The effects of actual and simulated visual impairments on the walking gait: A systematic review.

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REVIEW

The effects of actual and simulated visual impairments on the walking gait: A systematic review

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ABSTRACT

Background: Visual impairments (VI) affect over 2.2 billion people worldwide and are linked to an increased risk of falls. To date, no reviews have systematically synthesised evidence for the effect of VI on whole body gait biomechanics, to better understand how different types of VI might affect gait.
Methods: A systematic search up to July 2025 was conducted using PubMed (MEDLINE), Scopus, Web of Science, and ERIC. Eligible studies included adults, a diagnosed or simulated VI, a non-visually impaired comparator, and reported any of the following gait parameters: 1) Spatio-temporal; 2) Kinetics; 3) Kinematics; and 4) Muscle activity. Study quality was evaluated using quality assessment with diverse studies (QuADS) and a narrative synthesis undertaken (SWiM).
Findings: Forty-four studies were included. Twenty-seven examined straight-line level walking, 12 examined obstacle walking and five examined both straight-line level and obstacle walking. Of those examining straight-line level walking, 12 simulated VI and 15 explored diagnosed VI's. In the obstacle walking literature, nine simulated VI and six included participants with diagnosed VI's. Inconsistent findings were common across studies, with most reporting either a more cautious gait strategy with VI, or no difference between VI and non-VI conditions.
Interpretation: Differences between studies are likely explained by variation in gait measurement, non-standard VI simulation methods, and lack of detail surrounding the severity of diagnosis. This hinders provision of clinical recommendations based on existing evidence. We have proposed minimum reporting requirements around acuity, contrast sensitivity, visual field method/thresholds; simulation validation to facilitate clinical utilisation.

1. Introduction

The visual system has several roles in the regulation of locomotion, including postural control to maintain stability, hazard detection, foot placement, walking speed regulation, and route planning (Assaiante et al., 1989; Patla, 1997; Reynolds and Day, 2005). Reducing or removing visual feedback has been shown to lead to reduced walking speed, shorter step lengths, impaired control of step placement, increased step width variability, reduced pelvic rotation, increased knee flexion during stance, and reduced ankle plantarflexion during push-off (Bauby and Kuo, 2000; O'Connor and Kuo, 2009). These gait alterations result in a more cautious walking strategy and are often seen in older adults, who appear to rely more on visual feedback for balance control while walking compared to their younger counterparts (Franz et al., 2015). This is likely due to a decline in the quality of somatosensory signalling with advanced age (Shaffer and Harrison, 2007). As such, the visual system appears to have a fundamental role in postural control and balance during walking activities, and its absence or degradation can alter the walking gait and disrupt gait stability. This disruption is amplified in individuals with diminished compensatory sensory capacity, which can occur with normal aging, as well as in those with inherited or age-related and progressive ocular pathologies. This highlights the importance of examining how different types and severities of Visual Impairment (VI) might disrupt the walking gait.

The World Health Organisation estimates that at least 2.2 billion people have a near or distant VI (WHO, 2023) and in the UK, it is

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estimated that over 2 million people are living with low vision and that approximately 340,000 individuals are registered as blind or partially sighted (NHS, 2021). There are many types of VI, with refractive errors, presbyopia, cataracts, glaucoma, diabetic retinopathy and age-related macular degeneration reported among the most common disorders in adults (American Optometric Association, 2015). These disorders impair vision in different ways, for example, glaucoma causes loss of peripheral vision, which has been shown to affect control of gaze fixation (Cajar et al., 2016; Yu and Kwon, 2023), whilst age-related macular degeneration (AMD) affects central vision by causing blurriness and distortion of straight lines (Reed-Jones et al., 2013). Understanding the impact that these conditions have on the walking gait is important, because both central and peripheral visual impairments have been linked to an increased risk of falls, as they reduce an individual's ability to detect hazards (Buckley et al., 2010) likely caused by misjudgements of distances and/or misinterpretations of spatial information (Patino et al., 2010).

Although some VI's such as glaucoma (Freitag et al., 2023; Gomes et al., 2018) or cataracts (Ao et al., 2023; Durmus et al., 2011) have been reported to alter gait characteristics, the wide range of study designs and methodologies employed in the literature make it difficult to draw conclusions on the extent to which different types of VI can influence gait pattern. For example, some studies have simulated VI (e.g., Helbostad et al., 2009; Krishnan et al., 2017), while others have investigated diagnosed VI (e.g., Spaulding et al., 1995; Varadaraj et al., 2017a) This can produce contradictory results, for example Noh et al. (2023) investigated the effects of diagnosed cataracts on gait and found a reduction in step width and step length compared to healthy sighted individuals, whereas Krishnan et al. (2017) simulated cataracts and found no difference in step width and step length. It is therefore important to examine any differences between simulated and diagnosed VI on gait.

In studies that have recruited participants with diagnosed impairments, some include visual assessments to quantify the level of impairment. For example, Spaulding et al. (1995) describe the effects of VI in terms of levels of visual acuity and contrast sensitivity, however, others do not include a visual assessment (Krishnan et al., 2017). Different types of walking gait have also been investigated, such as walking over flat surfaces in a straight line (Hallemans et al., 2009b), and walking whilst negotiating obstacles (also known as obstacle walking) (Saucedo and Yang, 2017) which have clearly distinct mechanics of movement and so should be analysed separately.

To date, only one review has synthesised evidence in the area of visual impairment and gait, comparing the spatiotemporal gait variability between visually impaired and sighted individuals (Kahaki et al., 2023). They reviewed six studies and concluded that the stride pattern of blind and low-vision individuals is characterised by a slower speed, shorter stride length, decreased cadence and increased step width compared to non-visually impaired. In this systematic review that we are conducting we combined results from studies which investigated both, simulated and diagnosed VI. There is evidence to suggest that simulated and diagnosed VI may have different effects on gait (Majlesi et al. (2020). To the best of our knowledge, no review has systematically synthesised the existing literature to investigate how both, simulated and diagnosed visual impairments effect whole body walking gait mechanics across obstacle walking and straight-line level walking gait patterns.

Therefore, the primary aim of this systematic review was to synthesise the existing evidence on the effect of visual impairments on walking gait parameters. The secondary aims were to compare evidence that has used simulated and diagnosed visual impairment, and to compare evidence that have used straight-line level walking and obstacle walking patterns.

2. Methods

This systematic review is reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) criteria (Page et al., 2021). The protocol for the overall systematic review process has been registered in the International Prospective Register for Systematic Reviews (PROSPERO), registration number CRD42022346553.

2.1. Study inclusion and exclusion criteria

Studies were included in this systematic review if they included a comparator with a non-visually impaired condition. We have only included studies performed in adults over 18 with people diagnosed with visual or simulated visual impairment. To be eligible, studies must have reported any of the following gait parameters: 1) Spatio-temporal; 2) Kinetics; 3) Kinematics; and 4) Muscle activity. Studies must be published in English and in peer-reviewed journals.

Studies were excluded if participants used assistive walking devices during the trial or had musculoskeletal conditions that could affect gait. We have also excluded reviews, case studies, conference abstracts, dissertations, and opinion pieces.

2.2. Search strategy

The following databases were searched for this study: PubMed (MEDLINE), Scopus, Web of Science and ERIC. Databases were searched in December 2023 and updated in July 2025. No date restriction was applied in the searches. The search terms used were (“Visual impairment” OR “Vision impairment” OR “Cataracts” OR “Glaucoma” OR “Blind” OR “Retinal Disease” OR “Vision disorders” OR “Eye Disease” OR “Blindness” OR “Peripheral vision loss” OR “Blurry Vision” OR “Central Vision Loss” OR “gaze”) AND (“Gait” OR “Gait Parameters” OR “Gait Analysis” OR “Muscle Recruitment”).

2.3. Study selection

Titles and abstracts were screened for quality control between the four reviewers (JB, LA, MF and SH). The rest of the titles and abstracts were then split into two and independently screened and compared in pairs (LA and MF; JB and SH), disagreements were discussed in a meeting with the four reviewers (JB, LA, MF and SH).

Full-text copies were obtained after the initial screening and were examined independently in pairs (JB and MF; LA and SH). Discrepancies were resolved by discussions and consensus or by consultation with all reviewers.

2.4. Quality assessment

Since multiple study designs were included, study quality was evaluated using quality assessment with diverse studies (QuADS) (Harrison et al., 2021) This tool comprises 13 evaluative indicators covering different domains, including underlying theory, defined objectives, appropriateness and rigour of design, data collection methods, and analytical methods. Each indicator was measured on a four-point Likert scale, from 0 (not at all) to 3 (complete). Studies were scored independently, and final scores were agreed in pairs (JB and MF; LA and SH).

The QuADS tool does not provide cut-point score for reporting quality across the study. We opted to summarise the strength of evidence by arbitrarily grouping studies using the cut-points suggested in another study (Arbour-Nicitopoulos et al., 2018). The arbitrary cut points were set as low (<60%) (less than 22), moderate (60–80%) (23 to 30) or high (>80%) (31 or higher) and reported on QuADS Quality Appraisal table (Table 5).

2.5. Data extraction

A standardised data extraction form was piloted, completed by each of the reviewers (JB, LA, MF, SH or RH), and checked by the main author (MF). Reviewers extracted the following information: study design; participants' demographics (e.g., age, gender); sample size; type of vision impairment (e.g., simulated or diagnosed visual impairment); type of terrain or environmental factors (e.g., indoor, outdoor, lighting, obstacles); gait parameters data (e.g. temporal distance parameters, kinetics, kinematics and muscle activity); type of analysis and authors' conclusion.

2.6. Data synthesis

Because of heterogeneity across studies (including design, setting, measures of gait parameters, and analysis type), a meta-analysis was not appropriate. A narrative synthesis was therefore undertaken using the Synthesis Without Meta-Analysis (SWiM) (Campbell et al., 2020). To explore the effect of visual impairment on gait parameters, these two variables were sub-grouped as follows:

2.6.1. Types of walking gait

1) Straight-line level walking: straight-line walking over a flat and even surface (including motorised treadmill-based studies).
2) Obstacle walking gait: navigating some form of obstacle, including stairs, steps and uneven surfaces.

