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Scoping Review

A scoping review on the roles of foot and ankle proprioception and sensitivity related to postural control during upright standing

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HIGHLIGHTS

- The interplay between somatosensation and postural control is critical for biomechanics.
- The omission of foot and ankle proprioception biases studies of postural control.
- Integrating biomechanics with neurophysiological measures is crucial to study postural control.
- We recommend including proprioceptive and sensory evaluations in postural studies.

ABBREVIATIONS

CoP	Center of Pressure
DPN	Diabetic peripheral neuropathy
GRF	Ground reaction forces
LoS	Limits of stability
SND	Sensory neuron disease
WBV	Whole-body vibration

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BACKGROUND: Somatosensory information (sensitivity of proprioceptive and cutaneous aspects) is crucial for maintaining a stable upright posture, especially in aging and neurodegenerative diseases. Furthermore, studies implement interventions to manipulate somatosensory inputs to understand the role of sensory information on postural control.
AIM: In this scoping review we aimed to discuss how studies on postural control in upright standing incorporate both biomechanical parameters and somatosensory variables related to the foot and ankle. We explored this in the context of three sub-questions regarding aging, neuropathic conditions (mainly diabetes-induced), and sensory interventions / manipulations.
METHODS: A literature review was conducted using PubMed/MEDLINE. Eligible studies quantitatively examined postural control using biomechanical measures (e.g., center of pressure, CoP) in conjunction with somatosensory assessments (e.g., proprioception, cutaneous sensitivity) of the lower extremities.
RESULTS: The literature search identified 1,355 potentially relevant articles, of which 49 met the inclusion criteria. Most of these studies used the CoP as a biomechanical indicator of balance, while somatosensory assessment methods varied substantially across studies. Quiet upright standing was the predominant postural task with trials lasting on average 30 seconds. Only a minority of studies directly analyzed the relationship between biomechanical and sensory measures. We also show an overview of the most common experimental setups in recent decades and propose suggestions for future research.
INTERPRETATION: Whilst biomechanical analyses commonly focus on CoP as a key measure of balance, foot and ankle somatosensory assessments vary greatly, which could bias participant recruitment and study outcomes. We conclude that a methodological approach integrating biomechanics with neurophysiological measurements is crucial for a more comprehensive understanding of postural responses and recommends its consideration in future studies. Additionally, future studies should aim to standardize somatosensory assessments to improve the reliability of biomechanical findings in studies addressing postural control.

KEYWORDS: Lower extremity biomechanics | Balance | Posture | Somatosensory system | Proprioception | Cutaneous sensitivity

INTRODUCTION

Standing posture can be evaluated using biomechanical tools to quantify balance, a generic term describing the dynamics of body posture to prevent falling, being related to the inertial forces acting on the body and the inertial characteristics of body segments [1]. More recently, a study [2] has expanded this understanding by distinguishing two levels within the postural control system: one level governs the distribution of tonic muscle activity to maintain a stable posture, while the other is responsible for compensating for both internal and external perturbations, ensuring equilibrium is maintained. Biomechanical methods describe postural control by evaluating the characteristics of kinematics (movement patterns), kinetics (forces and moments), and muscular electrical activity (electromyography). However, several other components define the successes and failures in sustaining a stable upright position, e.g., reflexes and somatosensory afferent inputs [2]. These components are not always considered in studies focused on the biomechanical aspects of balance performance and may influence outcomes from participant recruitment to data analysis.

Intact postural control is widely recognized to primarily rely on afferent information from the vestibular, visual, and somatosensory systems [3–6]. Inputs of the sensory system influence both voluntary and involuntary motor actions, allowing the body to adapt and interact effectively with the world, whether through conscious movements or reflexive responses [7]. The somatosensory system detects cutaneous sensitivity inputs and proprioception [8]. While proprioception refers to the ability to perceive body movement and position, cutaneous sensitivity is responsible for perceiving touch, vibration, or pain [7]. Somatosensation is mediated by various mechanoreceptors divided into proprioceptors located in muscles (e.g., muscle spindles), tendons (e.g., Golgi-tendon organs), and joints (e.g., joint receptors, Ruffini endings); and cutaneous receptors (e.g., Pacinian or Meissner corpuscles) [9]. These organs are distributed throughout the human body, but in studies of postural control, the feet - being in contact with the ground and supporting body mass - are particularly important. This highlights the relevance of the feet as a key site for somatosensory input critical for identifying vertical body posture.

