implemented to measure foot motion, limiting validity of findings [37]. Given the observation of different foot/ankle kinematics across these two studies, it is not possible to draw definite conclusions. The kinematic parameters reported by Malone et al. [21] allow for the identification of general adaptations on a relief surface, such as a decreased center of mass peak velocity, which reflects a more cautious gait pattern [37], and an increased gait profile score that explains overall gait pathology [39].

4.3. Slope surfaces

This scoping review indicates that on 5 or 10° slopes (up and down), stride length is decreased compared to level ground. This adaptation of shorter steps may permit a flatter foot contact, as observed in healthy young adults on a destabilizing surface [40].

Making firm conclusions regarding kinematic adaptations on slopes was not always possible since the studies included report distinct metrics (e.g., hip range of motion for Topçuoglu et al. [30] and hip flexion at mid-stance for Stott et al. [25]). Nonetheless, this scoping review allows us to conclude that walking up a slope induces more flexion for the 3 lower-limb joints (ankle, knee, hip) at the beginning of the gait cycle while the opposite occurs when walking downslope, compared to level ground walking. The study by Topçuoglu et al. [30] is the only study that assessed different slope grades, thereby providing information on the "dose-response" relationship between slope inclination and gait adaptations: the steeper the incline (5 vs 10°), the more gait is affected (i.e. larger gait adaptations compared to level ground and effect sizes). Topçuoglu et al. [30] proposed that the increased functional length of the swing leg during downslope walking, obtained via reduced joint flexion, might be used to increase stability and assist the swing leg in reaching the floor in a more controlled manner. Moreover, this study reported a subjective increase in anxiety in children with CP, particularly on the 10° slope. Although the feeling of safety was assessed based on weak evidence (qualitative observation of facial expressions and gaze), this result raises important questions regarding the contribution of psychological state (fear of falling and anxiety) on gait adaptations on a steep slope.

The kinetic adaptations related to slope-up walking (e.g., increased peak hip extension moment [26] and ankle peak power at push-off [30]) can be explained by the kinematic adaptations previously described and a greater need to counteract gravity, compared to level walking, with the opposite effect occurring when walking downslope (e.g., decreased ankle peak power at push-off [30]). As only two studies reported on kinetic adaptations on a slope, evidence remains limited.

4.4. Staircase surfaces

The single study that assessed stair negotiation consisted of climbing and descending 5 steps (height and depth conventional size, width 100 cm) with a bilateral handrail. The authors mention that 8/17 patients used both handrails for support when walking up and down; however, the effects of weight-bearing on the handrails was not measured. This missing information is potentially relevant in stair climbing since handrail use has been shown to affect kinetics (e.g., peak ankle, knee, and hip joint moments on the affected side) of movement in people with chronic stroke [41] .

Walking upstairs and downstairs, compared to level walking, in adults with CP, lead to spatial-temporal changes (e.g., increased step time) and kinematic adaptations at the hip, pelvis, and knee joints (e.g., increased peak hip/knee flexion and pelvic obliquity during the swing phase). Also, walking up and downstairs leads to opposite gait adaptations for muscle activity of the vastus lateralis (decreased and increased activations, respectively); however, the study revealed highly variable muscle activity, suggesting that GMFCS level-specific activation patterns may be employed during stair negotiation. Indeed, muscle activation pattern discrepancies among different GMFCS level groups have been reported during gait in children with CP [42]. No comparison of these gait adaptations with other research is possible since no similar studies have been identified. Nevertheless, these adaptations reveal that stair negotiation, which is frequent in daily life, represents an increased biomechanical challenge compared to level walking and might differ between GMFCS levels according to neurophysiological properties [42].

4.5. Comparison with healthy individuals

Considering how individuals with CP differentially adapt to irregular surfaces, compared to healthy peers, is crucial in identifying functional impairments. In general, both groups implemented similar biomechanical strategies to contend with the irregular surface challenge; however, this scoping review has also identified CP-specific adaptations or lack of adaptations that are now discussed.

