Gait & Posture 122 (2025) 339–351

Contents lists available at ScienceDirect

Gait & Posture

journal homepage: www.elsevier.com/locate/gaitpost

Postural control imbalance in individuals with a minor lower extremity amputation: A scoping review

Maxime Acien [a,b,*], Ahmed Dami [a,b], Virginie Blanchette [c,d], Gabriel Moisan [b,c]

[a] Department of Anatomy, Université du Québec à Trois-Rivières, 3351, Boul. des Forges, Trois-Rivières, QC G8Z 4M3, Canada
[b] Groupe de Recherche sur les Affections Neuromusculosquelettiques (GRAN), 3351, Boul. des Forges, Trois-Rivières, QC G8Z 4M3, Canada
[c] Department of Human Kinetics, Université du Québec à Trois-Rivières, 3351, Boul. des Forges, Trois-Rivières, QC G8Z 4M3, Canada
[d] VITAM – Centre de recherche en santé durable, Centre intégré universitaire de santé et de services sociaux de la Capitale-Nationale, Québec, QC, Canada

ARTICLE INFO

Keywords:
Amputation
Biomechanical phenomena
Foot
Lower extremity
Postural balance
Review

ABSTRACT

Background: Minor lower extremity amputations (LEA) compromise postural control and increase the risk of falls. This issue is exacerbated by conditions such as diabetes, which affect proprioception and sensorimotor mechanisms. While orthopedic devices, including prostheses and orthoses, are frequently prescribed, their specific role in restoring postural control remains underexplored. This scoping review aimed to synthesize current research on postural control in individuals with a minor LEA and to evaluate the interventions that may improve balance.
Methods: A systematic search was conducted across databases (MEDLINE, CINAHL, SPORTDiscus, Cochrane) and grey literature, targeting studies employing biomechanics (e.g., kinetics, kinematics), functional tests (e.g., Functional Reach Test, Timed Up and Go) and self-reported assessments of balance confidence, fall risk, and physical performance.
Results: Fifteen articles involving 288 individuals with various levels of minor LEA were included. Increased risk of falling were evidenced by lower scores on functional balance tests, with postural deficits confirmed by biomechanical measurements in both static and dynamic conditions. Custom orthotic devices improved functional performance and biomechanical outcomes, suggesting their effectiveness in restoring balance. Prosthetic devices, such as custom prosthetic shoes, enhanced postural stability and facilitated smoother weight transitions during tasks. However, small sample sizes and inconsistent evaluation protocols, complicate understanding of their effectiveness in rehabilitation.
Conclusion: This scoping review highlights the underestimated postural challenges experienced by individuals with a minor LEA and supports the role of orthotic and prosthetic interventions in restoring balance. High-quality research to guide clinical decision-making in this population is needed.

1. Introduction

Lower extremity amputations (LEA), which can be classified as major (proximal to the ankle joint) or minor (through or distal to the ankle joint) [1], significantly disrupt an individual's functional abilities [2] and quality of life [3,4]. Diabetes mellitus (DM) and peripheral arterial diseases (PAD) are the two main etiologies of non-traumatic LEAs [5,6]. These diseases can lead to foot ulcers, infections and eventually LEA. The constant global rise in the prevalence of DM and PAD is contributing to the overall increase in the incidence of LEAs [7–9]. However, recent epidemiological studies indicate a decrease or stabilization in the rate of major LEAs, while the incidence of minor LEAs is rising [10,11]. This shift is primarily attributable to the timely and effective assessment and management of foot complication, as well as surgical practices that prioritize ankle joint preservation [12,13]. Despite this trend, research has predominantly focused on major LEAs, thereby leaving a gap in the understanding of the specific changes in biomechanics in individuals with a minor LEA. Among the functional deficits observed in individuals with a minor LEA, impairments in postural control are particularly concerning as they may exacerbate mobility limitations [13], increase the risk of falls [14], and compromise quality of life [4], highlighting the need for specific rehabilitation strategies designed for these individuals.

Postural control is essential for the safe execution of daily activities and involves integrating sensory information from the visual [15–18],

* Correspondence to: 3351, boulevard des Forges, Trois-Rivières, QC G8Z 4M3, Canada.
E-mail address: maxime.acien@uqtr.ca (M. Acien).

https://doi.org/10.1016/j.gaitpost.2025.08.064
Received 15 January 2025; Received in revised form 13 July 2025; Accepted 11 August 2025
Available online 12 August 2025

vestibular [16–19], and somatosensory systems [20–23], while activating motor strategies to stabilize the body and avoid falls [24,25]. Any disruption to these systems, regardless of the underlying cause, increases the risk of falls and compromises physical and mental health [26–28]. In individuals with a minor LEA, the loss of sensory receptors, and changes in joint and muscle structures can severely affect postural control by disrupting proprioceptive and somatosensory feedback [29–31]. This results in an overreliance on the visual and vestibular systems [32,33], weight-bearing asymmetries [30,34,35], and disrupted muscle activation patterns [36,37]. In addition, many LEAs are performed in individuals with DM, a condition that further exacerbates postural instability through peripheral nerve damage, impairing tactile sensitivity, lost or reduction of vibratory sensitivity, proprioception, and kinesthesia [21,38]. The combination of these factors in individual with a diabetes-related LEA results in even greater postural instability [39].

Previous literature reviews have explored the relationship between balance, postural control, and fall risk in individuals with a major LEAs [40–44]. Nevertheless, none has focused in individuals with a minor LEA, despite the fact that they are also affected by mobility impairments [45], reduced physical abilities [46], and an increased risk of secondary health complications [47]. Furthermore, external aids such as prostheses, ankle-foot orthoses (AFOs) and foot orthoses (FOs) are commonly prescribed following a minor LEA [48–50]. Although the efficacy of such devices has been demonstrated in populations with postural deficits and a high risk of falls [51], evidence of their effectiveness in restoring postural control in individuals with a minor LEA is still quite limited. Therefore, our primary objective is to synthesize published knowledge that have examined postural control in individuals with a minor LEA. This scoping review seeks to identify the postural control deficits in individuals with a minor LEA, providing a comprehensive overview of the current state of knowledge on the topic. Secondly, we will explore interventions to restore postural control in individuals with a minor LEA. An emphasis will be placed on external orthopedic interventions such as prostheses, AFOs and FOs, and in therapeutic reeducations designed to enhance balance and stability. By synthesizing these findings, this scoping review aims to inform future research and rehabilitation practices, thereby contributing to the development of more effective interventions to improve balance abilities and quality of life in this population.

2. Methods

This scoping review was conducted in accordance with the methodological framework developed for scoping reviews [52,53], and used the Preferred Reporting Items for Systematic Review and Meta-Analysis Protocols for Scoping Reviews (PRISMA-ScR) guidelines [54]. The protocol was published [55].

2.1. Research question

"What quantitative data are available regarding balance deficits in individuals who have undergone a minor LEA?" and "What tools and/or treatments are identified as capable of modifying postural control?"

2.2. Inclusion criteria

This scoping review includes individual of any age who have undergone a minor LEA at the ankle joint or more distal [1] (see Fig. 1). We focused on quantitative outcomes concerning the balance abilities and postural control of these individuals. This data must include biomechanical variables such as related to balance changes and fall risk, as well as information obtained from questionnaires and functional tests designed to assess postural abilities and balance confidence (see Table 1). Our secondary objective is to identify the various interventions aimed at improving function impaired in individuals with a minor LEA. These may include but not limited to prostheses, orthoses, orthopedic insoles, adapted footwear, as well as pre- and post-operative awareness or exercise programs.

Table 1
Inclusion and exclusion criteria for screening selection.

	Inclusion criteria	Exclusion criteria
Level of LEA	– Toe(s) – Ray(s) – Metatarsal-phalangeal – Transmetatarsal – Tarsometatarsal (Lisfranc) – Midtarsal (Chopart) – Ankle (Syme)	Experimental groups composed exclusively of individuals with major LEA level: – Transtibial – Knee – Transfemoral – Hip
Outcomes	– **Biomechanics**: kinetics (e.g., ground reaction force, peak plantar pressures, center of pressure excursion in medial-lateral and anterior-posterior planes during quiet or dynamic standing, …); kinematics (e.g., body displacement, joint angles, …); electromyography – **Functional balance test scores** – **Balance scales**	Study that tested tasks unrelated to balance and postural control
Study design	– Peer-reviewed original studies – Quantitative and quantitative part of mixed-method studies – Case reports/series, dissertation, thesis, annals of congresses, conference proceedings, presentations, posters	– Qualitative studies – Study protocol – Meta-analyses, narrative, and systematic reviews

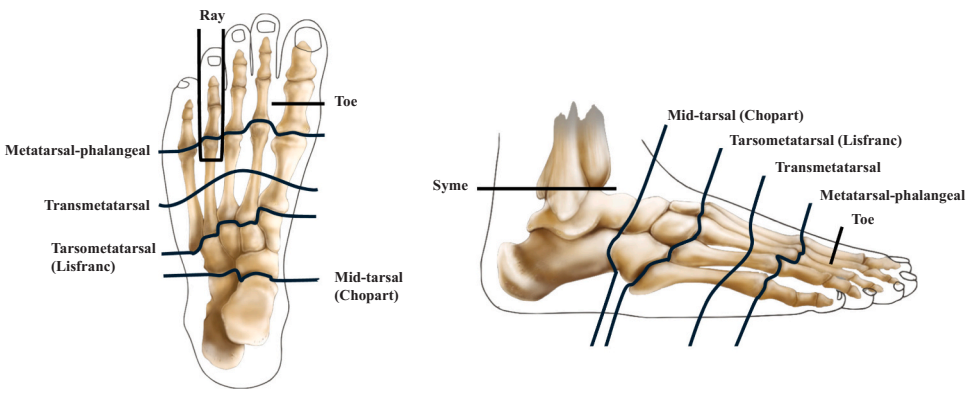

Fig. 1. Levels of minor LEAs. Modified from Kyle Kizziah's original work available at: https://www.artstation.com/artwork/L24VXk.

2.3. Search strategy

A comprehensive search, with an academic librarian, was undertaken across the following databases: SPORTDiscus, CINAHL, MEDLINE, and the Cochrane Library. Additionally, clinical trial registries such as ClinicalTrials.gov were consulted, as well as grey literature via BASE, ProQuest Dissertations and Theses, and to a lesser extent Google Scholar. The search terms included synonyms and keywords related to amputation, amputation level, balance and posture. No temporal limitations were applied. Only studies conducted in French or English and involving human subjects were considered. The preliminary search strategy has been described in the scoping review protocol [55], and was adapted specifically to each database (see Supplementary Material 1).