Studies utilising overground and motorised treadmill-based walking were included together in the straight-line level walking gait condition, as research indicates that these methods yield largely comparable spatio-temporal, kinematic, kinetic and electromyographic outcome measures (Semaan et al., 2022). Although some authors have identified differences in gait measures between overground and treadmill walking, particularly greater cadence, shorter stride length, and lower peak vertical ground rection force during push-off on a treadmill (Vickery-Howe et al., 2023), Riley et al. (2007) demonstrated that the magnitude of kinematic and kinetic differences are all within the normal variability of gait parameters for healthy individuals.

2.6.2. Types of visual impairment

The visual impairments were categorised in two main groups (1) Simulated VI and 2) diagnosed VI, and sub-grouped as follow:

1) Simulated VI: a) simulated blindness (combining eyes closed and blindfolded); b) visual blur (combining reduced visual acuity, simulated cataracts and visual blur); c) monocular blur; d) restricted visual field; e) lights off (in the dark); and f) simulated age-related macular degeneration (AMD).
2) Diagnosed (including both congenital and acquired VI): a) glaucoma; b) cataract; d) AMD; e) visual acuity 1.4–1.0 and/or visual field constriction; e) congenital blindness; f) acquired blindness; g) age-related maculopathy (ARM); and f) Low vision (LV) (including a range of visual impairments).

Indicative data (increase, decrease or no difference in gait parameters compared to healthy sight) were combined and synthesised based on gait type (i.e., straight-line level walking and obstacle walking) across simulated and diagnosed visual impairments. Gait parameters were also reported for different simulated and diagnosed visual impairment types.

3. Results

3.1. Study identification and selection

The search identified 12,718 studies. For quality control purposes, titles and abstracts from a batch of 608 studies were analysed by the four reviewers (JB, LA, MF and SH). Disagreements were low, and therefore 144 articles were read in full, and 44 articles met the inclusion criteria and were included in the review (Fig. 1). The selected studies included a total of 5976 participants, although 4438 of those were from two studies that answered questions with the same sample of participants (2219 participants in each study) (Thompson et al., 2023).

3.2. Organisation of the data

There were several contradictory findings within the results. To explore differences in walking gait biomechanics across different types of VI, we split the data into four discreet sections: 1) straight-line level walking with simulated VI; 2) straight-line level walking with diagnosed VI. 3) obstacle walking with simulated VI; and 4) obstacle walking with diagnosed VI; Although there was a range in the quality of the papers (see Table 5) all papers were included as they reflect the range in standard of reporting. The analysis in here is reported via a comparison between the visually impaired condition (simulated or diagnosed) versus a non-visually impaired group. Within each section the priority for narrative comparison was based on the number of papers that discussed a specific aspect of gait.

3.3. Frequency of studies examining different gait and VI conditions

Twenty-seven studies investigated straight-line level walking (Tables 1 and 2), while 12 studies focused on obstacle walking (Tables 2 and 3). Five studies explored both obstacle walking and straight-line level walking. Of those that included straight-line level walking, 12 simulated VI and 15 explored diagnosed VI's. In the obstacle walking literature, nine simulated VI and six included participants with diagnosed VI's.

For simulated VI conditions (Tables 1 and 3), the majority of straight-line level walking studies simulated blindness (no vision) (10 out of 12 studies), while three explored restricted vision (one study simulated no vision and restricted vision). In contrast, most studies examining obstacle walking employed restricted vision methods (8 out of 9 studies).

In terms of diagnosed VI (Tables 2 and 4), Glaucoma and Cataracts were the most investigated VI conditions with the inclusion of individuals with these conditions described in five studies each across the straight-line level and obstacle walking research. Age-related macular degeneration and congenital blindness were the next most common, each with three studies including a description of individuals with these conditions.

3.4. Straight-line level walking with simulated VI

Seven gait parameters (gait speed, gait cadence, step length, stride length, stance time, step width, and stride time) were investigated by more than two studies exploring straight-line level walking with simulated VI. For gait speed, five studies found a decrease (Bingenheimer et al., 2015; Cromwell et al., 2004;Hallemans et al., 2009a; Hallemans et al., 2010; Kanzler et al., 2016), whereas four studies found no difference (Bonnen et al., 2021; Krishnan et al., 2017; Majlesi et al., 2020; Pham et al., 2024). Gait cadence was reported to reduce in two studies (Cromwell et al., 2004; Hallemans et al., 2010), one study reported an increase (Saucedo and Yang, 2017), and four studies indicated no difference (Kanzler et al., 2016; Krishnan et al., 2017; Négyesi et al., 2025; Pham et al., 2024). For step length, two studies found a decrease (Bingenheimer et al., 2015; Saucedo and Yang, 2017), one study found

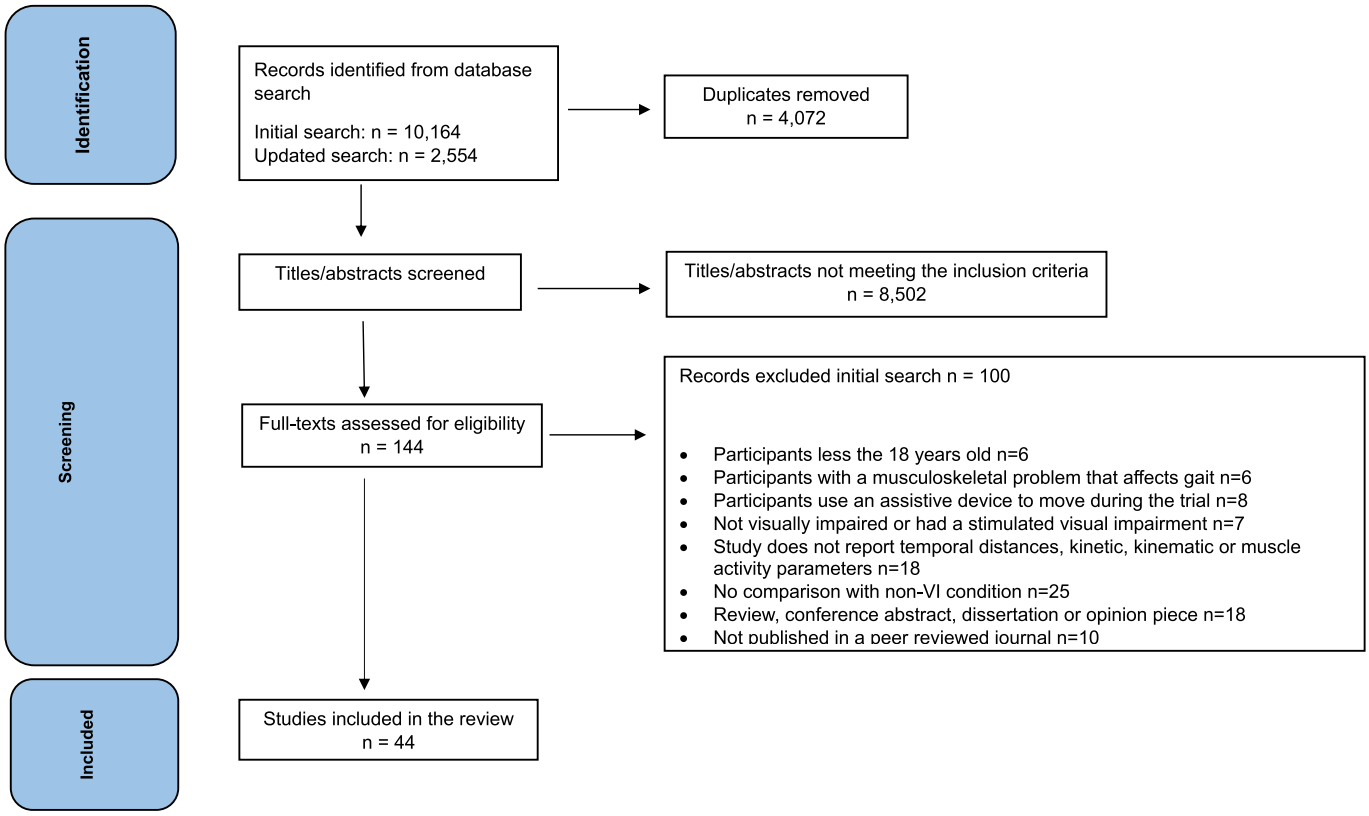

Fig. 1. Selection of studies for inclusion in the systematic review.

an increase (Shoja et al., 2020) and five studies found no difference (Krishnan et al., 2017; Majlesi et al., 2020; Négyesi et al., 2025; Oku et al., 2025; Pham et al., 2024). Stride length was also investigated in five studies; three studies found an increase in stride length (Hallemans et al., 2009a; Hallemans et al., 2010; Kanzler et al., 2016), whereas three studies found no difference (Krishnan et al., 2017; Majlesi et al., 2020; Négyesi et al., 2025). Stance time was investigated in five studies; one found a decrease (Saucedo and Yang, 2017), one reported an increase (Hallemans et al., 2009a) and the other two found no difference (Kanzler et al., 2016; Majlesi et al., 2020). Step width was measured in four studies with one study finding a decrease (Shoja et al., 2020), one showing and increase (Négyesi et al., 2025), and two studies finding no difference (Krishnan et al., 2017; Saucedo and Yang, 2017). Four studies measured stride time; Bingenheimer et al. (2015) found an increase in stride time with VI, Majlesi et al. (2020) found a decrease and Kanzler et al. (2016) and (Négyesi et al., 2025) found no difference (Table 1).