On an irregular surface, unlike their healthy peers, individuals with CP do not significantly change their ankle and foot motion. As suggested by Malone et al. [21], the inability to appropriately adapt ankle movement strategies may be a manifestation of selectivity and motor control impairments in individuals with CP. Böhm et al. [24] attributed the observed lack of adaptation to musculoskeletal disorders including equinus contractures and/or spasticity. Other non-adaptations were observed at the knee and hip in the sagittal plane which could contribute to impaired dynamic stability on irregular surfaces; however, a greater increase in step width was reported in individuals with CP, compared to healthy controls, presumably as an adaptative behavior to maintain mediolateral stability [43].

When walking up-slope, individuals with CP showed greater spatial-temporal alterations than healthy individuals (i.e., greater decrease in stride length and walking speed). This gait deterioration is reflected in the lack of increased gastrocnemius and soleus activity reported by Hösl et al. [29], and consequently decreased ankle power generation reported by Topçuoglu et al. [30]. The greater increase in forward trunk lean and lack of increased hip range of motion observed in individual with CP also supports these findings [25].

When walking down-slope, individuals with CP showed larger changes in adaptive behaviors compared to healthy peers. At initial contact, increased hip extension and plantarflexion, and decreasing knee flexion leads to a relative elongation of the supporting leg. This adaptative behavior may result from a greater requirement for a controlled foot strike compared to healthy individuals [30].

Based on the single stair negotiation study [31], it seems that individuals with CP are able to manage stairs similarly to their healthy peers by considerably increasing step time. However, a decreased peak ankle plantarflexion during stance was noted for both conditions and was attributed to a vaulting gait strategy by Lewerenz et al. [31]. Also, the authors suggest that gait adaptations more broadly relate to different muscle activation patterns and underlying compensation mechanisms, which were not investigated [31].

4.6. Literature limitations

The current literature presents limitations which lead to research gaps. First, all the studies that included individuals with different functional levels (GMFCS) and/or distinct CP types (e.g., hemiplegia and diplegia) ignored these comparisons. The motor prognosis by GMFCS level may underestimate lower extremity skills of children with hemiplegia and overestimate those of children with diplegia [44]. Moreover, CP type is associated with specific gait abnormalities (e.g., stiff knee, crouch, and knee varus gait) [2]. Thus, the absence of GMFCS level or CP type stratification may overlook relevant information such as the extent of adaptations required to cope with daily locomotion according to severity of functional impairments.

The second limitation concerns the walking surfaces themselves. The choice of surface is a complex challenge when designing studies on irregular surfaces. On one hand, learning about how the body adapts requires severe surfaces that induce major functional challenges. On the other hand, surfaces might be chosen to reflect those found in the real world to maximize ecological validity of results and to ensure participant safety. Three studies lack ecological validity as experimental surfaces are not representative of surface types encountered in the real-world. Malone et al. [21] created an irregular surface via bags of pebbles covered with a mat. Ramp grade standard vary depending on the country's legislation. In Canada, for instance, the maximum tolerated grade for an outdoor accessibility ramp of 10m length is 10% (5.7°) [45], while it is 6% (~3°) in Switzerland [46]. Thus, walking on a slope of 10°, as reported by Ma et al. [26] is not a walking task likely to be encountered by individuals with CP, except for street inclinations dependent on regional topography. Also, the use of a treadmill by Hösl et al. [29] and Ma et al. [26] may induce small but non-negligible adaptations in children with CP [47]. For instance, treadmill walking leads to less inter-joint coordination variability compared to free walking since it imposes a systemic regulation on dynamic neuromuscular control [48]. Finally, most studies focused only on a single irregular surface type (e.g., a single grade slope or type of relief) [21–29,31] or did not specify the type of surface [22,23].

In addition, 9 of 11 studies were conducted in a laboratory [21,24–31]. Only the two studies by Carcreff et al. [22,23] were conducted outdoors; however, they did not report gait adaptations by surface type since unique surfaces were not identified. Nonetheless, these studies provide quantitative evidence that spatial-temporal parameters assessed in the laboratory differ from parameters measured during daily life in children with CP (e.g., increased walking speed and decreased stride time outdoors, compared to in a laboratory environment) [23].

Finally, the use of 2D motion analysis by Stott et al. [25] leads to questions related to measurement validity [49]. Indeed, 2D hip, knee, and ankle angle measurements in the CP population differ from those obtained by 3D motion capture and do not reflect true sagittal joint orientations [50].