2.4. Study selection

Potential studies were imported into EndNote v.21.2 (Clarivate Analytics, PA, USA) to remove duplicates. Two independent reviewers (MA and AD) screened titles and abstracts in accordance with the established inclusion criteria. The remaining potential studies were then subjected to a full-text review for further evaluation (see Table 1). In case of disagreement between the reviewers, a third reviewer was consulted (GM). The selection process is documented using a PRISMA flow diagram [54].

2.5. Data analysis

The methodological quality of the selected articles was assessed using the open access Critical Appraisal Tools developed by the Joanna Briggs Institute [56]. The checklist contains between 8 and 13 questions, which differ depending on the study design. Each question was answered with a value of "yes" (1), "no", "unclear" or "n/a" (0). Consequently, higher scores indicate a higher level of methodological quality and a lower risk of bias. The quality assessment was carried out by two independent reviewers (MA and AD). Consequently, studies will be contrasted according to their respective results. However, a poor methodological quality score was not considered in determining inclusion. This evaluation was performed retrospectively after the studies selection.

Data were extracted from the studies included in this scoping review, synthesized and presented in tabular form, and subsequently summarized in narrative form.

3. Results

3.1. Literature search yield

The preliminary search of the databases yielded 5958 records. Initially, 1473 were identified as duplicates and were removed. Subsequently, the remaining 4485 original underwent title and abstract screening, resulting in the exclusion of 4303 that did not meet the inclusion criteria. Of the remaining studies, 182 were selected for a full-text comprehensive review. Finally, 169 were excluded, with the primary reasons for exclusion being the population or the task performed (see Supplementary Material 2 for the reasons for exclusion). Two supplementary articles [57,58] were subsequently identified through a

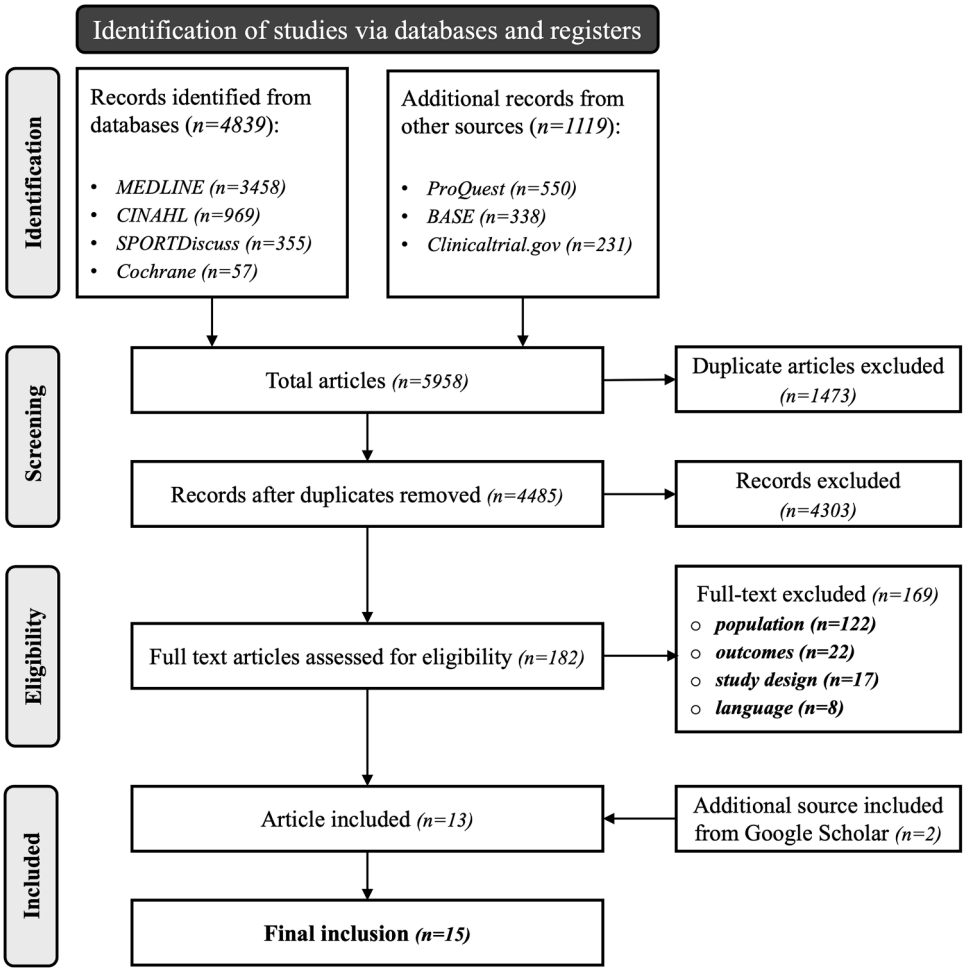

Fig. 2. Selection process flowchart according to preferred reporting items for systematic reviews and meta-analyses extension for scoping reviews (PRISMA-ScR).

manual search of Google Scholar. Consequently, 15 studies were included. The complete inclusion process is displayed in a PRISMA flowchart in Fig. 2 [54].

3.2. Quality assessment

Scores related to the quality assessment for the 15 included studies are displayed in Table 2. The detailed scoring is outlined in Supplementary Material 3. The Kappa statistic was used to assess the agreement between the reviewers (see Fig. 3). The Kappa value was 0.56 (95 % CI: 0.04–1.08, P = 0.037), which is categorized as a moderate agreement between the reviewers.

3.3. Characteristics of the included studies

The characteristics of the included studies are presented in Table 2. Most methodological designs were quasi-experimental studies (*n = 5*; 34 %) [60,64,65,68,70], followed by case reports (*n = 4*; 27 %) [57,58,66,71] and cross-sectional studies (*n = 4*; 27 %) [59,62,63,67]. The remaining two were a cohort study (*n = 1*; 6 %) [61] and a randomized controlled trial (*n = 1*; 6 %) [69]. The included studies were geographically diverse, with five originating from the United States of America (34 %), two from France (14 %), Canada (14 %) and United-Kingdom (14 %), and one from Italia (6 %), Uruguay (6 %), Turkey (6 %), and Egypt (6 %). We identified two studies published before 2000 (14 %), three between 2000 and 2009 (20 %), six between 2010 and 2019 (40 %) and four between 2020 and 2024 (28 %).

3.4. Population

The included studies comprised 288 participants, 213 male and 75 female (see Table 2). Of these, 152 individuals had a minor LEA, and 42 individuals were considerate as control and defined as healthy individuals with no particular health condition. Two studies included individuals with a major LEA in their sample [67,69]. These studies were included in the review as the results were disaggregated across the different amputation groups. A total of 48 individuals with a major LEA were identified across the included articles. Two studies included individuals with DM as the experimental group but at different stages of foot complications (diabetic neuropathy and diabetic foot ulcer, 23 individuals in both groups) [62,63]. These two articles involved the same participants on different tasks, both of which met the inclusion criteria for the review. Finally, one study included a cohort of individuals with a LEA who received a different treatment than the control group [69].

With the exception of three studies involving children [61,67,68], all other studies involved adults (>18 years old), the majority aged 50 or more. Participants ranged from 20 to 83 years. The average age of the adult participants was 59.7 years (± 7.5 years). In all studies including a control group, this group was matched for age, with a mean age of 62.1 years (± 7.4 years).

3.5. Level and etiology of amputation

Among the individuals with a minor LEA, the selected studies included different levels of amputation (see Fig. 1). We identified nine Syme amputations, one mid-tarsal disarticulation, two tarsometatarsal disarticulations, 75 transmetatarsal amputations (TMA), 24 ray amputations, 55 amputations of one or more toes (including four amputations of all toes and five hallux amputations). Fourteen participants across six studies [59–61,64,66,71] had a bilateral minor LEAs, while the remaining individuals had unilateral ones [57,58,62,63,65,67–70]. One study included two individuals with a TMA on one side and transtibial amputation (TTA) on the contralateral side [60].

The majority of minor LEAs were related to PAD with a primary etiology of DM (*n = 129*) [57,59,60,62–65,69]. Other causes of minor LEAs was meningococcemia (*n = 1*) [58], trauma (*n = 4 across four studies*) [66,68,70,71] and cancer (*n = 1*) [70]. In the three pediatric studies, the etiology was congenital (*n = 17*) [61,67,68].

3.6. Intervention

We identified seven out of fifteen studies that reported outcomes related to orthotic interventions that may improve the postural function in individuals with a minor LEA [57,58,60,64,65,70,71]. Two assessed total-contact FOs [64,65], two focused on AFOs [58,64], and one evaluated several therapeutic shoe configurations related to length (full; short) and combinations with AFOs, total-contact FOs, and rigid-rocker-bottom soles [60]. Other orthotic interventions included a custom tarsometatarsal prosthesis [57], two Syme prostheses [70], and a prosthetic shoe [71].

With regard to non-prosthetic interventions, one study evaluated the impact of pre-amputation education on post-amputation balance abilities [69], while another examined the influence of a vestibular stimulation system on postural control [66].

3.7. Outcomes

The outcomes and main results are presented in Table 3. The included studies are classified according to the type of variable of interest such as balance scales, functional balance tests, and biomechanics (e.g., quiet standing and dynamic balance tasks).

3.7.1. Balance scales

In five studies, postural abilities and balance on various ordinal scales were quantified. Two studies conducted the Physical Performance Test (PPT) [59,60], reporting significantly lower scores in individuals with a TMA-DM compared to the control, particularly in mobility and coordination tasks, such as walking with a turn, climbing flight of stairs or picking up a coin from the floor [59]. Specific adapted orthopedic prescriptions enhanced test performance in TMA-DM population. The PPT scores were improved in the conditions full-length shoe and rigid-rocker-bottom, short shoe and rigid-rocker-bottom, and short shoe with an AFO and rigid-rocker-bottom than in the control shoe condition [60].

One study administered the Community Balance and Mobility scale (CB&M) and observed lower scores for all three LEAs groups compared to the control individuals [67]. The performance in individuals with a Syme amputation was comparable to that reported in major LEAs, confirming the pronounced functional limitations. Statistical tests between subgroups were not performed due to the low sample size for each amputation level [67].

One study employed the Berg Balance Scale (BBS) to evaluate fall risk and post-amputation balance abilities in study participants [69]. The BBS scores was higher in the intervention group than in the control group. Statistically significant differences were demonstrated between the forefoot amputations (one or multiple toes) and TMA groups, but not between major LEAs groups.

Finally, a simplified version of the Activities-specific Balance Confidence (ABC) scale was assessed while wearing two Syme prostheses. However, the scores did not exceed the minimum detectable change values for either participant between conditions [70].