The abundance of somatosensory receptors in the foot and ankle complex plays a vital role in postural control by helping the body to control its position during standing and dynamic activities [9]. Joint receptors in the foot and ankle, including Ruffini endings, provide essential feedback on the joint angle and movement, which help regulate the body's position relative to the ground. This proprioceptive input allows for rapid adjustments to prevent falls, especially in response to changes in surface stability or unexpected perturbations. Studies have shown that disruptions in foot and ankle proprioception can lead to impaired balance and increased postural sway, underscoring its critical role in postural stability [10,11]. However, it is notable that studies addressing postural control and aging, for example, consider different characteristics of the participants (such as physical activity level, strength, among others), but in many cases do not mention any concern regarding disruptions in foot and ankle proprioception.

Impaired somatosensory inputs may emerge due to aging and neurodegenerative diseases. Regarding aging, the functional capacity of sensory receptors and afferent pathways to detect and provide reliable foot and ankle information is reduced in older adults. This reduction in sensory feedback can impair postural control and increase the risk of falls [12]. Similarly, neurodegenerative diseases, like diabetic peripheral neuropathy (DPN), also challenge postural control due to a reduced availability of somatosensory information, especially in the lower leg [10,13–21]. In addition to aging and DPN, various experimental methods have been used to explore the role of somatosensory information in postural control. To better understand the influence of plantar sensitivity and proprioception on balance, researchers have manipulated afferent sensory input in healthy participants by using techniques that either reduce (e.g., ischemia or cooling) or enhance (e.g., vibration or electrical stimulation) sensory activity. These methods allow for the examination of how changes in somatosensory feedback affect postural stability under different balance conditions [22–25].

Given the influence of somatosensory information on postural control, with regard to the context of aging, DPN, and manipulation of afferent information, it would be interesting to investigate biomechanical parameters related to postural control as well as neurophysiological variables related to somatosensory foot and ankle information in previous studies. In our scoping review paper, we intend to identify the methods employed in the studies reviewed. Furthermore, we aim to analyze how biomechanical studies of upright standing incorporate somatosensory (foot and ankle) parameters within the three contexts: aging, DPN, and afferent manipulations.

METHODS

Identifying the research question

Our general research question was: "How do studies in the field of upright standing incorporate biomechanical and somatosensory information from the foot and ankle?" Following this initial question, three sub-questions according to the above-mentioned contexts were identified to guide the searches:

1. How do studies including individuals experiencing aging incorporate biomechanical and somatosensory information from the foot and ankle?
2. How do studies including individuals with (diabetic) neuropathies incorporate biomechanical and somatosensory information from the foot and ankle?
3. How do studies including acute afferent manipulations incorporate biomechanical and somatosensory information from the foot and ankle?

Eligibility criteria for selection of studies

A study was included if it combined the following specific biomechanical measures of postural control with measures of proprioception and/or cutaneous sensitivity of the lower extremities: the center of pressure (CoP), ground reaction forces (GRF), joint angles and angular velocity, or muscle activation via electromyography, for example. Cutaneous sensitivity refers to the perception of touch, pressure, and vibration, while proprioception relates to the awareness of joint position and movement. Studies were included only if they involved human participants, if the manuscript reported results of empirical research based on quantitative data, and if the manuscript was written in English. Any titles or abstracts that did not meet at least one of the inclusion criteria were excluded.

Additionally, general exclusion criteria were the involvement of purely qualitative measurements or clinical tests (such as the timed up-and-go test and sit-to-stand test), gait and stepping analyses, as well as single-case studies (see Table 1 for details).