4.7. Recommendations for future studies

Future studies should include comparisons between CP and/or gait types to improve the specificity irregular surface gait adaptations. Indeed, gait patterns (e.g., stiff knee, crouch gait) in patients with CP differ significantly between CP types (e.g., hemiplegia, diplegia) [2], which suggests that gait adaptations on irregular surfaces should also differ.

To understand functional challenges of walking in real-world environments and help generate predictive equations of adaptations based on relief severity and/or slope grade, future studies should focus on variable levels of irregularity and assess how the "dose" affects the adaptive response.

This scoping review's selection criteria did not restrict results to either barefoot or shod gait studies. The studies presented herein do not allow us to parse the relative effect of footwear condition from those of surface type. The choice of footwear condition, including orthoses, orthotics, and other mobility aids, remains challenge for gait study design which should be guided by the underlying research question or purpose of the assessment.

While the identified investigations of this scoping review provide information on adaptations to surface irregularity challenges, further research conducted outside the laboratory would enhance the ecological validity of assessments. Indeed, other walking challenges such as dual tasking, endurance challenges, and interaction with the environment (e.g., other walkers or obstacles) may alter gait stability [51] and remain relevant. Thus, gait analysis of daily locomotion is a promising setting for future clinical gait assessments; however, significant methodological challenges need to be addressed before these approaches can be widely accepted. For example, data collection using automatic surface type detection algorithms could be implemented [52] to allow a more granular analysis of data in further studies.

Finally, the use of a metric such as the gait profile score is of particular interest. The gait profile score represents the root mean square difference between the subject's joint kinematic curve and the mean normative curve [39]. The metric is of clinical interest as it facilitates interpretation of gait assessment results by clinicians, allowing the quantification of kinematic adaptations compared to controls. Understanding how gait adaptations in individuals with CP differ from healthy populations on irregular surfaces, via, for example, the gait profile score, is relevant and should be explored further.

5. Conclusion

This scoping review examined the extent and nature of research related to gait adaptations on irregular surfaces in individuals with CP. Although the studies extracted do not enable the development of a theoretical framework for gait adaptations on irregular surfaces, this scoping review highlights gait adaptation of individuals with CP on challenging surfaces and how they differ from those of healthy controls. Also, this scoping review emphasizes the clinical and research interest of focusing future studies on more ecologically valid data collection approaches, such as conducting experiments in environments and on surfaces encountered by individuals with CP.

Conflict of interest

No potential conflict of interest was reported by the authors.

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Table 1. General and experimental characteristics of studies.