3.5. *Straight-line level walking with diagnosed VI*

Table 2 shows the 14 studies that investigated the effect of diagnosed VI on gait speed during straight-line level walking. Eight studies found a decrease in speed (Ao et al., 2023; da Silva et al., 2018; Durmus et al., 2011; Freitag et al., 2023; Gomes et al., 2018; Lee et al., 2021; Majlesi et al., 2020; Noh et al., 2023; Thompson et al., 2023; Thompson et al., 2025; Tomomitsu et al., 2013; Varadaraj et al., 2017a), compared to five studies that found no difference (da Silva et al., 2018; Freitag et al., 2023; Gomes et al., 2018; Heidarzadeh et al., 2024; Noh et al., 2023). Nine studies investigated stride length, with five studies finding a decrease (Ao et al., 2023; Hallemans et al., 2010; Majlesi et al., 2020; Noh et al., 2023; Spaulding et al., 1995) and four studies finding no difference (Durmus et al., 2011; Freitag et al., 2023; Lu et al., 2021; Varadaraj et al., 2017b). Gait cadence, double support duration, step length and stance time were each measured by five studies. Two studies found a decrease in cadence (Durmus et al., 2011; Lee et al., 2021), one study found an increase (Noh et al., 2023) and two studies found no difference (Gomes et al., 2018; Lu et al., 2021). When measuring double support duration, two studies found an increase (Ao et al., 2023; Varadaraj et al., 2017a) and three studies found no difference (Gomes et al., 2018; Lu et al., 2021; Majlesi et al., 2020). Two studies found an increase in step length (Majlesi et al., 2020; Zult et al., 2019), and three studies found no difference (Durmus et al., 2011; Gomes et al., 2018; Varadaraj et al., 2017b). An increase in stance time was found in three studies (Ao et al., 2023; Lee et al., 2021; Spaulding et al., 1995) whereas two studies found no difference (Gomes et al., 2018; Majlesi et al., 2020). Both single support duration and step width were measured in three studies. One study (Ao et al., 2023) found an increase in single support duration whereas two studies (Gomes et al., 2018; Majlesi et al., 2020) found no difference. All three studies that measured base of support (Durmus et al., 2011; Gomes et al., 2018; Varadaraj et al., 2017a) found no difference between VI groups and control groups.

When considering different VI conditions, 11 parameters of gait were reported across four studies in populations with cataracts (Ao et al., 2023; Durmus et al., 2011; Heidarzadeh et al., 2024; Noh et al., 2023). Of these, base of support and double support percentage parameters were not affected, five parameters had contradictory results (gait speed, gait cadence, step length, stride length and step variability), and four parameters were significantly affected (double and single support duration, stance time, and gait cycle time). Four studies included populations with a range of VI conditions and reported the results collectively (Hallemans et al., 2010; Lu et al., 2021; Thompson et al., 2023; Thompson et al., 2025). Eleven gait parameters were measured across these four studies, with seven parameters not affected by VI (gait cadence, double support duration, stride length variability, stride width, stride width variability, stride velocity, and log e pelvis deviation). Step length had contradictory results and gait speed, 'plantarfoot' contact at heel strike, and trunk 'anteflexion' were all significantly affected (Table 2).

Table 1
Straight-line level walking gait biomechanics with simulated visual impairments.*

Study	Type of simulated visual impairment (VI)	Method of VI	Walking protocol	Gait measurements	Biomechanical change from non-VI condition			
					Stride pattern	Joint, segment & whole-body kinematics	Kinetics	EMG
Bingenheimer et al. (2015)	Restricted vision (RV) No vision (NV)	RV = Glasses that blurred peripheral and central vision NV = Blindfold mask	Overground at preferred speed in each condition.	WS*, SL*, ST*, BoS*	RV = ↓WS*; ↓SL* ↑BoS* -ST* ↑BoS* NV = ↓WS*; ↓SL* ↑ST*; ↑BoS*			
Cromwell et al. (2004)	NV	Complete darkness	Overground at preferred speed in each condition.	WS*, C*, angular velocity of head and trunk	↓WS*; ↓C*	↓Trunk angular velocity; ↓Head angular velocity		
Hallemans et al. (2009a)	NV	Eyes closed	Overground at preferred speed in each condition	WS,* C*, SL*, SW*, DST*; postural sway (CoP* movement)	↓WS*; ↓SL*; ↓C* ↑SW*; ↑DST*	↑Postural sway		
Hallemans et al. (2009b)	NV	Eyes closed	Overground at preferred speed in each condition	Trunk, pelvis, hip, knee, and ankle joint angles		↑Knee flexion at initial foot contact ↓Trunk flexion; ↓ pelvic rotation ROM*; ↓ Hip adduction in stance; ↓Ankle plantarflexion at toe-off; ↓ Ankle plantarflexion ROM* at loading		
Hallemans et al. (2010)	NV	Glasses masked with black tape	Overground at preferred speed in each condition	WS*, SL*, C*, ST*, Trunk, hip, knee, and ankle joint angles	↓WS*; ↓SL*; ↓C* -ST*	↓Hip sagittal plane ROM*; ↓Ankle dorsiflexion at midstance; ↓Ankle plantarflexion at toe-off -Trunk angle; -Knee angle		
Krishnan et al. (2017)	RV	Blurred vision and peripheral vision loss – artificially imposed using goggles	Overground at preferred speed in each condition	WS*, SL*, C*, SW*, DST*, StrideT*	-WS*; -SL*; -C*; -SW*; -DST*; -StrideT*			
Majlesi et al. (2020)	NV	Closed eyes	Overground walking at a self-selected speed.	WS*, SL*, StrideL*, ST*, StrideT*, StepT*, DST*, SST* vGRF*, apGRF*, mlGRF* vImpulse*, apImpulse*, mlImpulse*	-WS*; -SL*; – StrideL*; -ST*; -DST* ↑StrideT*; ↑StepT*; ↑SST*		↓vGRF* at heel-strike -mlGRF*	
Négyesi et al. (2025)	RV	Glasses with left or right half field eye patching.	Treadmill at a self-selected speed.	Stride speed, SL*, C*, StrideT*, StepT*, SW*, MTC* Hip, knee, and ankle angles Lower-limb EMG*	-Stride speed; -SL*; -C*; –StrideT*; -StepT*; – MTC*; – SW*	- Hip, knee, and ankle joint angle kinematics.		
Oku et al. (2025)	NV	Blindfold	Overground walking (speed not defined)	SL*, StepT*, Foot lift height	-SL*; -StepT*; -Foot lift height			
Oliveira et al. (2017)	NV	Blindfold	Treadmill at 1.0 m/s	ST*, vGRF*	↓ST*		↓1st Peak vGRF*	
Pham et al. (2024)	RV	Goggles with tape to simulate peripheral vision loss	Overground walking at preferred speed in each condition.	WS*, SL*, C*, DST*,	-WS*, -SL*, -C*, -DST*			
Saucedo and Yang (2017)	NV	Eyes closed	Treadmill at a pre-determined self-selected speed (same speed in both vision conditions)	SL*, C*, SW*, ST*, Foot landing angle	↓SL*; ↓ST*; ↓ Foot landing angle -SW* ↑C*			

(*continued on next page*)

Table 1 (*continued*)

Study	Type of simulated visual impairment (VI)	Method of VI	Walking protocol	Gait measurements	Biomechanical change from non-VI condition			
					Stride pattern	Joint, segment & whole-body kinematics	Kinetics	EMG
Shoja et al. (2020)	NV	Liquid crystal glasses providing transparent or opaque view	Treadmill at preferred speed in each condition	SL*, SW*, vGRF*, apGRF*, mlGRF*, Dynamic stability index (D_N)	↓SL* ↑SW*	↑ D_N in 8 out of 10 participants in individual analysis - D_N for mean data	↑mlGRF* - apGRF*, – vGRF*	
Shoja et al. (2024)	NV	Liquid crystal glasses providing transparent or opaque view	Treadmill at preferred speed in each condition	Symmetry for SL*, ST*, SST* (between dominant & non-dominant leg) GRF* symmetry (between dominant & non-dominant leg) Hip, knee, and ankle angle ROM* Hip, knee, ankle angle symmetry (between dominant & non-dominant leg)	↓ST* symmetry; ↓SST* symmetry - SL* symmetry		↓vGRF* symmetry; ↓vertical impulse symmetry; ↓time to peak vGRF* symmetry; ↓ propulsive apGRF* symmetry; ↓ propulsive ap impulse symmetry - braking apGRF* symmetry; - braking ap impulse symmetry; - time to peak apGRF* symmetry	

↑ = increase; ↓ = decrease; – = no difference.

* WS = walking speed; SL = step length; C = cadence; SW = step width; ST = stance time; StrideT = stride time; StepT = step time; DST = double support time; SST = single support time; MTC = minimum toe clearance; BoS = base of support; CoP = centre of pressure; vGRF = vertical ground reaction force; apGRF = antero-posterior ground reaction force; mlGRF = medio-lateral ground reaction force; ROM = range of motion; EMG = electromyography; vImpulse = vertical impulse; mlImpulse = medio-lateral impulse; apImpulse = anterio-posterior impulse.

3.6. Obstacle walking with simulated VI

Table 3 includes data from the nine studies that have investigated the effects of simulated VI on obstacle walking. Most studies have employed protocols to restrict vision, rather than remove it ($n = 8$), with many using some form of simulated visual blur (e.g., Buckley et al., 2005a; Buckley et al., 2010; Elliott and Chapman, 2010; García-Pedreño et al., 2024; Novak and Deshpande, 2014; Zult et al., 2019). All studies reporting walking speed or obstacle negotiating speed found that it decreased with a simulated impairment (Kanzler et al., 2016; Novak and Deshpande, 2014; Vale et al., 2008). Single support time (SST) was the second most reported measure, with three studies reporting an increase in SST during simulated VI conditions (Buckley et al., 2005a;Vale et al., 2008; Zult et al., 2019) and two reporting no difference (Elliott and Chapman, 2010; Kanzler et al., 2016). Interestingly, Kanzler et al. (2016) reported a learning effect for spatio-temporal variables with simulated VI after comparing data for participants that completed the obstacle course without a visual impairment first, to those that started with the impaired condition. Those who completed the VI condition first showed a more cautious gait pattern (e.g., decreased speed, step length and cadence with an increase in stance time) compared to unimpaired walking, while those who completed the no-VI condition first showed no difference in gait between conditions.