3.7.2. Functional balance test

Mueller and colleagues [59,60] reported that the reaching abilities in individuals with a TMA-DM during the Functional Reach Test (FRT) were 64 % lower than those of the control group, indicating a limitation in their functional abilities. The scores of participants in the TMA-DM were associated with an increased risk of falls compared with the age-matched control group. Of the 15 participants with a TMA-DM, four had even lower scores, indicating a very high risk of falls [59]. A complementary study demonstrated that the reach distances remained comparable between six different orthotics conditions [60].

Table 2
Characteristics of the included studies.

Authors (year)	Country	Study design	Aim(s)	Sample size (M/F)	Experimental	Amputation Etiology	Control	Age	Quality assessment
Mueller et al. (1997) [59]	USA	Cross sectional	Compare function in patients with TMA-DM and age/gender-matched controls.	30 (18/12)	TMA (*n = 15*) • Unilateral (*n = 12*) • Bilateral (*n = 3*)	Diabetes (*n = 15*)	Healthy participants (*n = 15*)	62.3 ± 9.2	High
Mueller et al. (1997) [60]	USA	Quasi experimental	Determine whether therapeutic footwear improves functional mobility in patients with TMA-DM.	30 (20/10)	TMA (*n = 30*) • Unilateral (*n = 24*) • Bilateral (*n = 4*) • TMA with TTA (*n = 2*)	Diabetes (*n = 30*)	NA	61.7 ± 4.0	Moderate
Beyaert et al. (2003) [61]	France	Cohort	Evaluate anatomical and functional effects of second toe removal in children, including impacts on foot structure, balance, and gait.	11 (7/4)	Second toe (*n = 11*) • Unilateral (*n = 7*) • Bilateral (*n = 4*)	Digital reconstruction (*n = 11*)	NA	9.1	Low
Kanade (2006) [62]	UK	Cross sectional	Compare weight-bearing activities, such as a sit-to-stand task, between four diabetic groups at different stages of foot complications, including PFA and TTA.	84 (73/11)	TMA (*n = 5*), Ray (*n = 4*), Hallux (*n = 5*), All 5 toes (*n = 1*), First 2 toes (*n = 1*)	Diabetes (*n = 16*)	DNP (*n = 23*); DFU (*n = 23*); TTA (*n = 22*)	62.8 ± 7.1	High
Kanade et al. (2008) [63]	UK	Cross sectional	Compare standing balance between four diabetic groups, at different stages of foot complications, including PFA and TTA.	84 (73/11)	TMA (*n = 5*), Ray (*n = 4*), Hallux (*n = 5*), All 5 toes (*n = 1*), First 2 toes (*n = 1*)	Diabetes (*n = 16*)	DNP (*n = 23*); DFU (*n = 23*); TTA (*n = 22*)	62.8 ± 7.1	High
Spaulding et al. (2012) [64]	USA	Quasi experimental	Examine differences in balance and pressure distribution when wearing a FO alone or in combination with an AFO.	12 (12/0)	TMA (*n = 6*) • Unilateral (*n = 5*) • Bilateral (*n = 1*)	Diabetes (n = 6)	Healthy participants (*n = 6*)	58.0 ± 10.3	Low
El-Hilaly et al. (2013) [65]	Egypt	Quasi experimental	Investigate the effects of a total contact insole and a flat insole on the plantar pressure in patients with partial first ray amputations.	20 (9/11)	Ray (*n = 20*)	Diabetes (*n = 20*)	NA	60.0	High
Diot et al. (2014) [66]	France	Case report	Evaluate the effect of a vestibular biofeedback on the postural stability of an individual with a bilateral minor LEA, compared with a matched control group.	7 (7/0)	Bilateral minor LEA (*n = 1*) • Right foot: mid-tarsal • Left foot: all toes	Domestic accident (*n = 1*)	Healthy participants (*n = 6*)	52.9 ± 2.0	High
Parent et al. (2014) [58]	Canada	Case report	Compare biomechanics using articulated AFO and fixed carbon-fiber AFO, both combined to toe filler in patient with TMA.	1 (1/0)	TMA (*n = 1*)	Meningococcemia (*n = 1*)	NA	20.0	Low
Feick et al. (2016) [67]	Canada	Cross-sectional	Examine the relationships between balance and mobility measures in children with unilateral LEA and able-bodied control.	20 (10/10)	Major LEA (n = 7) Syme (*n = 3*)	Acquired (*n = 5*) Congenital (*n = 5*)	Healthy participants (*n = 10*)	9.7 ± 2.5	High
Geil et al. (2016) [68]	USA	Quasi experimental	Assess the effect of backpack loads on postural sway in children with a Syme amputation.	9 (4/5)	Syme (*n = 4*)	Congenital (*n = 3*) Trauma (*n = 1*)	Healthy participants (*n = 5*)	12.6 ± 3.3	High
Novo et al. (2023) [57]	Uruguay	Case report	Develop and functionally validate a new 3D-printed tarsometatarsal prosthesis prototype compared to a barefoot condition.	1 (1/0)	Tarsometatarsal (*n = 1*)	Diabetes (*n = 1*)	NA	65.0	Very low
Toygar et al. (2023) [69]	Turkey	Randomized controlled trial	Examine the effect of an educational intervention on balance in individuals with a LEA-DM compared to a matched population receiving no intervention.	60 (49/11)	Major LEA (n = 10) Tarsometatarsal (*n = 1*); TMA (*n = 6*); Toe (*n = 8*); Multiple toe (*n = 5*)	Diabetes (*n = 30*)	Major LEA (*n = 9*) TMA (*n = 4*); Toe (*n = 10*); Multiple toe (*n = 7*)	60.7 ± 8.4	Low

(*continued on next page*)

Table 2 (*continued*)

Authors (year)	Country	Study design	Aim(s)	Sample size (M/F)	Experimental	Amputation Etiology	Control	Age	Quality assessment
Slater et al. (2024) [70]	USA	Quasi experimental	Compare patient-reported outcomes between crossover and traditional energy-storing feet in two individuals with a Syme amputation.	2 (1/1)	Syme (*n = 2*)	Trauma (*n = 1*) Cancer (*n = 1*)	NA	42.5 ± 8.5	Very low
Storniolo et al. (2024) [71]	Italia	Case report	Explore balance impairments following amputation and identify appropriate interventions such as prosthetic fitting or targeted training.	1 (1/0)	Bilateral amputation of all five toes (*n = 1*)	Severe frostbite (*n = 1*)	NA	52.0	High

Abbreviations:
M=Male; F=Female; USA=United States of America; UK=United Kingdom; LEA=Lower Extremity Amputation; TTA=Transtibial Amputation; PFA=Partial Foot Amputation; TMA=Transmetatarsal Amputation; DM=Diabete Mellitus; DNP=Diabetic Neuropathy; DFU=Diabetic Foot Ulceration; FO=Foot Orthoses; AFO=Ankle Foot Orthoses; NA=Not Applicable.

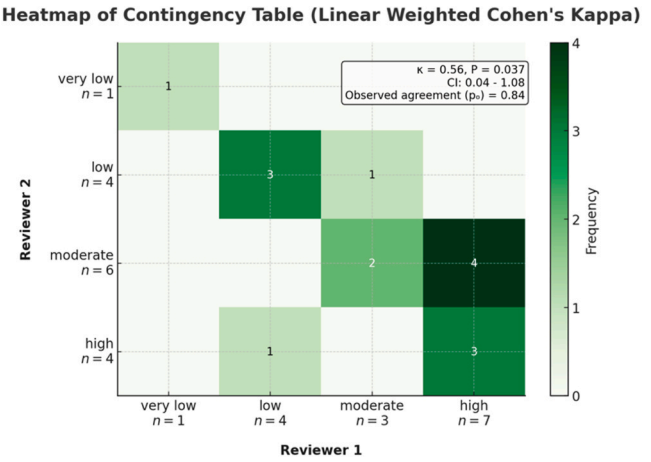

Fig. 3. Kappa contingency table. k = Kappa value; CI=Confidence interval.

The Timed Up and Go (TUG) test was reported in two articles [57,64]. TUG times were significantly longer in individuals with a TMA compared with a matched control group, and positively correlate with DM duration [64]. The use of a custom 3D-printed prosthesis in an individual with a tarsometatarsal amputation resulted in improved TUG performance, particularly in sit-to-stand transitions and in total TUG time [57].

3.7.3. Biomechanics

3.7.3.1. Quiet standing. Of the 15 articles included, ten reported biomechanical data collected in laboratory settings. Eight of these studies examined quiet standing tasks using one [58,61,63,66,67], two force plates [68,71], or F-Scan instrumented pressure insoles technology [65]. Some authors have introduced additional variables, including backpack loading [68], removal of visual sensory input [61,66], or one leg stance condition [61].

While a study revealed no statistically significant difference in center of pressure (CoP) root mean square in individuals with a Syme amputation compared to a control group (6.3 ± 2.3 mm vs. 5.9 ± 2.3 mm) [67], other demonstrated an increase in total CoP excursion in individuals with a Syme amputation compared to controls (313.43 ± 158.40 mm vs. 293.72 ± 165.99 mm) [68]. Another study demonstrated that individuals with a minor LEA exhibited a greater CoP excursion than the individuals with a TTA, despite not reaching statistical significance (minor LEA: 1.24 ± 0.41 m vs. TTA: 1.21 ± 0.44 m, P = 0.843). The results were consistent in both the anterior-posterior (AP) (minor LEA: 1.01 ± 0.34 m vs. TTA: 1.00 ± 0.36 m, P = 0.966) and medial-lateral directions (ML) (minor LEA: 0.54 ± 0.18 m vs. TTA: 0.50 ± 0.20 m, P = 0.583) [63].

The addition of progressive loads up to 25 % of body-weight resulted in a linear increase in both CoP excursion and velocity in the control group, while the perturbation in the Syme amputation group was complex and non-linear [68]. These disturbances occurred in the AP direction in the controls and in the ML direction in the Syme group [68]. The absence of visual afferents also exacerbates postural instabilities. Some authors demonstrated that CoP surface area was nearly five times larger in an individual with a minor LEA and eyes-closed in comparison to controls [66]. In individuals with a bilateral toe amputation, closing the eyes during one-legged stance significantly reduced stance time (20.0–13.3 ± 5.3 s, P = 0.01) and increased CoP displacement mean rate (+151 ± 66 to +263 ± 102 mm/s, P = 0.01). In individuals with a unilateral toe amputation, the operated side exhibited a greater reduction in stance time with eyes closed (14.7 ± 6.3–7.3 ± 4.7 s, P = 0.01) compared to the contralateral side (17.7 ± 5.2–10.6 ± 5.3 s, P = 0.01). The CoP displacement mean rate increased significantly in both groups after eye closure in the one-leg stand compared to the unoperated feet (+106 ± 92 mm/s vs. +32 ± 51 mm/s, P = 0.05) [61].