Table 1. Overview of the inclusion criteria for studies selected in this scoping review.

Eligibility Criteria	Inclusion	Exclusion
Population	Human participants	Animal studies, participants with conditions not relevant to the review's focus (e.g., non-neuropathic conditions)
Parameters of Interest	Studies examining biomechanical measures of postural control and somatosensory information	Studies focusing only on qualitative data, clinical tests (e.g., timed up-and-go, sit-to-stand), or gait and stepping analyses
Study Design	Empirical research, including experimental or observational studies	Single-case studies, reviews, and purely theoretical work
Language and Publication Type	English-language publications of full research papers	Non-English studies, conference abstracts, editorials, or unpublished theses

For the sub-question 1, related to aging, the following exclusion criteria were applied: studies that did not include older adults (older than 65 years old) or those incorporating participants with pathology, studies assessing the effects of acute or chronic interventions (for example, training, physical exercise, foot warming, massage, among others) or the effects of sensory manipulation on balance (for example, vision, different surfaces, different shoes, movement perturbation). For sub-question 2, related to neuropathies, studies that did not specify the reason for the neuropathy were excluded. However, studies explicitly stating that the neuropathy was induced by other causes other than diabetes (e.g., alcohol or chemotherapies) were also excluded. For sub-question 3, regarding the manipulation of afferent responses in the lower limbs, studies including alterations to other afferent information sources (such as vestibular or visual manipulations) or manipulations in certain parts of the body (e.g., spinal or neck manipulations) were also excluded, even if somatosensory manipulations were performed in isolation. This ensured our focus remained solely on somatosensory contributions to postural control.

Searches and article selection

The PubMed/MEDLINE search engine was used to conduct the literature search. The searches were undertaken in the second semester of 2023 without restrictions on the publication date. During the article selection, there was no blinding regarding information about the study author, institution, or journal. For the search of the three main sub-questions, three blocks of keywords were formulated, whereby the combination of words related to the subject somatosensation, as well as balance and postural control, were repeated for all three blocks. Supplemental material 1 details the keyword combination used. Initially, titles and abstracts of the studies found were analyzed considering the inclusion and exclusion criteria. The full texts were downloaded and analyzed to apply the eligibility criteria. Relevant papers in the reference list of the selected papers were added separately.

Charting of the data

For summarizing the outcomes from the articles selected, we defined the essential characteristics that described the main features of an article: publication year, study design, aim, participants, protocols, and key results. These data were extracted from each study by two authors. It is important to note that information were extracted considering our interest in understanding to what extent studies consider biomechanics (such as center of pressure and ground reaction forces) and somatosensory features (such as proprioception and cutaneous sensitivity) jointly when investigating postural control. This joint consideration was central to our study selection and analysis. Other conditions or variables investigated in the selected studies, which did not directly relate to biomechanical or sensory parameters, were not explored in our review.

RESULTS

Article selection

The literature search yielded 1,355 articles. After removing 1,034 due to duplication or unmet inclusion criteria, 321 full texts were reviewed. Ultimately, 49 studies met all eligibility criteria and were included in the synthesis. The corresponding procedure is illustrated in Figure 1. Detailed information on the sub-questions aging, neuropathies, and afferent interventions / manipulations is provided in supplemental materials 2, 3, and 4.

Participant characteristics

Most studies included both male and female participants with a wide age range. Aging studies reported a mean ± standard deviation age of 64 ± 14 years, primarily involving women. Neuropathy studies involved balanced gender groups with a mean age of 62 ±

12 years, while intervention studies included participants aged 30 ± 16 years.