Table 3 also indicates differences in foot position between simulated VI and no-VI conditions when negotiating obstacles. Two studies reported an increase in lead foot clearance height and distance, but no difference in placement of the trail foot (Vale et al., 2008; Zult et al., 2019). Elliott and Chapman (2010) reported increased lead and trail foot clearance with positive dioptric blur lenses (making objects appear larger and closer) compared to an optimal correction, with an opposite response when a negative dioptric blur lense (making objects appear smaller and further away) was employed (i.e., decreased lead and trail foot clearance).

3.7. Obstacle walking with diagnosed VI

The data in Table 4 shows that two aspects of gait have been investigated by more than two studies: gait speed (four studies) and single support time (three studies). In investigating gait speed, Alexander et al. (2014)(in step ascent), Lee et al. (2021), Nakamura (1997) and Tomomitsu et al. (2013) all showed a decrease in speed, but Alexander et al. (2014) showed no change in speed during step decent. When measuring single support time one study found an increase (Timmis et al., 2014) and two studies found no difference (Alexander et al., 2014; Nakamura, 1997).

3.8. Comparison of simulated and diagnosed VI

Of the 44 studies included in this review, three studies Hallemans et al. (2010), Khadive et al. (2022), and Majlesi et al. (2020) directly compared the effect of simulated and diagnosed VI on gait. Hallemans et al. (2010) found no significant differences in gait parameters between the experimental group (a mix of different visual impairments) and simulated blindness in straight-line level walking. Similarly, in obstacle walking, Khadive et al. (2022) reported twelve gait measures during stair ascent and descent and only found one significant difference between conditions, which was a decrease in midstance GRF in stair descent.

Majlesi et al. (2020) measured nine aspects of gait and found a significant difference in stride length and step length between simulated blindness (eyes closed) and diagnosed VI (congenital vision loss) groups, with both measures significantly higher in the eyes closed condition.

3.9. Environmental considerations

Two papers (Lu et al., 2021; Spaulding et al., 1995) described the lighting conditions under which data was collected. In each of these studies the lighting was part of the experimental condition. The remaining studies, where lighting was not part of the experimental condition, did not report the brightness or colour of the lighting.

3.10. Quality assessment

Thirty-one studies were considered moderate quality, seven were

Table 2
Straight-line level walking gait biomechanics with congenital/acquired visual impairments.

Study	Cause of visual impairment (VI)	Type & method of measuring VI	Walking protocol	Gait measurements	Walking gait change from non-VI condition			
					Stride pattern	Joint, segment & whole-body kinematics	Kinetics	EMG
Ao et al. (2023)	Cataracts	VA, Refraction, Slit-lamp biomicroscopy, Fundoscopy	Overground walking at a self-selected speed	WS*, SL*, ST*, DST*, SST*, SW*, SW* variability, StrideT* Sagittal plane hip, knee, pelvis, thigh, and shank ROM*, Coronal plane pelvis, thigh, and shank ROM*, Hip, knee, pelvis, thigh, shank ROM* symmetry	↓WS* -DST*; -SL*; -SW*; -SW* variability ↑StrideT*; ↑ST*; ↑SST*	↓Thigh symmetry -Hip ROM*; -Pelvis ROM*; -Coronal plane ROM* angles; -Hip, knee, pelvis, shank symmetry		
da Silva et al. (2018)	Retinitis Pigmentosa, Stevens-Johnson syndrome, Toxoplasmosis, Glaucoma, Trauma (VA* ranging from 1.4 to 1.0 on LogMAR scale and/or visual field constricted to a diameter of less than 40 degrees)	VA*	Overground walking at a self-selected speed	WS*	-WS*			
Durmus et al. (2011)	Cataracts	VA* logMAR measured	Overground walking at a self-selected speed	WS*, StepL*, SL*, C,* BoS*	↑WS*, -StepL*, -SL*, ↑C*, -BoS*			
Freitag et al. (2023)	Glaucoma	Visual field sensitivity, Peripheral retinal nerve fibre layer thickness, VA*	Overground walking at a self-selected speed	WS*, SL*, MTC*, WS* variability, SL* variability, MTC* variability	↓WS*; ↓SL*; -MTC*; -MTC* variability ↑WS* variability; ↑SL* variability			
Gomes et al. (2018)	Glaucoma	Octopus MD score	Overground walking at a self-selected speed	WS*, C*, SL*, BoS*, ST*, DST*, SST*	-WS*; -C*; -SL*, -BoS*, -ST*, -DST*, -SST*			
Hallemans et al. (2010)	Blind ($n = 4$), low vision (VA* $\leq$6/18; $n = 6$)	VA*	Overground walking at a self-selected speed	WS*, SL*, C*, ST* Trunk, hip, knee, and ankle joint angles and joint angle ROM's*	-SL -WS; -C; - ST	¯Ankle plantarflexion ROM* in stance; - Maximal trunk anteflexion -hip joint angles; -knee joint angles		
Heidarzadeh et al. (2024)	Cataracts	VA*	Overground walking using the 10-m walk test	WS*	-WS*			
Lee et al. (2021)	Glaucoma	Diagnosed Glaucoma by medical doctor	Overground walking at a self-selected speed	WS*, C*, ST*, StrideT*, COF* deviation, COF* excursion	↓WS*; ↓C*; ↑ST*; ↑StrideT*		- COF* deviation; - COF* excursion	
Lu et al. (2021)	Not specified	Behavioural Risk Factor Surveillance System	Overground walking at a self-selected speed	WS*, SL*, C*, SW*, DST*, SL* variability, SW* variability Pelvis deviation	-WS*; -SL*; -C*, -SW*; -DST*; -SL* variability; -SW* variability	-Pelvis deviation		
Majlesi et al. (2020)	Congenital vision loss (specific cause not reported)	Not reported	Overground walking at a self-selected speed.	WS*, SL*, StepL*, ST*, StrideT*, StepT*, DST*, SST*, vGRF*, apGRF*, mlGRF* vImpulse*,	↓WS*; ↓SL*; ↓StepL* -ST*; -StrideT*; -StepT*; -SST*; -DST*		↓vGRF*; ↓ propulsive apGRF*; ↓apImpulse* -braking apGRF*;	

(*continued on next page*)

Table 2 (*continued*)

Study	Cause of visual impairment (VI)	Type & method of measuring VI	Walking protocol	Gait measurements	Walking gait change from non-VI condition			
					Stride pattern	Joint, segment & whole-body kinematics	Kinetics	EMG
				apImpulse*, mlImpulse*			-vImpulse*; -mlImpulse*	
Nakamura (1997) *also compares congenital vs late blind – there is a difference.	Multiple (glaucoma, retinitis pigmentosa, diabetic retinopathy, Bechets disease, retinal detatchment, retinoblastoma, cataracts retinopathy of prematurity, buthalmos, retrolental fibroplasia)	Blind and late blind (blind after the age of 29). VI measurement not stated.	Overground walking at a self-selected speed	WS*, SL*, ST*, SST*	**Late blind:** ↓WS*; ↓SL*; ↓ST* -SST* Congenital blind ↓WS*; ↓SL*; ↓ST* -SST* **Late blind vs congenital blind:** ↓WS*; ↓SL*; ↓ST* -SST*			
Noh et al. (2023)	Cataracts	VA, Spherical equivalent refractive powers,	Overground walking at a self-selected speed	WS*, SL*, C*, StepL*, SW*	↓SL*; ↓StepL*; ↓SW* -WS* ↑C*			
Spaulding et al. (1995)	Age-related maculopathy	VA*, CS*	Overground walking at a self-selected speed	SL*, ST*, StrideT* Absolute foot angle, Horizontal hip velocity, Absolute foot angular velocity, Heel contact velocity, Metatarsal-to-hip horizontal velocity Lower limb EMG* vGRF*, apGRF*, vImpulse*, apImpulse*	↓SL* ↑ST*; ↑StrideT*	↑Absolute foot angle ↓Horizontal hip velocity; ↓Absolute foot angular velocity; ↓Heel contact velocity; ↓Metatarsal-to-hip horizontal velocity		↓Rectus femoris activity during stance; ↓Soleus activity during stance ↓Semitendinosus activity during swing; ↓Rectus femoris activity during swing ↓Semitendinosus activity at toe-off; ↓Soleus at toe-off; ↓tibialis anterior at toe-off
Thompson et al. (2023)	Several VI's* (specific type and cause of impairments not reported)	VA*, CS*, LCS*, SA*	Overground walking at a self-selected speed	WS*	↓WS*			
Thompson et al. (2025)	Reduced visual function. Specific cause not reported (VA* <20/40, LCS* <1.55)	VA*, LCS*, SA*	Overground at a self-selected speed	WS*	↓WS*			

↑ = increase; ↓ = decrease; − = no difference.

* WS = walking speed; SL = stride length; StepL = step length; C = cadence; SW = step width; ST = Stance time; StrideT = stride time; StepT = step time; DST = double support time; SST = single support time; MTC = minimum toe clearance; ROM = range of motion; BoS = Base of Support; vGRF = vertical ground reaction force; apGRF = antero-posterior ground reaction force; mlGRF = medio-lateral ground reaction force; COF = Centre of Force; EMG = electromyography; VA = Visual acuity; CS; Contrast sensitivity, LCS = Log contrast sensitivity, SA = stereoacuity; vImpulse = vertical impulse; apImpulse = antero-posterior impulse; mlImpulse = medio-lateral impulse.

low quality, and six were high quality (Table 5). Studies provided a good theoretical or conceptual underpinning of research and a clear statement of the aims. However, only one study (Gomes et al., 2018) provided evidence that research stakeholders have been considered in the research design or conduct. Likewise, most of the studies provided minimal description of the sampling process (e.g., calculation and discussion) (Alexander et al., 2014; Bingenheimer et al., 2015; Hallemans et al., 2009a; Ma et al., 2016; Nakamura, 1997; Noh et al., 2023; Novak and Deshpande, 2014; Oliveira et al., 2017; Saucedo and Yang, 2017; Shoja et al., 2020; Spaulding et al., 1995; Thomas et al., 2020; Timmis et al., 2014; Vale et al., 2008; Varadaraj et al., 2017b; Zult et al., 2019) and recruitment data (e.g., people approached, recruited, attrition and justification) (Alexander et al., 2014; Bingenheimer et al., 2015; Bonnen et al., 2021; Cromwell et al., 2004; Freitag et al., 2023; Ma et al., 2016; Nakamura, 1997; Noh et al., 2023; Novak and Deshpande, 2014; Oliveira et al., 2017; Saucedo and Yang, 2017; Shoja et al., 2020; Thomas et al., 2020; Thompson et al., 2023; Tomomitsu et al., 2013; Vale et al., 2008; Varadaraj et al., 2017a; Zult et al., 2019).