	Title	Authors	Year	Participant's demographics: n	CP type	Age (years)	Sex	GMFCS Level (n)	Protocol design: Motion capture system	Evaluated parameters	Surface types	Gait condition	Environment
1	Walking on uneven ground: How do patients with unilateral cerebral palsy adapt?	Romkes J, Freslier M, Rutz E, B. Schweizer K	2020	CP: 20 TD: 20	H	CP: 10.8 TD: 11.4	CP: 13M/7F TD: 10M/10F	Level I: 18 Level II: 2	Vicon	Spatial-temporal Kinematics	a) Relief floor panels b) Level	Barefoot	Laboratory
2	Stiff-knee gait in cerebral palsy: How do patients adapt to uneven ground?	Böhm H, Hösl M, Schwameder H, Döderlein L	2014	CP: 16 TD/H: 13	D	CP: 14.1 TD: 13.5	CP: 14M/2F TD: 7M/6F	Level I and II	Vicon	Spatial-temporal Kinematics Muscle activity	a) Relief floor panels b) Level	Barefoot	Laboratory
3	Do children with cerebral palsy change their gait when walking over uneven ground?	Malone A, Kiernan D, French H, Saunders V, O'Brien T	2015	CP: 17 TD: 17	H: 10 D: 7	CP: 10.0 TD:10.1	CP: 10M/7F TD: 8M/9F	Level I: 14 Level II: 3	Codamotion	Spatial-temporal Kinematics	a) 0.5cm pebbles covered with a 0.2cm mat b) Level	Barefoot	Laboratory
4	Level Versus Inclined Walking: Ambulatory Compensations in Children with Cerebral Palsy Under Outdoor Conditions	Stott N, Reynolds N, McNair P	2014	CP: 10 TD: 10	D	CP: 9.0 TD: 8.5	CP: 6M/4F TD: 5M/5F	Level II only	Siliconcoach	Spatial-temporal Kinematics	a) Slope-up (7°) b) Slope down (-7°) c) Level	Inside: Barefoot Outside: Shod	Outdoor & laboratory
5	How do children with bilateral spastic cerebral palsy manage walking on inclines?	Topçuoglu M, K. Krautwurst B, Klotz M, Dreher T, Wolf S	2018	CP: 18 TD: 19	D	CP: 7.9 TD: 8.2	CP: 11M/7F TD: 12M/7F	Level I: 9 Level II: 9	Vicon	Spatial-temporal Kinematics Kinetics	a) Slope-up (+5° and +10°) b) Slope down (-5° and -10°) c) Level	Shod	Laboratory
6	Comparison of gait characteristics between clinical and daily life settings in children with cerebral palsy	Carcreff L, N. Gerber C, Paraschiv-Ionescu A, De Coulon G, J. Newman C, Aminian K, Armand S	2020	CP: 14 TD/H: 14	H: 2 D: 12	CP: 12.6 TD: 12.3	CP: 6M/8F TD: 6M/8F	Level I: 6 Level II: 3 Level III: 5	Gait up	Spatial-temporal Kinematics	a) Outdoor b) Inside the laboratory	Inside: Barefoot Outside: Shod	Outdoor: 2 school days and 1 during the weekend. Inside: Laboratory
7	Contractile behavior of the medial gastrocnemius in children with bilateral spastic cerebral palsy during forward, uphill and backward-downhill gait	Hösl M, Böhm H, Arampatzis A, Keymer A, Döderlein L	2016	CP: 15 TD: 17	D	CP: 11.0 TD: 12.2	CP: 11M/4F TD: 9M/8F	Level I: 11 Level II: 4	Vicon	Spatial-temporal Kinematics Muscle activity	a) Slope-up (+12%) b) Slope down (-12%) c) Level	Barefoot	Laboratory
8	Walking Speed of Children and Adolescents with Cerebral Palsy: Laboratory Versus Daily Life	Carcreff L, N. Gerber C, Paraschiv-Ionescu A, De Coulon G, J. Newman C, Aminian K, Armand S	2020	CP: 15 TD/H: 14	H: 3 D: 12	CP: 12.8 TD: 12.2	CP: 6M/9F TD: 6M/8F	Level I: 6 Level II: 3 Level III: 6	Outdoor: Gait up Inside: Qualisys	Spatial-temporal	a) Outdoor b) Inside the laboratory	Inside: Barefoot Outside: Shod	Outdoor: 2 school days and 1 during the weekend. Inside: Laboratory
9	Gait Characteristics of Children with Spastic Cerebral Palsy during Inclined Treadmill Walking under a Virtual Reality Environment	Ma Y, Liang Y, Kang X, Shao M, Siemelink L, Zhang Y	2019	CP: 10 TD: 10	D	CP: 8.5 TD: 7.9	CP: 6M/4F	Level I: 5 Level II: 5	Vicon	Spatial-temporal Kinematics Kinetics	a) Slope-up (+10°) b) Level	Barefoot	Laboratory on a treadmill with virtual reality
10	Performance of stair negotiation in patients with cerebral palsy and stiff knee gait	Lewerenz A, Wolf, S I, Dreher T, Krautwurst B. K	2019	CP: 17 H: 25	D	CP: 34.3 H: 31.8	CP: 7M/10F H: 13M/12F	Level I: 1 Level II: 13 Level III: 3	Vicon	Spatial-temporal Kinematics Muscle activity	a) Upstairs (5 with handrail) b) Downstairs (5 with handrail) c) Level	Shod	Laboratory

Abbreviations: CP, cerebral palsy; TD, typically developing (children); H, healthy (adults); H, hemiplegia; D, diplegia; M, male; F, female; GMFCS, gross motor functional classification system.

Table 2. Gait adaptations in individuals with cerebral palsy on irregular surface compared to flat.