Postural tasks studied

The main postural task across studies was quiet upright standing, however, other protocols, such as limits of stability (LoS) and dynamic conditions, were also included. The dynamic tasks involved procedures such as unexpected external perturbations that challenged balance, requiring anticipatory and compensatory responses to maintain stability. In aging studies, quiet standing trials averaged 29.5 ± 5.0 s (range: 25.6–40.1 s), using force plates to record ground reaction forces and moments. Testing commonly involved open/closed eyes and uni-/bipedal stance, with visual focus directed at an undefined eye-level reference point. Neuropathy studies showed similar setups, with three trial repetitions averaging 34.0 ± 12.2 s. Intervention studies also followed comparable protocols, with trial durations ranging from 10 to 120 s (mean 35.4 ± 29.2 s). LoS tests appeared in two studies (sub-questions 2 and 3), reporting a maximum inclination period of 12.8 s or no duration. Dynamic tasks were rare, using tilt boards (one study) or translatory platforms (two studies), each with distinct setups.

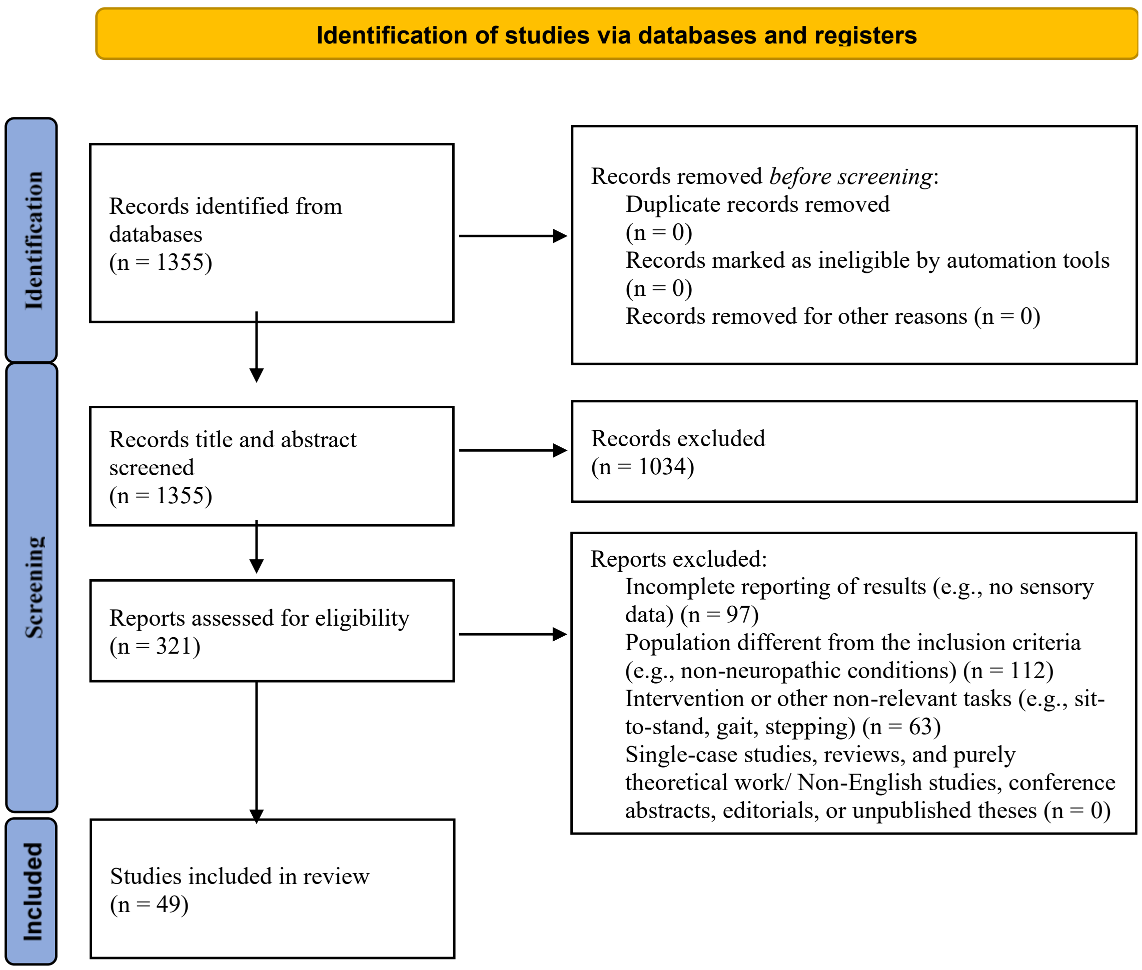

Figure 1. PRISMA flow chart.