4. Discussion

4.1. Main findings

This review set out to evaluate the effects of actual and simulated visual impairments on straight-line level walking and obstacle walking gait characteristics. There were over 100 different gait measures reported in the 44 studies identified, with few gait measures being reported consistently across studies. Furthermore, different methods for

Table 3
Obstacle walking gait biomechanics with simulated visual impairments.

Study	Type of simulated visual impairment (VI)	Method of VI and assessment	Type of adaptative gait	Gait measurements	Biomechanical change from non-VI condition			
					Stride pattern	Joint, segment & whole-body kinematics	Kinetics	EMG
Bonnen et al. (2021)	RV to simulate binocular vision	Blurring filter over one eye	Walking outdoors over uneven terrain	WS*	- WS*			
Buckley et al. (2005a)	RV to simulate the effect of cataracts	Light scattering lenses to reduce VA* and CS*	Stepping task (stepping up and down)	DST*, SST* Medio-lateral distance between CoM* and CoP* positions during single support (CoM* - CoP_{ml*}) mlGRF*, mlImpulse	↑DST* (up and down); ↑SST* (up and down) *stepping up involved ↑SST* and ↓DST* compared to stepping down	↓ CoM* - CoP_{ml}*	↑mlImpulse* (up and down) *↑mlImpulse* when stepping up compared to stepping down	
Elliott and Chapman (2010)	RV to simulate refractive errors	VA*, CS*, Stereoacuity	Stepping task, walking up to, and stepping onto a 15.2 cm raised surface.	SST* Lead foot position before step, Trail foot position before step, Lead foot heel position on step, Lead foot horizontal toe clearance, Lead foot vertical toe clearance, Trail foot horizontal toe clearance, Trail foot vertical toe clearance	-SST*	**With (+DS* compared to optimal correction):** ↑Trail foot position before step; ↑Lead foot vertical toe clearance; ↑Lead foot horizontal toe clearance; ↑Trail foot horizontal toe clearance ↓Lead foot heel position on step **With (-DS* compared to optimal correction):** ↓Trail foot position before step; ↓Lead foot vertical toe clearance; ↓Lead foot horizontal toe clearance; ↓Trail foot horizontal toe clearance ↑ Lead foot heel position on step - Trail foot vertical toe clearance; - Lead foot position before step		
García-Pedreño et al. (2024)	RV to simulate peripheral refractive errors	Lenses to impose positive defocus, negative defocus or astigmatism in the periphery.	Stepping obstacle involving ascent and descent of steps with heights of 12.6 cm	Crossing time, Lead foot ascent time, Lead foot descent time, Lead foot ascent speed, Lead foot descent speed	↓Lead foot ascent speed; ↓Lead foot descent speed -Lead foot descent time ↑Crossing time; ↑Lead foot ascent time			
Kanzler et al. (2016)	RV to simulate macular degeneration	Glasses with restricted central visual field	40 m walk (repeated walks on 10 m track) with rectangular boxes (one 12 cm high and one 24 cm high) used as obstacles.	WS*, SL*, C*, ST*, StrideT*, SST* SL* variability, ST* variability, StrideT* variability, SST* variability Maximum toe clearance	**Trials with VI condition completed before non-VI:** -WS*; -SL*; -C* -SST*; -SL* variability; -SST* variability -ST*; -StrideT*; -ST* variability; -StrideT* variability *There was no difference between any variables when trials started with NoVI.			

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Table 3 (*continued*)

Study	Type of simulated visual impairment (VI)	Method of VI and assessment	Type of adaptative gait	Gait measurements	Biomechanical change from non-VI condition			
					Stride pattern	Joint, segment & whole-body kinematics	Kinetics	EMG
Khadive et al. (2022)	No vision (NV)	Closed eyes	Stair ascent and descent	vGRF*, mlGRF*, apGRF* *Forces recorded at foot contact (FC), mid-stance (MS), and push-off (PO)				
Novak and Deshpande (2014)	RV to simulate the effect of dense cataracts	Custom blurring goggles	Overground walking for 6 m, stepping over a single obstacle in the centre of the walkway (20 cm high)	WS* (across the entire walkway - obstacle crossing included), SW* (pre, during, post obstacle), SL* (pre, during, post obstacle), StepT* (pre, during, post obstacle) vCOM* and mlCOM* displacement, Head pitch and roll angle, Trunk pitch and roll	↓WS*; -SW* post obstacle; ↓SL* (pre obstacle in older adults only) -SW* (pre and during obstacle); -SL* (during and post obstacle); -ST* (pre and post obstacle) ↑StepT* (during obstacle)	-Peak vCOM*; -Head pitch and roll; −Trunk pitch and roll ↑Peak mlCOM* displacement		
Uno et al. (2023)	RV to simulate tunnel vision	Goggles occluding peripheral vision	Crossing a gap during overground walking	Step height, step distance over gap	↓Step height; ↓Step distance over gap			
Vale et al. (2008)	RV	Occluding one eye with blur and occlusion (0.50 D, 1.00 D)	Overground walking at a self-selected speed and then steeping onto a 15.2 cm platform	WS*, SST*, Vertical lead toe clearance, Horizontal lead toe clearance, Lead foot position, Trail toe clearance, Trail foot position	↓WS* ↑SST*	-Trail toe clearance; -Trail foot position; -Lead foot position ↑Horizontal lead toe clearance; ↑Vertical lead toe clearance		
(Zult et al., 2019)	RV	Full aperture trial case lenses of plus 4 to plus 6 dioptres (VA* = 0.95 ± 0.07 logMAR)	Overground walking with a floor-based obstacle step over task. Single 10 cm high obstacle in the centre of a walkway.	Lead VTC*, Trail VTC*, Lead horizontal toe velocity, Trail horizontal toe velocity, Penultimate FP*, Final FP*, Lead foot SST*, Trail foot SST*	-Trail foot SST*; -Penultimate FP* ↑Final FP*; ↑Lead foot SST*	-Trail VTC*; -Trail horizontal toe velocity; ↑Lead horizontal toe velocity; ↑Lead VTC*;		

↑ = increase; ↓ = decrease; − = no difference.

* RV = restricted vision; RoU = rate of unloading; FC = foot contact; DF = flat foot; PO = push off, MS = mid-stance; WS = walking speed; SL = step length; C = cadence; SW = step width; ST = stance time; StrideT = stride time; StepT = step time; DST = double support time; SST = single support time; MTC = minimum toe clearance; BoS = base of support; CoP = centre of pressure; vGRF = vertical ground reaction force; apGRF = antero-posterior ground reaction force; mlGRF = medio-lateral ground reaction force; ROM = range of motion; EMG = electromyography; DS = diopter sphere.

measuring the same gait parameters have often been employed between studies, which makes it difficult to compare different types of simulated VI versus diagnosed conditions. Where it was possible to evaluate gait characteristics resulting from a particular visual impairment, we found conflicting evidence. Studies that reported a difference in walking gait biomechanics with a VI tended to show a more cautious gait strategy (e.g., reduced movement speed, shorter step length, reduced cadence, increased double support time, reduce joint angle range of motion) and reduced stability (e.g., increased step width, increased postural sway). However, others reported no walking gait differences when comparing a VI with a non-VI condition, and we did not find consistency in walking gait differences across the different types of VI condition. This lack of consistency appears to be due to methodological differences in how VI is simulated or how the severity of diagnosed VI is measured and stratified.

4.2. Straight-line level walking characteristics

4.2.1. Simulated VI

There is mixed evidence for the speed of straight-line level walking when visual impairment is simulated, with most studies finding a decrease in speed compared to a control condition (Bingenheimer et al., 2015; Cromwell et al., 2004; Hallemans et al., 2009a; Hallemans et al., 2010; Kanzler et al., 2016), but three studies reporting no difference (Bonnen et al., 2021; Krishnan et al., 2017; Majlesi et al., 2020). Studies that found a reduction in speed tend to have employed a physical restriction to simulate vision loss, such as a blindfold, goggles, or no lighting (Bingenheimer et al., 2015; Cromwell et al., 2004; Hallemans et al., 2009a; Hallemans et al., 2010), whereas Majlesi et al. (2020) simulated loss of sight using closed eyes and found no difference in gait speed. It is possible that the ability to open the eyes at any point gives an individual more confidence when walking compared to having to remove a blindfold or goggles, which may have led to the reduced speed in studies that physically restricted vision. This appears similar to a phenomenon reported by Reynard and Terrier (2015), who found that minimising the feeling of uncertainty and the fear of falling during visual deprivation improves gait stability, and a more cautious gait pattern (e.g., reduced speed) may only be adopted in simulated VI conditions when there is an increased feeling of uncertainty or fear of falling. Bingenheimer et al. (2015) also found a reduction in speed when goggles were used to simulate visual blur. This contrasts with Krishnan et al. (2017), who found no difference in gait parameters in response to blur. The contrasting results may be due to differences in the level of "blur". There is no clear indication of the actual loss of VA in the study by Krishnan et al. (2017), but the image supplied to demonstrate the level of blur suggests that there might have been sufficient visual information to comfortably walk at a normal speed on a straight flat walkway.