The use of assistive devices, including prostheses [71], FOs [58,65], and a vestibular-tactile sensory substitution system [66], enhanced standing abilities. A biofeedback system significantly reduce (-39 %) the CoP trajectory surface area in an individual with a bilateral minor LEA, compared to the initial condition [66]. With regard to the orthopedic devices, a total-contact insole led to a more pronounced reduction of plantar-pressure than both a flat insole and no-insole condition, while standing, particularly under the first metatarsal, midfoot, medial and lateral heel areas [65]. Orthotics design and materials also affected CoP parameters in individuals with a minor LEA. A fixed carbon AFO allowed the CoP to be projected forward of the center of base in comparison to an articulated AFO, indicating improved weight distribution over the support base [58]. The type of footwear worn also has an impact on CoP during quiet standing task. In the barefoot condition, CoP shifted anteriorly compared to a prosthetic shoes condition (44.65 vs. 37.54 mm), reflecting a reduced AP base of support. The barefoot base of support was also narrower than in the shod condition (22.5 vs. 24.9 cm). However, CoP oscillations in AP and ML were similar in both conditions [71].

3.7.3.2. Dynamic balance tasks. The three tasks explored were sit-to-stand transitions [62], gait initiation [71] and TUG [57]. During sit-to-stand transitions, the time to reach full knee extension and postural stabilization did not differ significantly between the minor LEA

Table 3
Methods, Outcomes and Main Results of the Included Studies.

Authors (year)	Methods (Outcomes)	Intervention	Results
Balance Scales			
Mueller et al. (1997) [59]	**Physical Performance Test (PPT)** (8items: writing a sentence, simulated eating, lifting a book to put on a shelf, putting on and removing a jacket, picking up a penny from the floor, turning 360°, walking 15.2 m, climbing a flight of stairs (12 steps); 7items: excludes stair climbing).	NA	Lower scores in participants with a minor LEA (8-items: 21.1 vs 27.9 / 32; 7-items: 18.7 vs 24.1 / 28, $P < 0.001$). Marked differences in times (**t**) and marks (**m**) for mobility and coordination tasks: walking + turn (**t**: 22.7 ± 7.0 s vs 14.9 ± 3.0 s, $P < 0.001$; **m**: 2.5 ± 1.0 vs 3.7 ± 0.6, $P < 0.001$), climbing stairs (**t**: 11.5 ± 8.7 s vs 4.8 ± 0.9 s, $P < 0.01$; **m**: 2.5 ± 0.8 vs 3.8 ± 0.8, $P < 0.001$), picking up a coin from the floor (**t**: 4.8 ± 1.8 s vs 3.1 ± 1.1 s, $P = 0.005$; **m**: 2.2 ± 0.8 vs 3.1 ± 0.7, $P = 0.003$).
Mueller et al. (1997) [60]	**PPT** (8items: writing a sentence, simulated eating, lifting a book to put on a shelf, putting on and removing a jacket, picking up a penny from the floor, turning 360°, walking 15.2 m, climbing a single of stairs (12 steps)).	Six types of footwear conditions: (1) full-length standard shoe, with a toe filler. (2) full-length shoe, TCI and an AFO. (3) full-length shoe, TCI, and a RRB sole. (4) full-length shoe, TCI, RRB sole and AFO. (5) short shoe, TCI, and RRB sole. (6) short shot, TCI, AFO, and RRB sole.	Scores differed by footwear ($P < 0.001$). Scores were significantly higher in conditions 3 (21.8), 5 (22.4), and 6 (22.7) compared to the control condition 1 (20.4, $P < 0.05$)
Feick et al. (2016) [67]	**Community Balance & Mobility (CB&M) scale** (CB&M score on 96)	NA	Scores were significantly lower in children with a LEA than in their able-bodied peers (54 ± 12 vs 77 ± 11, $P < 0.01$). Scores were particularly low in children with Syme (48−69) and transfemoral (43−56) amputations. However, no statistical comparisons were performed between subgroups.
Toygar et al. (2023) [69]	**Berg Balance Scale (BBS)** (BBS score on 56)	Two educations groups: (1) intervention group: specific education (gait suggestions, orthosis, and prosthesis, exercise to strengthen the low-extremity muscles, stump care/hygiene, and coping strategies). (2) control group: routine care and education.	In individuals with minor LEAs, scores were significantly higher in the intervention group vs. control (29.6 ± 16.6 vs 18.4 ± 17.4, $P = 0.045$). Significant improvements were observed across subgroups: single toe (47.0 ± 14.5 vs 32.7 ± 7.1, $P = 0.003$), multiple toes (34.8 ± 9.7 vs 22.1 ± 8.7, $P = 0.038$), and TMA (33.0 ± 9.2 vs 16.5 ± 7.1, $P = 0.038$). One participant with a tarsometatarsal amputation scored 38 (no control comparison available). Most intervention group participants were classified as low fall risk, whereas controls were mostly high risk. No significant difference was found in major LEA scores ($P = 0.067$).
Slater et al. (2024) [70]	**Activity-specific Balance Confidence (ABC) scale** (5-option response 0–4)	Two Syme prosthesis conditions: (1) low-profile energy-storing feet (ESF). (2) high-profile crossover feet (XF).	No difference in scores between the ESF and XF conditions. Participant 1 rated both prostheses equally (4.00), while Participant 2 felt more balanced with the ESF prosthesis (ESF = 3.63 vs. XF = 3.53).
Functional Balance Test			
Mueller et al. (1997) [59]	**Functional Reach Test (FRT)** (reaching distance).	NA	FRT distance was shorter in the TMA-DM group vs control (19.1 ± 8.6 cm vs 31.5 ± 9.1 cm).
Mueller et al. (1997) [60]	**FRT** (reaching distance).	Six types of footwear conditions: (1) full-length standard shoe, with a toe filler. (2) full-length shoe, TCI and an AFO. (3) full-length shoe, TCI, and a RRB sole. (4) full-length shoe, TCI, RRB sole and AFO. (5) short shoe, TCI, and RRB sole. (6) short shot, TCI, AFO, and RRB sole.	FRT distance did not significantly differ across conditions (18.6, 18.8, 18.0, 18.1, 19.3, 17.5 cm, $P = 0.46$).
Spaulding et al. (2012) [64]	**Timed Up and Go (TUG)** (TUG time)	Two orthotic conditions: (1) below-ankle (BA) with shoes and insoles. (2) combination of above and below-ankle (AABA) with shoes, insoles and the addition of the Blue Rocker AFO.	TUG time was significantly longer in partial foot amputation (PFA) participants vs controls (8.2 ± 1.5 s vs 6.0 ± 1.5 s, $P = 0.025$), with a positive correlation between TUG time and diabetes duration ($r = 0.82$). All PFA participants reported better balance using the BA orthosis, only one participant (PFA3 who had the longest diabetes duration and the worst TUG time) felt more balanced with the AABA.
Novo et al. (2023) [57]	**TUG** (transition times from Sit-to-Stand and Stand-to-Sit; Gait time in Forward and Backward Directions: Average gait time; Total Time Analysis: Average duration of the whole trial).	Two conditions: (1) barefoot. (2) a custom-made 3D-printed tarsometatarsal prosthesis.	TUG time was reduced when using the prosthesis, particularly during Sit-to-Stand transitions. No difference for Stand to Sit, and only a slight improvement was observed for round-trip walking.
Biomechanics			
Beyaert et al. (2003) [61]	**Quiet Standing on a force plate; eyes-closed in double and single-barefoot stance** (stance time, ML/AP sway frequency (>5 mm), and mean CoP displacement rate (cumulated displacement divided by the time in balance)).	NA	In bilateral toe amputees, eye closure reduced one-leg stance time ($P = 0.01$) and increased CoP displacement rate ($P = 0.01$), with no significant change in sway frequency. In unilateral cases, eye closure also reduced stance time, more on the operated side ($P = 0.01$) than on the non-operated

(*continued on next page*)

Table 3 (*continued*)