Biomechanical analysis of postural control

Center of pressure (CoP) analysis was the primary method used to assess body sway. Most studies employed tridimensional force plates, while some used custom-made devices. Details on CoP data processing were generally limited to sampling frequency and filtering. In some cases, CoP was analyzed over different time intervals to evaluate anticipatory and compensatory responses [26]. One study assessed anteroposterior sway control via torque rather than CoP, though calculation details were lacking [27]. Additional parameters, such as EMG and center of mass, were also analyzed in another study [28].

Measurements of somatosensory information

The studies used a wide range of protocols to assess somatosensory information, particularly for the lower leg. Cutaneous sensitivity was commonly measured using monofilaments (filaments to assess cutaneous pressure sensitivity) or vibratory thresholds, while proprioception was assessed via joint position sense. The studies also exhibited varying parameters, anatomical locations, and number of trials.

In aging studies (see supplemental material 2), ankle proprioception was evaluated in the sagittal plane through joint position sense, direction, and velocity discrimination using custom devices like motorized pedals [29] and torque motors [30]. Vibratory thresholds were mainly measured with tuning forks at the tibial tuberosity [31], but other sites included below the patella, the medial 1st metatarsal head, medial malleolus, metatarsophalangeal joints, toes, and heel. One study used a biothesiometer (a device that delivers controlled vibrations to measure perception thresholds) for vibratory thresholds [32], and another applied a Semmes-Weinstein aesthesiometer (filaments to assess cutaneous pressure sensitivity) at the hallux, 1st metatarsal head, and heel to assess tactile sensitivity [33].

Neuropathy studies (see supplemental material 3) frequently used Semmes-Weinstein monofilaments on both feet, focusing on plantar [34–39] and dorsal regions [40,41]. Additionally, motor nerve conduction tests were performed [3]. Five studies assessed multiple modalities, such as vibration thresholds at the hallux, tactile sensitivity at the lateral malleolus, and proprioception via matching tasks [42]. Vibration assessments with tuning forks included various foot regions, often without comparing sites [34,40,43–45]. Skin sensitivity results were typically averaged across foot and ankle regions [46], and some extended to adjacent areas like the patella and hip joint [47]. Joint position sense was occasionally measured but rarely linked directly to postural control [15,36,40,48].

Pain sensitivity was examined in only a few studies (e.g., [15,49]), and proprioceptive assessments beyond the sagittal plane were rare [35]. Although not explicitly detailed in most studies, the results of somatosensory assessments tend to be averaged across the various assessed regions of the foot and ankle [46]. To include somatosensory assessments in the protocols is a crucial aspect of neuropathy diagnosis. In several cases, however, somatosensory assessments served mainly for diagnostic classification rather than exploring associations with postural control [50–52].

Afferent manipulation/intervention studies (see supplemental material 4) applied varied methods, including proprioceptive training, cryotherapy, tactile and vibration stimuli, thermal interventions, whole-body vibration (WBV), kinesiology tape, and short-/long-term Tai Chi, to assess an impact on postural control and sensory feedback. From these, seven studies included proprioceptive measures, primarily joint position sense [22,23,28,53–56], assessed in the ankle and/or knee [23,28,53,55,56]. Cutaneous sensitivity was addressed in eight studies [24,26,57–62], often distinguishing between plantar and dorsal sites. Two studies assessed both vibration and touch pressure perception [61,62] and one combined touch pressure with electrical current perception [59]. Proprioception protocols included active [28,53,54,56], passive [23,55], and combined (active and passive) joint position sense setups [22].