Table 4
Obstacle walking gait biomechanics with congenital/acquired visual impairments.*

Study	Cause of visual impairment (VI)	Type & method of measuring VI	Type of adaptive gait	Gait measurements	Biomechanical change from non-VI condition			
					Stride pattern	Joint, segment & whole-body kinematics	Kinetics	EMG
Alexander et al. (2014)	AMD	Habitual visual acuity between 0.6 and 1.3 logMAR (i.e., 20/80 to 20/400) in the best eye	Curb ascent and descent in different lighting conditions	SST*, RoU* vGRF*	-Descent SST*	-Ascent RoU*	-Ascent vGRF* -Descent vGRF*	
Gomes et al. (2018)	Glaucoma	Diagnosed by glaucoma specialist. Participants categorised as 0.7 to +4.4 dB (early) or + 4.5 to+9.4 dB (moderate) glaucoma severity in their better eye using the OctopusMD	Stepping over and obstacle Stepping round an obstacle. No further detail given.	WS*, C*, StepL*, BoS*, SST*, ST,* DST*	-WS*, -C*, -StepL*, -BoS*, -SST*, -ST*, -DST*			
Khadive et al. (2022)	Congenital blindness	No detail given	Stair ascent and descent	vGRF*, mlGRF*, apGRF*			Ascent: -vGRF* (FC*, DF*, PO*) -mlGRF* (MS*), -apGRF* (FC*, PO*) Descent: ↓vGRF* (FC*), ↑vGRF* (DF*, PO*) -mlGRF* (MS*), -apGRF* (FC*, PO*)	
Lee et al. (2021)	Glaucoma	Not included	Stepping over 'an obstacle'. No further detail given	WS*, C*, ST*, StrideT, * COF* deviation, COF* excursion	↓WS*; ↓C*; ↑ST*; ↑StrideT*		- COF* deviation; - COF* excursion	
Timmis et al. (2014)	AMD* / macular hole	Central visual field loss. VA: −0.10 ±0.08 logMAR CS: 1.09 ±0.31 log. Visual field was assessed using the Humphrey Field Analyzer SITA-Standard 24–2 threshold test. VF score 21+/−8db	8 cm, 16 cm, 23.5 cm step heights were stepped onto	PFP,* FFP*, LTC*, TTC*, TTHV*, SST*, DST*	All step heights: -PFP*, -FFP*, -LTC*, -TTC*, ↓ LTHV*, -TTHV*, ↑SST*, ↑DST*			
Tomomitsu et al. (2013)	Low vision (several types - optic nerve abnormalities, retina disorders, glaucoma, Stargardt's disease, macular degeneration, retinitis pigmentosa and congenital toxoplasmosis	VA (< 6/18 but equal to or better than 3/60) and ophthalmoscopic screening	Step onto and over a 20 cm high step from a stationary starting position.	Movement time, Lift-up index (% body weight exerted to lift leading leg onto step), Impact index (% body weight used to step down onto force plate)	↑ Movement time		↓Lift up index -Impact index	

↑ = increase; ↓ = decrease; − = no difference.
* FC = foot contact; DF = flat foot; PO = push off, MS = mid-stance; PFP = penultimate foot placement; FFP = final foot placement; LTC = lead toe clearance; TTC trail toe clearance; TTHV = trail toe horizontal velocity; LTHV = Lead toe horizontal velocity; RoU = rate of unloading; WS = walking speed; SL = step length; C = cadence; SW = step width; ST = stance time; StrideT = stride time; StepT = step time; DST = double support time; SST = single support time; MTC = minimum toe clearance; BoS = base of support; CoP = centre of pressure; vGRF = vertical ground reaction force; apGRF = antero-posterior ground reaction force; mlGRF = medio-lateral ground reaction force; ROM = range of motion; EMG = electromyography.

Bingenheimer et al. (2015) indicated that the simulated blurred vision equated to a visual restriction of category IV of the International Classification of Disease 10th Version (ICD-10). This means that vision is limited to light perception with no detail and would therefore be much more restricted than in the study by Krishnan et al. (2017), resulting in a different gait speed response.

The evaluation of research on the effect of simulated VI on straight-line level walking is a good example of the difficulties in generalising the effect of VI on gait. If we take cadence, seven studies have investigated the effects of simulated VI on cadence, with two showing a decrease (Cromwell et al., 2004; Hallemans et al., 2010), one an increase (Saucedo and Yang, 2017) and four no difference (Kanzler et al., 2016; Krishnan et al., 2017;Négyesi et al., 2025; Pham et al., 2024). An explanation for this discrepancy could be the differences in experimental protocols employed. For example, Saucedo and Yang (2017) had participants walk on a treadmill at a pre-determined self-selected speed and reported a significant increase in cadence and reduction in step length with eyes closed compared to eyes open. The same fixed speed in both VI and non-VI conditions would have a clear impact on the gait pattern compared to Hallemans et al. (2010), whose participants walked over an 11 m wooden walkway with significantly slower self-selected speed and a reduced cadence and step length in the VI condition compared to the

Table 5
QuADS quality appraisal.

Study ID	Theoretical or conceptual underpinning to the research	Statement of research aim/s	Clear description of research setting and target population	The study design is appropriate to address the stated research aim/s	Appropriate sampling to address the research aim/s	Rationale for choice of data collection tool/s	The format and content of data collection tool is appropriate to address the stated research aim/s	Description of data collection procedure	Recruitment data provided	Justification for analytic method selected	The method of analysis was appropriate to answer the research aim/s	Evidence that the research stakeholders have been considered in research design or conduct.	Strengths and limitations critically discussed	Total score (quality rating (% and classification)
Alexander et al., 2014	3	3	2	3	1	0	3	3	1	1	3	0	2	25 (64%, moderate)
Ao et al., 2023	3	3	3	3	3	2	3	3	2	1	3	0	2	31 (80% high)
Bingenheimer et al., 2015	3	3	1	3	1	2	3	3	1	1	3	0	1	25 (64% moderate)
Bonnen et al., 2021	3	2	3	3	2	2	3	3	1	2	3	0	0	27 (69% moderate)
Buckley et al., 2005a	3	3	3	3	2	1	3	3	2	0	3	0	1	27 (69% moderate)
Buckley et al., 2005b	3	3	3	3	2	1	3	3	2	2	3	0	2	30 (77% moderate)
Cromwell et al., 2004	3	1	1	3	2	2	3	2	1	2	3	0	0	23 (59% low)
da Silva et al., 2018	1	3	3	3	2	2	2	3	2	2	3	0	2	28 (72% moderate)
Durmus et al., 2011	3	2	3	2	2	2	2	3	3	1	3	0	1	27 (69% moderate)
Elliott and Chapman, 2010	3	3	3	3	2	2	3	3	2	2	3	0	2	31 (80% high)
Freitag et al., 2023	3	2	3	3	3	2	3	3	1	3	3	0	2	31 (80% high)
García-Pedreño et al., 2024	3	3	3	2	1	2	3	3	1	2	3	0	2	28 (72% moderate)
Gomes et al., 2018	3	2	3	3	3	2	3	3	2	0	3	1	2	30 (77% moderate)
Hallemans et al., 2009a	3	3	2	3	1	2	3	3	2	2	3	0	2	29 (74% moderate)
Hallemans et al., 2009b	3	3	3	3	2	2	3	2	2	0	3	0	2	28 (72% moderate)
Hallemans et al., 2010	3	3	3	3	2	2	3	3	2	0	3	0	3	30 (77% moderate)
Heidarzadeh et al., 2024	2	3	3	3	3	2	2	2	1	2	2	0	2	27 (69% moderate)
Kanzler et al., 2016	3	3	3	2	2	2	3	3	2	2	3	0	2	30 (77% moderate)
Khadive et al., 2022	3	3	3	3	2	2	3	3	2	0	3	0	1	28 (72% moderate)
Krishnan et al., 2017	3	3	3	3	2	0	3	2	2	2	3	0	2	28 (72% moderate)
Lee et al., 2021	3	2	3	3	2	2	3	3	2	0	3	0	2	28 (72% moderate)
Lu et al., 2021	3	3	3	2	2	2	3	3	2	2	3	0	0	28 (72% moderate)
Majlesi et al., 2020	3	3	3	3	2	2	3	3	2	0	3	0	2	29 (74% moderate)

(*continued on next page*)

Table 5 (*continued*)

Study ID	Theoretical or conceptual underpinning to the research	Statement of research aim/s	Clear description of research setting and target population	The study design is appropriate to address the stated research aim/s	Appropriate sampling to address the research aim/s	Rationale for choice of data collection tool/s	The format and content of data collection tool is appropriate to address the stated research aim/s	Description of data collection procedure	Recruitment data provided	Justification for analytic method selected	The method of analysis was appropriate to answer the research aim/s	Evidence that the research stakeholders have been considered in research design or conduct.	Strengths and limitations critically discussed	Total score (quality rating (% and classification)
Ma et al., 2016	3	2	3	3	1	3	3	3	1	1	1	0	2	26 (67% moderate)
Nakamura, 1997	1	1	1	1	1	0	1	1	1	0	1	0	0	9 (23% low)
Négyesi et al., 2025	3	3	1	3	3	3	3	3	1	3	3	0	2	31 (80% high)
Noh et al., 2023	3	3	1	2	1	2	3	3	1	1	3	0	1	24 (61% moderate)
Novak and Deshpande, 2014	3	3	1	2	1	2	2	2	1	2	2	0	1	22 (56% low)
Oku et al., 2025	3	3	2	0	1	1	2	3	1	1	3	0	1	21 (54% low)
Oliveira et al., 2017	3	3	1	2	1	2	3	3	1	3	2	0	2	26 (67% moderate)
Pham et al., 2024	3	3	2	3	2	3	2	2	2	2	3	0	3	30 (77% moderate)
Saucedo and Yang, 2017	3	3	1	2	1	1	2	2	1	1	2	0	2	21 (54% low)
Shoja et al., 2020	3	3	1	2	1	1	2	3	1	3	2	0	0	22 (56% low)
Shoja et al., 2024	3	3	1	3	1	2	2	1	1	2	2	0	1	22 (56% low)
Spaulding et al., 1995	3	3	2	3	1	3	3	3	2	3	3	0	2	31 (80% high)
Thomas et al., 2020	3	1	1	2	1	3	3	3	1	3	3	0	1	25 (64% moderate)
Thompson et al., 2023	2	2	3	2	2	2	2	3	3	3	3	0	2	29 (74% moderate)
Thompson et al., 2025	2	2	3	3	3	3	3	3	3	3	3	0	3	34 (87% high)
Timmis et al., 2014	2	1	0	2	1	2	3	3	1	2	3	0	1	21 (54% moderate)
Tomomitsu et al., 2013	2	3	2	2	3	1	2	3	1	1	3	0	2	25 (64% moderate)
Uno et al., 2023	3	3	2	2	3	0	2	3	1	0	3	0	2	24 (61% moderate)
Vale et al., 2008	3	2	3	2	1	2	3	3	1	2	1	0	1	24 (61% moderate)
Varadaraj et al., 2017a	3	2	3	2	1	2	3	2	1	2	3	0	3	27 (69% moderate)
Zult et al., 2019	3	1	1	2	1	2	3	3	1	3	3	0	1	24 (61% moderate)