Authors (year)	Methods (Outcomes)	Intervention	Results
			side (P = 0.01). Mean CoP displacement increased in both groups, with higher values on operated feet compared to non-operated feet (P = 0.05).
Kanade et al. (2006) [62]	**Sit-to-Stand movement** (time to complete full extension and stability; net joint moments (hip, knee and ankle); weight-bearing symmetry.	NA	No significant differences between groups in time to full extension or stabilization (P = 0.209 and P = 0.201). The DNP and PFA groups exhibited symmetrical weight-bearing. In contrast, 56.5 % of participants in the DFU group shifted weight on the contralateral limb, indicating asymmetry.
Kanade et al. (2008) [63]	**Quiet Standing on a force plate, in two feet stance during 30 s** (distance between the ankles, mean anterior CoP position, CoP excursion (total, AP, ML), and weight distribution between limbs).	NA	Significant differences were found among the four groups for total and AP CoP excursion (P = 0.001 and P < 0.001), with a general decline in balance from the DNP to TTA group, although PFA showed greater CoP excursion than TTA. ML CoP excursion varied significantly (P < 0.050) but showed no clear trend. Ankle distance increased significantly from DNP to TTA (P = 0.001), while forward CoP position and weight-bearing did not differ between groups.
El-Hilaly et al. (2013) [65]	**Quiet Standing with F-Scan sensors** (average pressure in five metatarsal areas (M1–5), mid foot area (MF), medial heel (MH) and lateral heel (LH) areas).	Three insole conditions: (1) shoe, with no insole (NI). (2) shoe, with custom total-contact insole (TCI) (3) shoe, with regular flat insole (FI).	Highest peak pressures were at the mid metatarsal (M3, M4), MF and the heel areas while standing. Compared to the NI condition, both FI and TCI reduced peak plantar pressures, with more pronounced decrease when using the TCI. Significant pressure decreases were observed at M1 (FI: –16 %, P = 0.015; TCI: –26 %, P = 0.022), MF (FI: –19 %, TCI: –50 %, both P < 0.001), MH (FI: –23 %, TCI: –56 %, both P < 0.001), and LH (FI: –24 %, P < 0.001; TCI: –44 %, P = 0.022).
Diot et al. (2014) [66]	**Quiet Standing on a force plate; eyes closed in double feet stance** (CoP trajectory, CoP surface area).	Vestibular biofeedback.	CoP trajectory surface area was greater in the minor LEA participant than in able-bodied participants, in both no-biofeedback and biofeedback conditions. Greater stabilizing effect of biofeedback for the minor LEA participant (−39 %) than for the able-bodied group (−28 %).
Parent et al. (2014) [58]	**Quiet Standing on a force plate** (CoP displacement)	Two AFO conditions: (1) articulated AFO with a toe filler. (2) fixed carbon-fiber AFO with a toe filler.	CoP displacement was projected forward the center of the base of support with the fixed carbon-fiber AFO compared with the articulated AFO.
Feick et al. (2016) [67]	**Quiet Standing on a force plate** (CoP root mean square (RMS) in combined AP/ML direction)	NA	No significant difference in CoP RMS between the able-bodied and LEA groups. Within LEA subgroups, the Syme participant showed higher minimum CoP RMS (4.1 mm) than the transtibial (2.6 mm) and transfemoral (2.7 mm) participants.
Geil et al. (2016) [68]	**Quiet Standing on dual force plate, 40 s under four backpack load conditions: 0, 10, 20, 25 %** (CoP excursion (total, ML, AP); mean CoP velocity (total, ML, AP); 95 % confidence ellipse of CoP excursion; weight bearing distribution).	NA	In response to increasing backpack weight, CoP excursion and velocity increased progressively in the control group, while a non-linear pattern was observed in children with a Syme amputation. Values increased from 0 % to 10 % BW, decreased from 10 % to 20 % BW, and increased again from 20 % to 25 % BW. Sway path shifted in the AP direction in controls but in the ML direction in the Syme group.
Novo et al. [57]	**TUG with inertial sensor** (acceleration average and range (AP, ML, vertical) during Sit-to-Stand and Stand-to-Sit transitions; average angular velocity during Mid and End turning phases.	Two conditions: (1) barefoot. (2) a custom-made 3D-printed tarsometatarsal prosthesis.	Using a custom prosthesis led to reduced acceleration across all planes, indicating improved overall stability. Angular velocity during mid-turn remained unchanged but increased at the end of the movement when using the prosthesis.
Storniolo et al. (2024) [71]	**Quiet Standing on a dual force plate, 30 s** (CoP position (AP, ML), CoP length, CoP range (AP, ML), CoP total velocity, CoP ellipse area, weight distribution, ankle joint centers position). **Gait Initiation** (EMG: Erector Spinae, Obliquus Abdominis, Biceps Femoris, Vastus Medialis, Tibialis Anterior and Soleus; AP CoP excursion).	Two conditions: (1) barefoot. (2) a prosthetic shoe.	During quiet standing, AP CoP range and velocity were ~50 % higher than in the ML direction. In the barefoot condition, the CoP moved forward toward the geometric center of the base of support. In the shoe condition, the CoP moved backwards, closer to the ankle joints, without improving overall stability. EMG and CoP analyses revealed different gait initiation strategies. Barefoot condition induced a pivoting motion with contralateral trunk engagement (increased erector spinae activation), while shod condition led to a faster and symmetrical forward motion.

Abbreviations:
EMG=Electromyography; CoP=Center of Pressure; ML=Medial-Lateral; AP=Anterior-Posterior; BW=Body Weight; PPT=Physical Performance Test; CB&M=Community Balance & Mobility; BBS=Berg Balance Scale; ABC=Activity-specific Balance Confidence; FRT=Functional Reach Test; TUG= Timed Up and Go; LEA=Lower Extremity Amputation; TFA=Transfemoral Amputation; TTA=Transtibial Amputation; PFA=Partial Foot Amputation; TMA=Transmetatarsal Amputation; DM=Diabete Mellitus; DNP=Diabetic Neuropathy; DFU=Diabetic Foot Ulceration; RRB=Rigid Rocker-Bottom; AFO=Ankle Foot Orthoses; ESF=Energy-Storing Feet; XF=Crossover Feet; BA=Below-Ankle; AABA=Above Ankle and Below-Ankle; NI=No Insole; FI=Flat Insole; TCI=Total-Contact Insole; RMS=Root Mean Square; NA=Not Applicable.
Bolded text indicates the methodology and specific test(s) used in each study.

group and the diabetic neuropathy (DNP), diabetic foot ulcer (DFU) and TTA groups (P = 0.209). Nevertheless, the time required to achieve postural stability following full extension was found to be longer in the minor LEA (7.4 s) and TTA (7.5 s) groups compared to the DNP (6.8 s). The DFU group exhibited the longest time (9.1 s), though this did not reach statistical significance (P = 0.201) [62]. Net force moments and weight bearing during the sit-to-stand task demonstrated that unilateral minor LEA did not affect the symmetrical movement performance, unlike in DFU and TTA individuals [62]. During gait initiation task, the participant demonstrated varying postural strategies, depending on the experimental conditions. In the barefoot condition, the CoP demonstrated slower and more limited displacement, with a smaller amplitude in AP direction and reduced speed. The CoP demonstrated a faster and wider displacement with prosthetic shoes, which resulted in an improvement in propulsion. The body rotation is evidenced by the higher AP amplitude of the scapular and pelvic markers. In contrast, the postural adjustments in shoes exhibited bilateral inhibition of the erector spinae, enabling a symmetrical and dynamic strategy [71]. Finally, a custom-made tarsometatarsal prosthesis improved the spatiotemporal variables of the TUG test. Wearing the prosthesis resulted in more regular and controlled accelerations during sit-to-stand and stand-to-sit transitions, reducing fluctuations in AP, ML, and vertical directions. Without the prosthesis, these movements showed increased variability, indicating reduced stability. Angular velocity did not significantly change during mid-turns, but a slight increase was observed at the end of turns with the prosthesis [57].

4. Discussion

This scoping review examined postural deficits in individuals with a minor LEA and the efficacy of various treatments, especially orthopedic, in enhancing their postural function.

4.1. Outcomes

Minor LEAs, often perceived as having a relatively limited functional impact compared to major LEAs, are associated with postural deficits that are often underestimated. Some authors have described these disturbances as "*functional challenges*" [57], "*considerable functional limitations*" [59], or "*considerably disrupted postural control*" [66]. In some cases, these deficits are comparable to those observed in individuals with major LEAs [62,63,67,69].

These deficits are due to several biomechanical and neurosensory changes. Primarily, decrease in foot length and loss of toes [63,71], reduces the plantar-flexor lever arm and the ability to generate plantar-flexor torque at the ankle [59,68]. As result, individuals have challenges during activities requiring shifting weight to the forefoot [59,60,71]. Minor LEAs also involve resection of the plantar aponeurosis, loss of intrinsic foot muscles and toe proprioceptors [59,61,71] and a disruption in somatosensory afferents [63,66] as a consequence of plantar nerve resection [61,71]. Suppression of visual afferents exacerbate postural disturbances and, unlike able-bodied participants who can use vestibular and somatosensory inputs from the feet and ankles, individuals with a minor LEA rely almost exclusively on vestibular information to control posture due to the reduced base of support and loss of associated somatosensory afferents [61,66]. Similar observations have been documented in studies evaluating standing in control participants supported on a partial foot support [72], and a hallux sensory deprivation system [73], simulated a minor LEA condition. Furthermore, PAD, DM and related complications (i.e., neuropathy), reducing the proprioceptive and tactile capacity of the foot, further limiting the effectiveness of postural mechanisms already compromised by the partial loss of plantar structures [62,63,74]. It has been proposed that the forward displacement of the CoP during balance tasks may be associated with an attempt to enhance the afferent inflow from the residual forefoot [71]. In addition to somatosensory damage, DM can also affect the visual system (e.g., diabetic retinopathy) thereby adding another level of complexity to postural impairments [75,76].

In response to biomechanical alterations, individuals with a minor LEA frequently implement compensatory postural strategies to maintain their balance. From a kinetic point of view, multiple studies have documented an increase in CoP excursion in both the AP [63,71] and ML [68,71] directions. Such an increase in CoP ML excursion may indicate an increased reliance on hip abduction/adduction mechanisms rather than an ankle dorsi/plantarflexion mechanism to compensate for ankle proprioceptive deficits [68]. Authors have reported that individuals with a minor LEA tend to increase their base of support to compensate for deficits in ML stability [63,71]. Such asymmetries will be particularly pronounced in dynamic balance activities [62].

In addition, certain levels of LEAs may predispose to increased postural instability and even lead to new comorbidities such as foot deformities or secondary amputations [61,65]. Toe amputation can result in insufficient intermetatarsal stability due to the widening of the intermetatarsal space caused by the removal of the segment [61]. These deformities can also occur on the contralateral foot. Preferential weight bearing on this limb would lead to excessive mechanical stress on the contralateral great toe, which may contribute to the development of hallux valgus [61]. Moreover, in cases of first ray amputation, individuals tend to have a supinated foot in the absence of the metatarsal head and a portion of the metatarsal bone. This results in a lateral shift of plantar-pressure in the standing position [65]. The loss of the pivoting effect of the hallux and first toe, and the reduction in support area, results in a shift of weight to the mid-metatarsal and midfoot regions, which are not physically designed to withstand increased pressure [65]. Excessive plantar-pressure in certain areas of the foot could result in an increased risk of ulceration and subsequent amputation [65].

4.2. Interventions

This scoping review placed particular emphasis on external orthopedic devices for the rehabilitation of postural function. The efficacy of FOs, such as total-contact insoles, in managing postural deficits following a minor LEA was demonstrated in three studies [60,64,65]. The use of a therapeutic shoe with a rigid-rocker-bottom sole and a total-contact insert significantly improved function in individuals with a TMA-DM [60]. In another study, the same research team demonstrated that this same orthotic reduced maximum plantar-pressure on the residual limb compared to wearing standard shoes with toe fillers, thereby reducing the risk of skin lesions on the residual limb and foot ulcers [77]. Similarly, total-contact FOs enabled a significant redistribution of maximum plantar-pressure in ulcer-prone areas compared to a flat insole, improving both static and dynamic postural function [65]. Bayaert et al. [61] in discussing their findings, also suggested that the use of a FO could promote local tissue repair, particularly of the intermetatarsal ligament and delay the onset of contralateral mechanical problems [61]. Moreover, in a population with TMA, all participants exhibited an improvement in balance with the use of a total-contact FO, in comparison to no FO condition. [64]. In contrast, the use of AFOs, while intended to provide increased stability for the user, often caused problems in individuals with a TMA [60,64]. In both studies, between 50 % and 59 % of participants refused to wear conditions that included AFOs during the one-month adaptation period, reporting that they could not tolerate the restriction of ankle mobility [60,64]. Some exceptions were reported by the authors. Individuals with a bilateral TMA seemed to prefer shortened therapeutic shoes [60]. An individual with anterior compartment paralysis exhibited a preference for wearing AFOs conditions [60], and another with the longest duration of DM felt more balanced with the AFO than with the total-contact FO [64]. This participant also had the longest TUG time, which led the authors to suggest that the TUG might be an effective clinical test for differentiating between patients with a TMA who are likely to benefit from an AFO versus an FO design [64]. A recent study demonstrated not only an

improvement in TUG time but also improvements in gait quality, symmetry, and spatiotemporal parameters at different test phases when an individual with a tarsometatarsal amputation performed the assessment using a custom 3D-printed prosthesis [57]. The authors even report a significant improvement in the quality of life and ability to perform activities of daily living in device users [57]. During gait initiation, the use of a prosthetic shoe allowed for a smoother transition of body weight and also promoted better symmetry in weight transfer in a participant with a bilateral amputation of all toes [71]. These adjustments reduced the reliance on costly compensatory strategies, such as pivoting movements. Similarly, the forward displacement of the CoP while maintaining a static posture may represent a postural strategy to accomplish the task in a safer manner. The use of a prosthetic shoe allows for a more dynamic and efficient movement, which is typical of physically active individuals [71]. The aforementioned studies emphasize the significance of prosthetic design in enhancing postural control and functional mechanisms in individuals with a minor LEA.