	ES	Spatial-temporal	ES	Kinematics	ES	Kinetics	ES	Muscle activity
Relief	1.00, ♦, 0.58 0.73, ♦ 0.70 0.25 1.19 1.11 ♦, 0.70 3.43, ♦	↓ cadence (1,2,3) ↑ stride width (1,2) ↑ Step time (3) ↓ Step length (3) ↑ double support time (1) Later toe-off occurrence (1) ↓ walking speed (2,3) ↑ toe clearance height (1,2)	0.32 ♦, ♦ 0.31 ♦ 0.53 0.89 ♦, ♦, 1.31 0.33 0.21 ♦ 0.39 0.59 0.34	↓ lateral trunk lean (3) ↑ hip flexion during swing (1,2) ↑ hip peak extension (3) ↑ pelvic anterior tilt during swing (2) ↓ pelvic lateral tilt (3) ↑ knee ROM (3) ↑ knee flexion during swing (1,2,3) ↑ knee flexion at IC (3) ↓ ankle ROM (3) ↓ foot inward progression at initial swing (2) ↓ Subtalar/midfoot ROM (3) ↓ COM peak velocity (3) ↑ Gait Profile Score (3)		No information		No information
Slope-up	[1.15], 0.66 0.73 [0.75], 0.74	↓ walking speed (5,9) ↑ % stance phase (9) ↓ stride length (5,9)	1.01 1.64* and 1.90* [0.87] 1.76*, [1.60,2.70] and 1.37* 1.50, 0.94 1.20 0.63 0.15 2.22/ 2.29/ 0.40 0.96* ,1.10, 2.88 2.66 [0.86, 1.57], 0.60,1.36 1.40, 1.07 1.11 [0.93,1.13] [♦] [♦] 1.99	↓ trunk peak extension (9) ↑ trunk forward lean at IC (4) and MS (4) ↑ trunk obliquity ROM (5) ↑ hip flexion at IC (4,5) and MS (4) ↑ hip peak flexion during swing (7,9) ↑ hip minimum flexion during stance (7) ↓ hip extension (9) ↓ hip peak abduction (9) ↑ pelvic peak anterior/ posterior/ oblique tilt (9) ↑ knee flexion at IC (4,7,9) ↑ knee flexion at LR (9) ↑ ankle dorsiflexion at IC (5,7,9) ↑ ankle dorsiflexion during stance (7,9) ↓ ankle peak plantarflexion (9) ↑ ankle ROM (5) ↑ % forefoot contact (5) ↓ % heel contact (5) ↓ anterior distance between COM and COP (9)	1.15 1.35 [0.63] 0.70	↓ hip peak flexion moment (9) ↑ hip peak extension moment (9) ↑ ankle peak power at push-off (5) ↓ ankle peak dorsiflexion moment (9)	1.000 0.600 0.500	↑ eccentric excursion of the medial gastrocnemius (7) ↓ max length of the medial gastrocnemius (7) ↑tibialis anterior activity (7)
Slope-down	0.84* 1.74*, [0.87] [1.02]	↑ walking speed (4) ↓ stride length (4,5) ↑ cadence (5)	[2.06] 0.97*, [1.35,2.34] [0.64,0.61] [1.08] [0.54,0.95] [1.34]	↓ hip ROM (5) ↓ hip flexion at IC (4,5) ↓ knee flexion at IC (5) ↑ knee ROM (5) ↑ plantar flexion at IC (5) ↓ ankle ROM (5)	[0.76]	↓ ankle peak power at push-off (5)		No information
Upstairs	1.34	↑ step time (10)	3.64 0.51 0.91 0.85 3.12 2.71	↑ hip peak flexion during swing (10) ↑ hip peak abduction during swing (10) ↑ pelvic peak obliquity (elevation) during swing (10) ↑ knee peak flexion velocity during swing (10) ↑ knee peak flexion during swing (10) ↑ knee peak flexion (10)		No information	♦	↓ % of activation of vastus lateralis (10)
Downstairs	1.54	↑ step time (10)	0.65 0.52 4.79 1.99	↑ hip peak flexion during swing (10) ↑ pelvic peak obliquity (elevation) during swing (10) ↑ knee peak flexion during swing (10) ↑ knee peak flexion (10)		No information	♦	↑ % of activation of vastus lateralis (10)

Significant gait adaptations in children with cerebral palsy (study number based on Table 1) for each irregular surface compared to flat. Effect size (Cohen's d or Glass's delta*) are presented respective to the articles order, if available (♦ if not). Effect size values in brackets of study 5 are for [5°,10°], and for [10°] if one value is presented. Abbreviations: ES, effect size; IC, initial contact; MS, mid-stance; ROM, range of motion; COM, center of mass; COP, center of pressure; ↑, increased/higher; ↓, decreased/lower.