Note: Coding reference

1. Theoretical or conceptual underpinning to the research

0 No mention at all.

1 General reference to broad theories or concepts that frame the study. e.g. key concepts were identified in the introduction section.

2 Identification of specific theories or concepts that frame the study and how these informed the work undertaken. e.g. key concepts were identified in the introduction section and applied to the study.

3 Explicit discussion of the theories or concepts that inform the study, with application of the theory or concept evident through the design, materials and outcomes explored. e.g. key concepts were identified in the

introduction section and the application apparent in each element of the study design.

2. Statement of research aim/s

0 No mention at all.

1 Reference to what the sought to achieve embedded within the report but no explicit aims statement.

2 Aims statement made but may only appear in the abstract or be lacking detail.

3 Explicit and detailed statement of aim/s in the main body of report.

3. Clear description of research setting and target population

0 No mention at all.

1 General description of research area but not of the specific research environment e.g. 'in primary care'.

2 Description of research setting is made but is lacking detail e.g. 'in primary care practices in region [x]'.

3 Specific description of the research setting and target population of study e.g. 'nurses and doctors from GP practices in [x] part of [x] city in [x] country.'

4. The study design is appropriate to address the stated research aim/s

0 No research aim/s stated or the design is entirely unsuitable e.g. a Y/N item survey for a study seeking to undertake exploratory work of lived experiences.

1 The study design can only address some aspects of the stated research aim/s e.g. use of focus groups to capture data regarding the frequency and experience of a disease.

2 The study design can address the stated research aim/s but there is a more suitable alternative that could have been used or used in addition e.g. addition of a qualitative or.

3 The study design selected appears to be the most suitable approach to attempt to answer the stated research aim/s. quantitative component could strengthen the design.

5. Appropriate sampling to address the research aim/s

0 No mention of the sampling approach.

1 Evidence of consideration of the sample required e.g. the sample characteristics are described and appear appropriate to address the research aim/s.

2 Evidence of consideration of sample required to address the aim. e.g. the sample characteristics are described with reference to the aim/s.

3 Detailed evidence of consideration of the sample required to address the research aim/s. e.g. sample size calculation or discussion of an iterative sampling process with reference to the research aims or the case selected for study.

6. Rationale for choice of data collection tool/s

0 No mention of rationale for data collection tool used.

1 Very limited explanation for choice of data collection tool/s. e.g. based on availability of tool.

2 Basic explanation of rationale for choice of data collection tool/s. e.g. based on use in a prior similar study.

3 Detailed explanation of rationale for choice of data collection tool/s. e.g. relevance to the study aim/s, co-designed with the target population or assessments of tool quality.

7. The format and content of data collection tool is appropriate to address the stated research aim/s

0 No research aim/s stated and/or data collection tool not detailed.

1 Structure and/or content of tool/s suitable to address some aspects of the research aim/s or to address the aim/s superficially e.g. single item response that is very general or an open-response item to capture content which requires probing.

2 Structure and/or content of tool/s allow for data to be gathered broadly addressing the stated aim/s but could benefit from refinement. e.g. the framing of survey or interview questions are too broad or focused to one element of the research aim/s.

3 Structure and content of tool/s allow for detailed data to be gathered around all relevant issues required to address the stated research aim/s.

8. Description of data collection procedure

0 No mention of the data collection procedure.

1 Basic and brief outline of data collection procedure e.g. 'using a questionnaire distributed to staff'.

2 States each stage of data collection procedure but with limited detail or states some stages in detail but omits others e.g. the recruitment process is mentioned but lacks important details.

3 Detailed description of each stage of the data collection procedure, including when, where and how data was gathered such that the procedure could be replicated.

9. Recruitment data provided

0 No mention of recruitment data.

1 Minimal and basic recruitment data e.g. number of people invited who agreed to take part.

2 Some recruitment data but not a complete account e.g. number of people who were invited and agreed.

3 Complete data allowing for full picture of recruitment outcomes e.g. number of people approached, recruited, and who completed with attrition data explained where relevant.

10. Justification for analytic method selected

0 No mention of the rationale for the analytic method chosen.

1 Very limited justification for choice of analytic method selected. e.g. previous use by the research team.

2 Basic justification for choice of analytic method selected e.g. method used in prior similar research.

3 Detailed justification for choice of analytic method selected e.g. relevance to the study aim/s or comment around of the strengths of the method selected.

11. The method of analysis was appropriate to answer the research aim/s

0 No mention at all.

1 Method of analysis can only address the research aim/s basically or broadly.

2 Method of analysis can address the research aim/s but there is a more suitable alternative that could have been used or used in addition to offer a stronger analysis.

3 Method of analysis selected is the most suitable approach to attempt answer the research aim/s in detail e.g. for qualitative interpretative phenomenological analysis might be considered preferable for experiences vs. content analysis to elicit frequency of occurrence of events.
12. Evidence that the research stakeholders have been considered in research design or conduct
0 No mention at all.
1 Consideration of some the research stakeholders e.g. use of pilot study with target sample but no stakeholder involvement in planning stages of study design.
2 Evidence of stakeholder input informing the research. e.g. use of pilot study with feedback influencing the study design/conduct or reference to a project reference group established to guide the research.
3 Substantial consultation with stakeholders identifiable in planning of study design and in preliminary work e.g. consultation in the conceptualisation of the research, a project advisory group or evidence of stakeholder input informing the work.
13. Strengths and limitations critically discussed
0 No mention at all.
1 Very limited mention of strengths and limitations with omissions of many key issues. e.g. one or two strengths/limitations mentioned with limited detail.
2 Discussion of some of the key strengths and weaknesses of the study but not complete. e.g. several strengths/limitations explored but with notable omissions or lack of depth of explanation.
3 Thorough discussion of strengths and limitations of all aspects of study including design, methods, data collection tools, sample & analytic approach.

non-VI condition. Other differences could be due to the effectiveness of the VI simulation. For example, Kanzler et al. (2016) used goggles with black dots in the centre to simulate macular degeneration, with nothing to stop the participants looking up or down to bypass the black dot. Therefore, the effectiveness of this form of VI simulation is questionable and resulted in no difference in cadence. Other studies that reported no difference in cadence have also attempted to partly occlude vision (Négyesi et al., 2025; Pham et al., 2024).

4.2.2. Diagnosed VI

The studies presented here indicate that congenital or acquired VI had a varied effect on walking speed, with eight studies finding a decrease and five reporting no difference. This variation may be due to the type of VI in the populations tested. For example, both studies that tested participants with glaucoma (Freitag et al., 2023; Gomes et al., 2018) found no difference in gait speed, whereas Majlesi et al. (2020) and Varadaraj et al. (2017b) both investigated congenital blindness and found a reduction in speed. Two of the four studies that examined populations with cataracts found reduced speed (Ao et al., 2023; Durmus et al., 2011), but the others found no difference (Heidarzadeh et al., 2024; Noh et al., 2023). This might be because the control group in Noh et al. (2023) were older adults with cataracts who had not worn corrective lenses before, and the experimental group was the same population but with corrective lenses. It's possible that, given more time with the corrective lenses, the participants would start to adapt and walk faster. Indeed, the control groups in Durmus et al. (2011) and Ao et al. (2023) were the experimental populations four weeks post cataract surgery, which might have allowed time for gait adaptions (increased speed) following their improved vision post-surgery.

Stride length also showed inconsistent results, with five studies showing a decrease (Ao et al., 2023; Hallemans et al., 2010; Majlesi et al., 2020; Noh et al., 2023; Spaulding et al., 1995) and four studies showing no difference (Durmus et al., 2011; Freitag et al., 2023; Majlesi et al., 2020; Varadaraj et al., 2017a). This may be due to the different types of VI conditions, (i.e., Glaucoma, AMD, congenital blindness and ARM) with only one study investigating each condition, and therefore comparisons were not possible. Inconsistencies were also noted for stride length where multiple studies examined populations with cataracts, with Durmus et al. (2011) finding no difference, whereas Ao et al. (2023) and Noh et al. (2023) noticing a significant decrease.

4.3. Obstacle walking characteristics with simulated and diagnosed VI

4.3.1. Simulated VI

When considering obstacle walking, the varied types of obstacles employed created a level of complication (i.e., step up, down, over, or around an obstacle) when drawing comparisons between studies. There was also inconsistency with the gait measures reported, with only step duration measured by several studies. When stepping, the size of the obstacle appears to affect the magnitude of step duration adaptations between visually impaired and non-impaired individuals. Elliott and Chapman (2010) found no difference between groups when stepping on a 15.2 cm raised surface, but Buckley, Heasley [47] reporting a significantly longer step duration for those with a visual impairment when stepping onto a 21.6 cm step height. This is further supported by Buckley, Heasley [47] showing no difference in step duration with 7.2 cm and 14.4 cm step heights.