Educational interventions have also demonstrated notable improvements in balance in individuals with a minor LEA [69]. The authors assert that there is a strong correlation between balance and walking in individuals with LEAs. Therefore, enhancing postural control will facilitate improved ambulation and mitigate the risk of falls and fall-related fear in individuals with a minor LEA [69]. Another study has highlighted the urgent need to consider balance training in individuals with a minor LEA, as is already provided for the rehabilitation of individuals with a major LEA [63].

4.3. Literature gaps

Seven of the studies exhibited a moderate to very low quality. The majority of studies included are case reports [57,58,66,71], pilot studies [64,67,68], or have a limited number of participants [70]. Several authors expressed concerns regarding the limited statistical power [64,67,68], and the incapacity to conduct statistical analysis [66,70], due to the limited sample sizes. This may be attributed to the inherent difficulty in recruiting patients with a minor LEA for research protocols [78]. This poor statistical power limits the ability to generalize findings [68] and optimize rehabilitation protocols.

Differences in assessment protocols, materials, and measures used make it difficult to directly compare results across studies [67,68]. The use of a single force platform may have precluded the observation of certain mechanisms and postural compensations, particularly those pertaining to AP and ML mechanisms, which require the use of two force platforms [63,79]. The majority of biomechanical studies have concentrated on the evaluation of quiet and static standing. However, the authors concur that it is crucial to examine the postural adaptations in individuals with a minor LEA in "*more stressful situations*" [61] or in "*dynamic balance and dual-task conditions*" [63].

Some studies lack matched control groups [61,65] or comparisons with other LEA levels, which limits the ability to specifically attribute observed effects to the intervention or LEA level [67]. Kanade et al. [62,63] included individuals with various levels of minor LEAs in the "*partial foot amputation*" group, which obscured the specific characteristics associated with each type of minor LEAs. Furthermore, the populations studied are often specific and mainly composed of patients with DM [57,59,60,62–64,66,69], which limits our understanding of the impact of minor LEAs on postural control in individuals without systemic complications [59]. To the best of our knowledge, no study has yet compared postural control between a population with a minor LEA-DM and a population with a minor traumatic LEA, nor has any study examined the differences associated between several minor LEAs level.

Finally, longitudinal research on the long-term effects of interventions remains underexplored. Studies mainly focus on the immediate benefits of the intervention [57,58,65,71], with limited attention paid to long-term adaptive processes and the potential influence on individuals' quality of life [61,69]. Toygar et al. [69], only performed the BBS measurement three days after the operation, which may not reflect the patient's long-term state in terms of balance. A longer-term evaluation or reassessment would have provided further evidence as to the persistence of the educational effect over time. Similarly, Spaulding et al. [64], recorded TUG time during the inclusion visit "*in the hope of using this as a pre-prescription analysis*". However, the measurement was not reassessed after the acclimatization period to the orthotics solutions. Additionally, there is a notable lack of rigorous comparative studies, particularly between different prosthetic or orthotic, to determine which is best suited to specific needs, such as the level or etiology of minor LEAs, the most recent dates back to the last century and only looked at TMA-DM individuals [60]. Robust longitudinal studies are therefore required in order to gain insight into the progression of postural impairments in individuals with a minor LEA and to ascertain the long-term efficacy of rehabilitation interventions.

4.4. Perspectives

These limitations underscore several research priorities. It is recommended that future studies aim to recruit larger samples, including diverse subgroups, to ensure representation across different LEAs etiologies, including traumatic and vascular cases, as well as varying levels of LEAs. Longitudinal designs are essential for understanding the adaptive processes that occur over time and for evaluating the sustained efficacy of interventions, particularly in the case of custom FOs.

The integration of advanced biomechanical analysis tools, including motion capture, EMG, and dual force plates, will facilitate a more detailed comprehension of compensatory postural strategies. Research should incorporate dynamic balance assessments, such as TUG and FRT, which are well-suited for evaluating fall risk and balance in individuals with postural control disorders [42]. The TUG is particularly valuable as it encompasses a range of challenging tasks, including sit-to-stand transitions, gait initiation, and turns, which are frequently impaired in individuals with a LEA [57,71]. Instrumentation of such tests would provide reliable and repeatable biomechanical data on dynamic postural control in individuals with a minor LEA [80–82].

Personalized orthotic solutions should be evaluated not only for their biomechanical benefits, but also for their impact on functional independence and quality of life. Future studies should use validated clinical scales [42], to complement objective biomechanical assessments with subjective assessments of balance and confidence.

4.5. Limitations

Significant heterogeneity in methodologies, participant characteristics, and LEAs levels precluded the possibility of conducting meta-analyses, thereby limiting the ability to quantitatively synthesize findings. The review was limited to articles published in French and English, which may have excluded relevant studies published in other languages.

5. Conclusion

This scoping review highlights the significant postural deficits associated with minor LEAs and emphasizes the potential of various orthotic and prosthetic interventions to mitigate these challenges. Distances reached by this population were 64 % shorter on the FRT test, TUG times were 36 % slower, and there were an increased CoP excursions while standing quietly, indicating a high risk of falling and significant postural control imbalance. However, methodological limitations such as heterogeneous protocols and various outcomes measurements limit the generalizability of the current findings. The interventions tend to demonstrate efficacy in improving postural control in individuals with a minor LEA. However, given limited high-quality evidence, small overall sample sizes, heterogeneity of interventions, and short or absence of longitudinal assessments, our findings should be interpreted with caution and should not be considered conclusive

regarding the effectiveness of the intervention. Future research should focus on larger, diverse subgroups of minor LEAs, longitudinal outcomes, advanced biomechanical assessments, and comprehensive evaluations of functional and psychosocial outcomes. A more comprehensive understanding of the postural mechanisms affected in minor LEAs could improve care and quality of life in individuals with such conditions.

CRediT authorship contribution statement

Maxime Acien: Writing – original draft, Visualization, Methodology, Investigation, Conceptualization. **Gabriel Moisan:** Writing – review & editing, Supervision, Project administration, Funding acquisition. **Virginie Blanchette:** Writing – review & editing, Funding acquisition. **Ahmed Dami:** Writing – review & editing, Investigation.

Funding

This project is supported by a grant from War Amps Canada and the Fonds de Recherche du Québec-Santé awarded to GM (https://doi.org/10.69777/347697) and VB (https://doi.org/10.69777/347730). The funding agreement ensures the authors' independence in designing the study, writing, and publishing this article.

Declaration of Competing Interest

We wish to confirm that there are no known conflicts of interest associated with this publication, and there has been no significant financial support for this work that could have influenced its outcome.

We confirm that the manuscript has been thoroughly read and approved by all named authors and that there are no other individuals who meet the authorship criteria but are not listed. Furthermore, the order of authors listed in the manuscript has been collectively agreed upon by all contributors.

We have given due consideration to the protection of intellectual property associated with this work, ensuring that there are no impediments to its publication, including timing-related concerns. All institutional regulations concerning intellectual property have been duly followed.

We understand that the Corresponding Author is the primary contact during the editorial process, including communications via the Editorial Manager system and direct correspondence with the editorial office. The Corresponding Author assumes responsibility for keeping all co-authors informed about the progress of the submission, revisions, and final approval of proofs.

We confirm that the Corresponding Author has provided a valid and active email address, accessible for communications regarding this manuscript: maxime.acien@uqtr.ca

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2025.08.064.

References

[1] J.J. Van Netten, S.A. Bus, J. Apelqvist, P. Chen, V. Chuter, R. Fitridge, et al., Definitions and criteria for diabetes-related foot disease (IWGDF 2023 update), Diabetes Metab. Res. Rev. 40 (3) (2024) e3654, https://doi.org/10.1002/dmrr.3654.

[2] S. van Twillert, I. Stuive, J.H. Geertzen, K. Postema, A.T. Lettinga, Functional performance, participation and autonomy after discharge from prosthetic rehabilitation: barriers, facilitators and outcomes, J. Rehabil. Med. 46 (9) (2014) 915–923, https://doi.org/10.2340/16501977-1846.

[3] J.M.P. de Godoy, D. Braile, S. Buzatto, O. Longo, O. Fontes, Quality of life after amputation, Psychol. Health Med. 7 (4) (2002) 397–400, https://doi.org/10.1080/1354850021000015212.

[4] M. Quigley, M.P. Dillon, Quality of life in persons with partial foot or transtibial amputation: a systematic review, Prosthet. Orthot. Int. 40 (1) (2016) 18–30, https://doi.org/10.1177/0309364614546526.

[5] B. Imam, W.C. Miller, H.C. Finlayson, J.J. Eng, T. Jarus, Incidence of lower limb amputation in Canada, Can. J. Public Health 108 (2017) 374–380, https://doi.org/10.17269/CJPH.108.6093.

[6] M. Narres, T. Kvitkina, H. Claessen, S. Droste, B. Schuster, S. Morbach, et al., Incidence of lower extremity amputations in the diabetic compared with the non-diabetic population: a systematic review, PLoS One 12 (8) (2017) e0182081, https://doi.org/10.1371/journal.pone.0182081.

[7] W. Animaw, Y. Seyoum, Increasing prevalence of diabetes mellitus in a developing country and its related factors, PloS One 12 (11) (2017) e0187670, https://doi.org/10.1371/journal.pone.0187670.

[8] M.A. Eid, K.S. Mehta, P.P. Goodney, Epidemiology of peripheral artery disease, Semin Vasc. Surg. 34 (1) (2021) 38–46, https://doi.org/10.1053/j.semvascsurg.2021.02.005.