Table 3. Gait adaptation differences on irregular surface in individuals with cerebral palsy compared to healthy individuals.

	ES (CP vs TD/H)	Spatial-temporal	ES (CP vs TD/H)	Kinematics	Kinetics	ES (CP vs TD/H)	Muscle activity
Relief	0.73 vs 0.90, ♦	↑ increased stride width (1,2)	0.31 vs 0.40	↓ decreased hip peak extension (3)	No information		No information
	0.25 vs 0.40	↓ decreased step length (3)	0.33 vs 0.65	↓ increased knee flexion at IC (3)			
	0.60 vs 0.90	↓ decreased walking speed (1)	0.89 vs 0.40	↑ increased knee ROM (3)			
	3.43 vs 3.52, ♦	↑ increased toe clearance height (1,2)	♦	↑ increased knee flexion during swing (2)			
			♦	↓ increased ankle dorsiflexion during stance (1)			
			♦	↓ increased ankle dorsiflexion during swing (2)			
			0.21 vs 0.75	↓ decreased ankle ROM (3)			
			0.39 vs 0.67	↓ decreased subtalar/midfoot ROM (3)			
			♦	↓ increased external foot progression angle (1)			
Slope-up	[0.75 vs 0.08], 0.74 vs 0.23	↑ decreased stride length (5,9)	0.23 vs 0,71	↓ increased trunk peak rotation (9)	No information	1.00 vs ♦	↑ increased eccentric excursion of medial gastrocnemius (7)
	[1,15 vs 0.74]	↑ decreased walking speed (5)	1.50 vs 0.25*	↑ increased forward trunk lean at IC (4)		♦ vs 1.20	↓ increased medial gastrocnemius activity (7)
			1.90 vs 0.31*	↑ increased forward trunk lean at MS (4)		♦ vs 0.80	↓ increased soleus activity (7)
			[1.51 vs 3.68]	↓ increased hip ROM (5)			
			[0.28 vs 1.12, 0.31 vs 0.83]	↓ decreased knee ROM (5)			
			♦ vs 1.40	↓ increased minimum knee flexion during stance (7)			
			♦ vs 1.60	↓ decreased maximum knee flexion during swing (7)			
			[1.13 vs 1.72]	↓ increased ankle ROM (5)			
			1.63 vs 1.31	↑ increased ankle dorsiflexion at IC (9)			
			♦ vs 1.00	↓ increased ankle dorsiflexion during swing (7)			
Slope-down	[1.02 vs 0.01]	↑ increased cadence (5)	1.14 vs 0.43*	↑ increased hip extension at IC (4)	No information		No information
	[0.87 vs 0.22]	↑ decreased stride length (5)	[2.06 vs 1.46]	↑ decreased hip ROM (5)			
			[0.64 vs 0.25, 0.61 vs 0.53]	↑ decreased knee flexion at IC (5)			
			[0.54 vs 0.08, 0.95 vs 0.05]	↑ increased plantarflexion at IC (5)			
Upstairs		No information	3.64 vs 4.50	↓ increased hip peak flexion during swing (10)	No information		No information
			0.51 vs 0.42	↓ decreased hip peak abduction during swing (10)			
			0.12 vs 0.84	↓ decreased ankle peak plantarflexion during stance (10)			
Downstairs	1.54 vs 1.00	↑ increased step time (10)	0.52 vs 0.36	↑ increased pelvic peak obliquity (elevation) during swing (10)	No information		No information
			0.00 vs 1.09	↓ decreased hip peak abduction during swing (10)			
			0.13 vs 0.61	↓ decreased ankle peak plantarflexion during stance (10)			

Significant gait adaptations differences on irregular surface in individuals with cerebral palsy compared to healthy individuals (study number based on Table 1). Effect size (Cohen's d or Glass's delta*) are presented respective to the articles order, if available (♦ if not). Effect size values in brackets of study 5 are for [5°,10°], and for [10°] if one value is presented. Abbreviations: CP, cerebral palsy; TD, typically developing; H, healthy; ES, effect size; IC, initial contact; MS, mid-stance; ROM, range of motion; ↑, higher or present in cerebral palsy individuals; ↓, lower or missing in cerebral palsy individuals.