Measures for the nexus of biomechanics and somatosensory information

Although all studies included both biomechanical and somatosensory measures, only a few directly examined their interaction in the context of postural control. In aging-related studies, one regression analysis found an association between proprioception and center of mass sway area [29], and another included proprioception as a covariate [31]. Two studies analyzed the correlation between cutaneous sensitivity and sway [27,32], and cluster analyses were used to link plantar sensitivity to postural parameters [33]. These studies demonstrated that integrating somatosensory information is crucial for maintaining balance, particularly in conditions of sensory perturbation or impairment.

The sub-question of neuropathies included the largest number of articles linking sensory variables to postural control and fall risk. While these studies used diverse neurophysiological measures, many applied them mainly for group classification or description, rather than analytical evaluation - neglecting their potential utility in analytical contexts. One study emphasized the need to include vibration perception thresholds in fall risk assessments for older adults [34]. Another correlated center of pressure with three vibration assessment methods: tuning fork (vibrating at a fixed frequency to qualitatively assess sensation), neurothesiometer (delivering controlled vibrations to quantify perception thresholds), and audiometer (assesses vibration sensitivity via bone conduction) [43]. An interesting investigation related neurophysiological clinical scores and balance (limits of equilibrium) via receiver operating characteristic analysis to understand the nexus of biomechanics and somatosensory information [47].

Manipulating sensory input resulted in observable changes in biomechanical parameters, confirming an interaction between somatosensory inputs and balance control. However, few studies directly analyzed relationships between somatosensory measures (e.g., proprioception or cutaneous sensitivity) and biomechanical outcomes. Most of these studies relied on correlation analyses, and comprehensive, integrated investigations remain limited.

DISCUSSION

We conducted a scoping review to examine how studies on upright standing integrate biomechanical and somatosensory information from the foot and ankle. We explored three sub-questions: the impact of aging, impairments associated with neuropathies, and the effects of somatosensory manipulations / interventions on postural biomechanics. Our review focuses on whether studies combine biomechanical and neurophysiological aspects in their interpretations rather than analyzing the underlying mechanisms of postural control.

Biomechanical and somatosensory integration in studies related to aging

Studies on aging combining biomechanical and neurophysiological measurements aim to understand how older individuals adapt to somatosensory changes. Ankle proprioception, mainly assessed via joint position sense, shows a positive association with balance. For example, a large study (n=366) found that ankle joint position sense correlated with balance [29]. Similarly, one study reported that movement discrimination is linked to body sway, highlighting the role of specific proprioceptive aspects for postural stability [30]. These findings likely reflect a reweighting process, where the central nervous system increasingly relies on proprioception as other sensory inputs decline. However, correlations may vary depending on the proprioceptive measure assessed.

Regarding cutaneous sensitivity, vibration thresholds assessed at the tibia (256 Hz) showed no significant association with body sway [32]. Positive associations emerged when testing the 1st metatarsal bone, medial malleolus, and medial tibia [27]. Biomechanical parameters, such as the center of pressure, are broadly accepted indicators of postural control, whereas sensory neurophysiological measures require greater specificity concerning stimulus type and anatomical location.

Determining which measurements should be implemented to properly consider proprioception or cutaneous sensitivity when studying biomechanical components of postural control remains challenging. Determining which measurements appropriately capture proprioception or cutaneous sensitivity in relation to postural control remains challenging. Nonetheless, certain somatosensory measures consistently indicate interactions with biomechanical parameters in aging individuals. One study reported associations between tactile sensitivity and body sway, noting that participants with poor tactile acuity and less efficient postural control exhibited greater plantar sensitivity fluctuations, accompanied by an afternoon decline in postural stability [33]. These findings highlight the potential impact of daily fluctuations on postural control assessments when sensory data are not monitored.