[9] J. Liu, Z.-H. Ren, H. Qiang, J. Wu, M. Shen, L. Zhang, J. Lyu, Trends in the incidence of diabetes mellitus: results from the global burden of disease study 2017 and implications for diabetes mellitus prevention, BMC Public Health 20 (1) (2020) 1415, https://doi.org/10.1186/s12889-020-09502-x.

[10] M.A. Hussain, M. Al-Omran, K. Salata, A. Sivaswamy, T.L. Forbes, N. Sattar, et al., Population-based secular trends in lower-extremity amputation for diabetes and peripheral artery disease, CMAJ 191 (35) (2019) E955–E961, https://doi.org/10.1503/cmaj.190134.

[11] M. Spoden, U. Nimptsch, T. Mansky, Amputation rates of the lower limb by amputation level–observational study using German national hospital discharge data from 2005 to 2015, BMC Health Serv. Res 19 (2019) 1–9, https://doi.org/10.1186/s12913-018-3759-5.

[12] H. Coman, B. Stancu, N.A. Gâvan, F.L. Bowling, L. Podariu, C.I. Bondor, G. Radulian, Diabetes-Related lower extremity amputations in Romania: patterns and changes between 2015 and 2019, Int. J. Environ. Res Public Health 20 (1) (2022) 557, https://doi.org/10.3390/ijerph20010557.

[13] M.P. Dillon, T.M. Barker, Preservation of residual foot length in partial foot amputation: a biomechanical analysis, Foot Ankle Int. 27 (2) (2006) 110–116, https://doi.org/10.1177/107110070602700207.

[14] Y. Sonoda, N. Maeshige, M. Uemura, S. Imaoka, N. Kawabe, H. Hayashi, et al., Effect of partial foot amputation level on gait independence in patients with chronic lower extremity wounds: a retrospective analysis of a Japanese multicenter database, 15347346231158864, Int. J. Low. Extrem Wounds (2023), https://doi.org/10.1177/15347346231158864.

[15] B.G. Bardy, W.H. Warren, B.A. Kay, The role of central and peripheral vision in postural control during walking, Percept. Psychophys. 61 (7) (1999) 1356–1368, https://doi.org/10.3758/BF03206186.

[16] H.-C. Diener, J. Dichgans, On the role of vestibular, visual and somatosensory information for dynamic postural control in humans, Prog. Brain Res. 76 (1988) 253–262, https://doi.org/10.1016/S0079-6123(08)64512-4.

[17] F.B. Horak, Postural orientation and equilibrium: what do we need to know about neural control of balance to prevent falls? Age Ageing 35 (_2) (2006) ii7–ii11, https://doi.org/10.1093/ageing/afl077.

[18] M.S. Tomomitsu, A.C. Alonso, E. Morimoto, T.G. Bobbio, J. Greve, Static and dynamic postural control in low-vision and normal-vision adults, Clin. Sci. 68 (2013) 517–521, https://doi.org/10.6061/clinics/2013(04)13.

[19] F. Black, C. Shupert, F. Horak, L. Nashner, Abnormal postural control associated with peripheral vestibular disorders, Prog. Brain Res. 76 (1988) 263–275, https://doi.org/10.1016/S0079-6123(08)64513-6.

[20] A. Kavounoudias, J.C. Gilhodes, R. Roll, J.P. Roll, From balance regulation to body orientation: two goals for muscle proprioceptive information processing? Exp. Brain Res. 124 (1) (1999) 80–88, https://doi.org/10.1007/s002210050602.

[21] A. Kavounoudias, R. Roll, J.P. Roll, The plantar sole is a 'dynamometric map' for human balance control, Neuroreport 9 (14) (1998) 3247–3252, https://doi.org/10.1097/00001756-199810050-00021.

[22] A. Kavounoudias, R. Roll, J.P. Roll, Foot sole and ankle muscle inputs contribute jointly to human erect posture regulation, J. Physiol. 532 (3) (2001) 869–878, https://doi.org/10.1111/j.1469-7793.2001.0869e.x.

[23] R.W.M. Van Deursen, G. Simoneau, Foot and ankle sensory neuropathy, proprioception, and postural stability, J. Orthop. Sports Phys. Ther. 29 (12) (1999) 718–726. ⟨https://www.jospt.org/doi/10.2519/jospt.1999.29.12.718⟩.

[24] P. Gatev, S. Thomas, T. Kepple, M. Hallett, Feedforward ankle strategy of balance during quiet stance in adults, J. Physiol. 514 (3) (1999) 915–928, https://doi.org/10.1111/j.1469-7793.1999.915ad.x.

[25] B.E. Maki, W.E. McIlroy, The role of limb movements in maintaining upright stance: the "change-in-support" strategy, Phys. Ther. 77 (5) (1997) 488–507, https://doi.org/10.1093/ptj/77.5.488.

[26] J.M. Haddad, S. Rietdyk, L.J. Claxton, J.E. Huber, Task-dependent postural control throughout the lifespan, Exerc Sport Sci. Rev. 41 (2) (2013) 123–132, https://doi.org/10.1097/JES.0b013e3182877cc8.

[27] J. Johansson, A. Nordström, Y. Gustafson, G. Westling, P. Nordström, Increased postural sway during quiet stance as a risk factor for prospective falls in community-dwelling elderly individuals, Age Ageing 46 (6) (2017) 964–970, https://doi.org/10.1093/ageing/afx083.

[28] L. Pizzigalli, A. Filippini, S. Ahmaidi, H. Jullien, A. Rainoldi, Prevention of falling risk in elderly people: the relevance of muscular strength and symmetry of lower limbs in postural stability, J. Strength Cond. Res. 25 (2) (2011) 567–574, https://doi.org/10.1519/JSC.0b013e3181d32213.

[29] C.R. Claret, G.W. Herget, L. Kouba, D. Wiest, J. Adler, V. von Tscharner, et al., Neuromuscular adaptations and sensorimotor integration following a unilateral transfemoral amputation, J. Neuroeng. Rehabil. 16 (2019) 1–11, https://doi.org/10.1186/s12984-019-0586-9.

[30] E. Isakov, J. Mizrahi, H. Ring, Z. Susak, N. Hakim, Standing sway and weight-bearing distribution in people with below-knee amputations, Arch. Phys. Med. Rehabil. 73 (2) (1992) 174–178. ⟨https://pubmed.ncbi.nlm.nih.gov/1543414/⟩.

[31] T.M. Quai, S.G. Brauer, J.C. Nitz, Somatosensation, circulation and stance balance in elderly dysvascular transtibial amputees, Clin. Rehabil. 19 (6) (2005) 668–676, https://doi.org/10.1191/0269215505cr857oa.

[32] A. Geurts, T.W. Mulder, B. Nienhuis, R. Rijken, Dual-task assessment of reorganization of postural control in persons with lower limb amputation, Arch. Phys. Med. Rehabil. 72 (13) (1991) 1059–1064. ⟨https://pubmed.ncbi.nlm.nih.gov/1741657/⟩.

[33] P. Jayakaran, G.M. Johnson, S.J. Sullivan, Postural control in response to altered sensory conditions in persons with dysvascular and traumatic transtibial amputation, Arch. Phys. Med. Rehabil. 96 (2) (2015) 331–339, https://doi.org/10.1016/j.apmr.2014.09.037.

[34] G.R. Fernie, P.J. Holliday, Postural sway in amputees and normal subjects, J. Bone Jt. Surg. 60 (7) (1978) 895–898. ⟨https://pubmed.ncbi.nlm.nih.gov/701337/⟩.

[35] I. Gaunaurd, R. Gailey, B.J. Hafner, O. Gomez-Marin, N. Kirk-Sanchez, Postural asymmetries in transfemoral amputees, Prosthet. Orthot. Int. 35 (2) (2011) 171–180, https://doi.org/10.1177/0309364611407676.

[36] A. Aruin, J. Nicholas, M.L. Latash, Anticipatory postural adjustments during standing in below-the-knee amputees, Clin. Biomech. (Bristol Avon) 12 (1) (1997) 52–59, https://doi.org/10.1016/S0268-0033(96)00053-8.

[37] K.E. Wagner, L.A. Nolasco, D.C. Morgenroth, D.H. Gates, A.K. Silverman, The effect of lower-limb prosthetic alignment on muscle activity during sit-to-stand, J. Electro Kinesiol 51 (2020) 102398, https://doi.org/10.1016/j.jelekin.2020.102398.

[38] D.W. Zochodne, Diabetes mellitus and the peripheral nervous system: manifestations and mechanisms, Muscle Nerve 36 (2) (2007) 144–166, https://doi.org/10.1002/mus.20785.

[39] Y. Hermodsson, C. Ekdahl, B. Persson, G. Roxendal, Standing balance in trans-tibial amputees following vascular disease or trauma: a comparative study with healthy subjects, Prosthet. Orthot. Int. 18 (3) (1994) 150–158, https://doi.org/10.3109/03093649409164400.

[40] S.W. Hunter, F. Batchelor, K.D. Hill, A.-M. Hill, S. Mackintosh, M. Payne, Risk factors for falls in people with a lower limb amputation: a systematic review, e1, PM R. 9 (2) (2017) 170–180, https://doi.org/10.1016/j.pmrj.2016.07.531.

[41] P. Jayakaran, G.M. Johnson, S.J. Sullivan, J.C. Nitz, Instrumented measurement of balance and postural control in individuals with lower limb amputation: a critical review, Int. J. Rehabil. Res. 35 (3) (2012) 187–196, https://doi.org/10.1097/MRR.0b013e3283550ff9.

[42] R. Johansson, L. Jensen, C.T. Barnett, D.F. Rusaw, Quantitative methods used to evaluate balance, postural control, and the fear of falling in lower limb prosthesis users: a systematic review, Prosthet. Orthot. Int 47 (6) (2023) 586–598, https://doi.org/10.1097/PXR.0000000000000250.

[43] P.X. Ku, N.A.A. Osman, W.A.B.W. Abas, Balance control in lower extremity amputees during quiet standing: a systematic review, Gait Posture 39 (2) (2014) 672–682, https://doi.org/10.1016/j.gaitpost.2013.07.006.

[44] M. Seth, E. Lamberg, Standing balance in people with trans-tibial amputation due to vascular causes: a literature review, Prosthet. Orthot. Int. 41 (4) (2017) 345–355, https://doi.org/10.1177/0309364616683819.

[45] M.P. Dillon, S. Fatone, M.C. Hodge, Biomechanics of ambulation after partial foot amputation: a systematic literature review, J. Prosthet. Orthot. 19 (8) (2007) P2–P61, https://doi.org/10.1097/JPO.0b013e3180ca8694.