The overall effect of simulated VI on obstacle walking appears to be less stability and more cautious gait strategy, with increases in step width (Shoja et al., 2020), medio-lateral GRF impulse (Buckley et al., 2005a) and medio-lateral displacement (Novak and Deshpande, 2014) indicating less stability and increases in double support time (Buckley et al., 2005a), and knee flexion and ankle plantarflexion at initial contact when stepping down (Buckley et al., 2005b) indicating a more cautious movement strategy.

4.3.2. Diagnosed VI

Single support duration in populations with diagnosed VI was investigated by four studies with varied results. Buckley et al. (2005a) indicated an increase in step duration in the trail limb when stepping up to three different height steps. Elliott and Chapman (2010) and Kanzler et al. (2016) indicated no difference in step duration. Where Buckley et al. (2005a) allowed a walk up to the step, Elliott and Chapman (2010) started half a foot length behind the step, meaning the step up would be the first step. The mechanics of the initial step are different to the mechanics of a mid-gait step, therefore, it is not surprising that these results differ. The efficacy of the simulation presented by Kanzler et al. (2016) has already been discussed, it should be noted that in this study it is inferred that the participants are expected to walk around the obstacles rather than step over them which would further alter the gait cycle. The method in Zult et al. (2019) was different again as they examined gait when stepping over rather than onto or around an obstacle. They found that there was a difference in results when comparing the lead limb and trail limb, with the lead limb increasing in single support time and the trail limb decreasing in single support time when vision is blurred. Other studies (Buckley et al., 2005a; Khadive et al., 2022; Saucedo and Yang, 2017) did not discriminate between lead and trail limb, further demonstrating the methodological issues when trying to determine the effects of VI on gait.

4.4. Quality of evidence, study design, and VI definition

The studies presented here highlight that the reporting of visual function, level of change of visual function due to simulation, quality of simulations and reporting of underlying causes of visual impairment is highly variable across studies. The quality of the evidence presented in Table 5 indicates a range of quality standards in the studies included in this review. The QuADS tool is widely used as it has been shown to be valid and reliable (Harrison et al., 2021), however, the QuADS quality rating of the studies did not necessarily reflect the nuances of investigating the effects of visual impairment on gait. For example, Négyesi et al. (2025) produced a high-quality study in terms of the QuADS rating examining the effects of limb dominance on gait with half the field of vision restricted. However, within the study they did not state the visual acuity of the participants prior to the VI simulation. If the visual acuity of the two groups tested were different to start with then any observed differences in gait may not be due to the application of the simulation. The paper by Spaulding et al. (1995) also achieved a high QuADS rating. They clearly stated the visual acuity scores of the participants but gave no indication of the method of visual acuity assessment or the duration of the age-related maculopathy, both factors which could influence the results. Because of this the studies included in the review were not weighted in the narrative synthesis based on the quality of the study but are included in Table 5 for transparency. Across the studies, there is a lack of standardisation in reporting and stratifying visual impairments for research. The total absence of reporting of visual function in some studies (Khadive et al., 2022; Krishnan et al., 2017; Lee et al., 2021) makes it difficult for comparison purposes but also fails to make it applicable in a clinical environment. While it can be difficult to recruit and conduct gait research in visually impaired people, simulation of the conditions offers a cost-effective approach, but only if executed well. The use of simulated VI in individuals with normal vision is common in scientific research and there are several methods that have been implemented, which can be broadly separated into simulated goggles, blindfolding, electronic displays, and lens filters for spectacles (Abraham et al., 2024). Whilst these methods provide an alternative to recruiting participants with a diagnosed VI, the expected level of impairment doesn't always match the actual level. For example, Lehsing et al. (2019) reported 0.40 LogMAR visual acuity with 0.1 occlusion filters, which should result in a visual acuity of 1.00 LogMAR. Furthermore, Raveendran et al. (2019) suggested that individual participants required different lens powers to achieve a desired level of simulated visual impairment. The reporting of visual outcomes, when VI is simulated is necessary to determine if the simulation achieved the same level of visual impairment as can be expected in diagnosed conditions. If studies do not provide this information, the clinical applications of the information provided will be limited.

Another area which needs to be addressed is the type of vision loss. This is because certain conditions lead to different areas of the visual field, or different functions being deprived. Hence analysing information by combining different visual impairments in one single group (e.g., Hallemans et al., 2010; Lu et al., 2021; Tomomitsu et al., 2013) is not appropriate. The independence of an individual largely relies on one's mobility, hence, research to improve mobility in visually impaired patients' needs to be fit for purpose. This can only be achieved by conducting research which accounts for the different visual functions involved when moving. Of particular note, in this review, we found that studies conducted by multidisciplinary teams (including professionals with a vision science, biomechanics and rehabilitation background) reported a greater amount of detail on visual function loss, type of underlying cause or simulation employed and segregating patients depending on the type of impairment. Furthermore, such studies also tended to report the level of visual impairment by providing WHO, IBSA or country specific classifications. This is particularly useful considering that this information is closely linked with planning and delivering support initiatives and helps in forward planning of health costs. We propose that future studies consider the importance of multidisciplinary input in their research design at all stages of the project. We also propose a minimum reporting on visual parameters and underlying causes to facilitate better study comparison and clinical utilisation.

There is also an absence of reporting of environmental conditions within the literature. Of the 44 studies identified, only 2 (Lu et al., 2021; Spaulding et al., 1995) measured and reported environmental lighting conditions. Lu et al. (2021) found that participants stride length and stride velocity reduced under 8.3 fc white and 7.3 fc blue lighting conditions. This suggests both colour and brightness of the lighting may affect gait patterns and so should be considered when designing gait protocols.

4.5. Recommended reporting standards for future research

We propose the minimum reporting requirements for research conducted on visually impaired patients or where a visual impairment is simulated:

i. Where visually impaired patients are studied:
   a. Type of condition which led to visual impairment.
   b. Disease duration.
   c. Visual acuity and method of assessing.
   d. Contrast sensitivity and method of assessing.
   e. Visual field parameters and method of assessing.
   f. World Health Organisation (WHO) classification of visual impairment (International Classification of Disease 10th Version (ICD-10)) and where available IBSA or country specific visual impairment classification.

ii. Where simulation techniques are used on healthy individuals the following should be clearly stated and explained:
   a. Type of condition simulated, type of simulation tool (goggles, blindfold, spectacles, contact lenses, or other).
   b. Visual acuity before and during simulation (including the method of assessing).
   c. Contrast sensitivity and method of assessing (before and during simulation).
   d. Visual field parameters and method of assessing (before and during simulation).
   e. Relevant WHO classification of visual impairment and where available IBSA.

In all protocols investigating gait VI the environmental conditions concerning walking surface type and lighting should be clearly communicated. Desirable other parameters would be colour vision and how glare impacts visual outcomes. This is likely to be more appropriate for research looking at occupational activities and those related to traffic.

4.6. Strengths and limitations

To our knowledge, this is the first systematic review evaluating the effects of simulated and diagnosed visual impairments on whole body biomechanics during straight-line level and obstacle walking. Our narrative synthesis highlighted issues with VI simulation techniques, a lack of consistency in reported gait parameters and limited information on the severity of diagnosed VI in the current literature. We hope our recommendations for reporting standards in future research will provide a starting point to address this.

Although Riley et al. (2007) reported that the magnitude of gait differences between overground and treadmill-based walking are within normal variability of gait parameters in healthy individuals, a meta-analysis by Vickery-Howe et al. (2023) found differences in cadence, stride length and peak vertical GRF at push-off between the conditions. As such, including both overground and treadmill-based studies in the straight-line level walking tasks could be considered a limitation and the findings of this review should be interpreted with the method of straight-line walking in mind (e.g., treadmill or overground). Furthermore, we grouped stair-climbing and stepping over obstacles together in the obstacle walking gait condition, which could also be considered a limitation of this review. Although these are both adaptive gait stepping tasks, stepping up/down requires different gait biomechanics to stepping up and over an obstacle. As such, grouping them together could have a potential impact on task-specific biomechanical interpretation and the discussion presented here should be considered in that context.

A meta-analysis was not deemed feasible because of the lack of standardised measurements for simulating visual impairment, the differences in reporting the severity of diagnosed impairments, and the methodological differences in gait measures between studies. This resulted in a heterogeneous sample. As such, a narrative synthesis was considered the best approach for providing an in-depth analysis on this body of research, although by not including a meta-analysis we reduced the objectivity of evaluating the research parameters.

5. Conclusion

The aim of this systematic review was to synthesise the existing evidence on the effect of visual impairments on walking gait parameters. Over 100 different gait measures were reported across the 44 studies that met the inclusion criteria. Alongside this, the body of evidence included 11 different VI simulation techniques and eight types of diagnosed VI. Inconsistencies in how the gait parameters were measured, how visual impairments were simulated, or the severity and stratification of diagnosed impairments led to inconsistent findings across the gathered evidence. The differences in methodological design and reporting across the literature make it difficult to draw conclusions on precisely how different types of VI might affect gait.

6. Practical application

To allow for meaningful clinical decisions from future research, for example better separating gait responses to different impairment aetiologies or integrating ecological walking conditions, we propose a set of minimum reporting standards for research conducted on visually impaired patients or where a visual impairment is simulated. These will hopefully improve the reporting quality of future studies investigating the effects of visual impairment on the walking gait.

CRediT authorship contribution statement

Michael Fish: Writing – review & editing, Writing – original draft, Visualization, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Sean Hudson:** Writing – review & editing, Writing – original draft, Resources, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Julia Bader:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation. **Rebekka Heitmar:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis, Data curation. **Liane B. Azevedo:** Writing – review & editing, Writing – original draft, Project administration, Methodology, Investigation, Formal analysis, Data curation, Conceptualization.

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Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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