[46] F.C.L. De Oliveira, S. Williamson, C.L. Ardern, K. Fagher, N. Heron, D.C.C.J. Van Rensburg, et al., Association between the level of partial foot amputation and gait: a scoping review with implications for the minimum impairment criteria for wheelchair tennis, Br. J. Sports Med. 57 (4) (2023) 237–248, https://doi.org/10.1136/bjsports-2022-105650.

[47] M.P. Dillon, M. Quigley, S. Fatone, Outcomes of dysvascular partial foot amputation and how these compare to transtibial amputation: a systematic review for the development of shared decision-making resources, Syst. Rev. 6 (2017) 1–20, https://doi.org/10.1186/s13643-017-0433-7.

[48] K.M. Anderson, R.E. Evans, C.E. Connerly, M. Pacha, J.M. Wilken, Custom dynamic orthoses and physical therapist intervention for bilateral midfoot amputation: a case report, Phys. Ther. 101 (4) (2021) pzab028, https://doi.org/10.1093/ptj/pzab028.

[49] M.L.G. Fernandez, R.M. Lozano, M.I.G.-Q. Diaz, M.A.G. Jurado, D.M. Hernandez, J. V.B. Montesinos, How effective is orthotic treatment in patients with recurrent diabetic foot ulcers? J. Am. Podiatr. Med. Assoc. 103 (4) (2013) 281–290, https://doi.org/10.7547/1030281.

[50] D.J. Janisse, E.J. Janisse, Shoes, orthoses, and prostheses for partial foot amputation and diabetic foot infection, Foot Ankle Clin. 15 (3) (2010) 509–523, https://doi.org/10.1016/j.fcl.2010.04.004.

[51] A. Aboutorabi, M. Bahramizadeh, M. Arazpour, R. Fadayevatan, F. Farahmand, S. Curran, S.W. Hutchins, A systematic review of the effect of foot orthoses and shoe characteristics on balance in healthy older subjects, Prosthet. Orthot. Int. 40 (2) (2016) 170–181.

[52] H. Arksey, L. O'Malley, Scoping studies: towards a methodological framework, Int. J. Soc. Res. Method. 8 (1) (2005) 19–32, https://doi.org/10.1080/1364557032000119616.

[53] D. Levac, H. Colquhoun, K.K. O'brien, scoping studies: advancing the methodology, Implement Sci. 5 (2010) 1–9, https://doi.org/10.1186/1748-5908-5-69.

[54] A.C. Tricco, E. Lillie, W. Zarin, K.K. O'Brien, H. Colquhoun, D. Levac, et al., PRISMA extension for scoping reviews (PRISMA-ScR): checklist and explanation, Ann. Intern Med. 169 (7) (2018) 467–473, https://doi.org/10.7326/M18-0850.

[55] M. Acien, A. Dami, V. Blanchette, G. Moisan, Postural control imbalance in individuals with a minor lower extremity amputation: a scoping review protocol, F1000Research 13 (2025) 309.

[56] Joanna Briggs Institute, Critical appraisal tools. ⟨https://jbi.global/critical-appraisal-tools⟩, 2016 (accessed).

[57] C. Novo, W. Haller, E. Ruiz, Development and functional validation of tarsometatarsal prosthesis, Appl. Bionics Biomech. 7 (1) (2023) 124–131, https://doi.org/10.15406/mojabb.2023.07.00185.

[58] A. Parent, A. Pouliot-Laforte, M. Laberge, R. Hamdy, R. Rochelle, L. Ballaz, Articulated vs. Fixed carbon-fibre prosthesis after transmetatarsial amputation: a case study, Comput. Methods Biomech. Biomed. Eng. 17 (sup1) (2014) 106–107, https://doi.org/10.1080/10255842.2014.931384.

[59] M.J. Mueller, G.B. Salsich, M.J. Strube, Functional limitations in patients with diabetes and transmetatarsal amputations, Phys. Ther. 77 (9) (1997) 937–943, https://doi.org/10.1093/ptj/77.9.937.

[60] M.J. Mueller, M.J. Strube, Therapeutic footwear: enhanced function in people with diabetes and transmetatarsal amputation, Arch. Phys. Med. Rehabil. 78 (9) (1997) 952–956, https://doi.org/10.1016/S0003-9993(97)90056-3.

[61] C. Beyaert, S. Henry, G. Dautel, N. Martinet, F. Beltramo, P. Lascombes, J.-M. André, Effect on balance and gait secondary to removal of the second toe for digital reconstruction: 5-year follow-up, J. Pedia Orthop. 23 (1) (2003) 60–64, https://doi.org/10.1097/00004694-200301000-00012.

[62] R.V. Kanade, Functional outcome in people with diabetic neuropathy at four stages of foot complications, Cardiff University (United Kingdom), 2006.

[63] R. Kanade, R.W.M. Van Deursen, K.G. Harding, P.E. Price, Investigation of standing balance in patients with diabetic neuropathy at different stages of foot complications, Clin. Biomech. 23 (9) (2008) 1183–1191, https://doi.org/10.1016/j.clinbiomech.2008.06.004.

[64] S.E. Spaulding, T. Chen, L.-S. Chou, Selection of an above or below-ankle orthosis for individuals with neuropathic partial foot amputation: a pilot study, Prosthet. Orthot. Int. 36 (2) (2012) 217–224, https://doi.org/10.1177/0309364612437005.

[65] R. El-Hilaly, O. Elshazly, A. Amer, The role of a total contact insole in diminishing foot pressures following partial first ray amputation in diabetic patients, Foot 23 (1) (2013) 6–10, https://doi.org/10.1016/j.foot.2012.10.002.

[66] B. Diot, P. Halavackova, J. Demongeot, N. Vuillerme, Sensory substitution for balance control using a vestibular-to-tactile device, Multisens. Res. 27 (5-6) (2014) 313–336, https://doi.org/10.1163/22134808-00002458.

[67] E. Feick, P.-R. Hamilton, M. Luis, M. Corbin, N.M. Salback, R. Torres-Moreno, J. Andrysek, A pilot study examining measures of balance and mobility in children with unilateral lower-limb amputation, Prosthet. Orthot. Int. 40 (1) (2016) 65–74, https://doi.org/10.1177/0309364614560941.

[68] M.D. Geil, K.J. Wasco, J. Wu, C. Coulter, Z. Safaeepour, Y.T. Wang, A pilot investigation of the effect of postural control strategies and balance in children with unilateral lower-limb amputation, JPO J. Prosthet. Orthot. 28 (4) (2016) 180–185, https://doi.org/10.1097/JPO.0000000000000105.

[69] İ. Toygar, S. Suçeken, F. Eti Aslan, M.E. Çelebi, S. Batar, Effect of the educational intervention on the balance of diabetic foot amputees: a randomized controlled study, 15347346231171436, Int. J. Low. Extrem Wounds (2023), https://doi.org/10.1177/15347346231171436.

[70] C. Slater, B.J. Hafner, S.J. Morgan, Effects of high-profile crossover feet on gait biomechanics in 2 individuals with syme amputation, Prosthet. Orthot. Int. 48 (5) (2024) 510–518, https://doi.org/10.1097/PXR.0000000000000295.

[71] J.L. Storniolo, V. Farinelli, M. Onesti, L. Correale, L.A. Peyré-Tartaruga, R. Esposti, P. Cavallari, Case report: new perspectives on gait initiation strategies from a case of full toes amputation in a professional mountain climber, Front. Hum. Neurosci. 18 (2024) 1463249, https://doi.org/10.3389/fnhum.2024.1463249.

[72] Y. He, F. Pu, F. Wu, S. Li, D. Li, Y. Fan, Frequency spectral characteristics of standing balance with partial foot support, 3rd Int. Conf. Biomed. Eng. Inform. 5 (2010) 1827–1830, https://doi.org/10.1109/BMEI.2010.5639977.

[73] S.W. Chou, H.Y.K. Cheng, J.H. Chen, Y.Y. Ju, Y.C. Lin, M.K.A. Wong, The role of the great toe in balance performance, J. Orthop. Res. 27 (4) (2009) 549–554, https://doi.org/10.1002/jor.20661.

[74] E. Katoulis, M. Ebdon-Parry, S. Hollis, A. Harrison, L. Vileikyte, J. Kulkarni, A. Boulton, Postural instability in diabetic neuropathic patients at risk of foot ulceration, Diabet. Med. 14 (4) (1997) 296–300, https://doi.org/10.1002/(SICI)1096-9136(199704)14:4%3C296::AID-DIA344%3E3.0.CO;2-5.

[75] S. Feldman-Billard, B. Dupas, Eye disorders other than diabetic retinopathy in patients with diabetes, Diabet. Metab. 47 (6) (2021) 101279, https://doi.org/10.1016/j.diabet.2021.101279.

[76] A. Kovacova, K. Shotliff, Eye problems in people with diabetes: more than just diabetic retinopathy, 34-39a, Pr. Diabetes 39 (1) (2022), https://doi.org/10.1002/pdi.2378.

[77] M.J. Mueller, M.J. Strube, B.T. Allen, Therapeutic footwear can reduce plantar pressures in patients with diabetes and transmetatarsal amputation, Diabetes Care 20 (4) (1997) 637–641, https://doi.org/10.2337/diacare.20.4.637.

[78] R. Kanade, R.W.M. Van Deursen, K.G. Harding, P.E. Price, Difficulties in recruiting subjects with partial foot amputations for kinesiological research, Foot 16 (4) (2006) 224–225, https://doi.org/10.1016/j.foot.2006.08.002.

[79] D.A. Winter, F. Prince, J.S. Frank, C. Powell, K.F. Zabjek, Unified theory regarding A/P and M/L balance in quiet stance, J. Neurophysiol. 75 (6) (1996) 2334–2343, https://doi.org/10.1152/jn.1996.75.6.2334.

[80] P. Ortega-Bastidas, B. Gomez, P. Aqueveque, S. Luarte-Martinez, R. Cano-de-la-Cuerda, Instrumented timed up and go test (itug)—More than assessing time to

predict falls: a systematic review, Sensors 23 (7) (2023) 3426, https://doi.org/10.3390/s23073426.
[81] E. Maranesi, F. Di Nardo, R. Rabini, G. Ghetti, L. Burattini, O. Mercante, S. Fioretti, Muscle activation patterns related to diabetic neuropathy in elderly subjects: a functional reach test study, Clin. Biomech. (Bristol Avon) 32 (2016) 236–240, https://doi.org/10.1016/j.clinbiomech.2015.11.005.
[82] E. Maranesi, G. Ghetti, R.A. Rabini, S. Fioretti, Functional reach test: movement strategies in diabetic subjects, Gait Posture 39 (1) (2014) 501–505, https://doi.org/10.1016/j.gaitpost.2013.08.035.