A significant relationship between postural control, maximum great toe pressure, and tactile sense was observed among older, but not younger, participants [63], suggesting a reweighting of afferent information based on age, for example. Somatosensory information is important when evaluating postural control in aging individuals, even if proprioception and cutaneous sensation are not the main focus. Their influence should not be overlooked, especially in populations with altered sensorimotor conditions. For example, one study on upright postural sway and hippocampal volume in aging adults included somatosensory measures as covariates [31]. Occasionally, biomechanical parameters show no differences between adults and older adults, whereas sensitivity measures reveal group distinctions [27]. Overall, somatosensory variables may highlight differences not detected by biomechanical assessments alone.

Biomechanical and somatosensory integration in studies related to (diabetic) neuropathies

The neuropathy investigations included in this review provide additional insights into postural control studies, emphasizing the importance of proprioception and skin sensitivity. Peripheral neuropathy, often an irreversible condition, results from various diseases [64] and is primarily associated with type 2 diabetes (DPN) [65–68]. The diminished sensory response in individuals with DPN is a well-established phenomenon. Most selected studies combined at least two types of sensory information. For touch sensitivity, the monofilament test was most frequently used, while vibration assessments varied widely regarding devices and frequency ranges. One study also evaluated warmth, cold, and heat-pain thresholds [69]. Although thermal sensation seems less important for balance control, it may help in early detection of neuropathy [70]. Proprioception was never assessed in isolation but always combined with other sensory inputs, such as cutaneous sensitivity or visual feedback. Protocols differed by anatomical site and task type (e.g., matching, movement detection, angular velocities, active/passive). This variability complicates the clinical application of proprioceptive methods for balance assessment. Although various sensory measures were collected, sensory data were often used mainly for group classification without being integrated into postural control analyses. Applying advanced statistical methods, such as multivariate models accounting for sensory variables, could improve understanding of how proprioception and cutaneous sensitivity influence balance. Additionally, variability between laboratory and clinical measurement protocols should be considered, as clinical assessments often prioritize efficiency over precision, affecting the real-world integration of sensory data.

Similar to the notes mentioned in the sub-question on aging, the biomechanical measure of balance - mostly using CoP data for 30 s while standing upright - is a strong marker for stability across the studies. A specific example is that neuropathy severity influences postural control deficits, as evidenced by larger body sway in patients with sensory neuron disease (SND) compared to those with DPN [49]. The larger body sway in these patients suggests that balance assessments could provide valuable diagnostic information and help distinguish between DPN and SND patients. However, this suggestion should be approached with caution. While balance assessments using a stabilometric platform successfully differentiated between neuropathic patients and healthy controls, they may not effectively discriminate between patients with different types of neuropathies [47]. Various protocols, such as closed or open eyes, firm or foam surfaces, one-leg stances, and both-leg or tandem stances, were incorporated. Further variations include sway-referenced surfaces and maximum leaning tasks (limits of stability). Biomechanical methods are more standardized, mainly using a quiet 30-second upright stance, simplifying their clinical application.

A key finding is that more affected neuropathy participants show worse postural control, especially on firm surfaces [3,15,40,45,51,69,71,72]. Ankle proprioception and stability are more critical for functional mobility in PN individuals [35]. A correlation exists between the increased loss of foot sensation and the escalating impairment of balance [41]. Diabetes duration affects biomechanical and neurophysiological measures, with patients having diabetes for five or more years showing significant differences in vibration perception, reaction time, and CoP compared to healthy controls. In contrast, those with a diabetes duration of less than five years show variations only in some parameters. Hence, diabetes duration appears to influence postural control and proprioception [46]. Technologies allowing a quick postural control assessment and a long-term follow-up are valuable for safely administering exercise and rehabilitation programs. Quick postural control as well as sensory assessments emerge as a potential field for technological development in biomechanics.

Biomechanical and somatosensory integration in studies related to manipulations/interventions

Interventions targeting sensory systems in DPN patients can affect sensitivity and postural control, but effects vary. Thai foot massage improved foot and ankle cutaneous sensation and postural control [36]. Type 2 diabetics participating in Tai Chi demonstrated improved ankle proprioception and decreased plantar forefoot pressure, but no changes in balance or tactile sensation [48]. Tai Chi, however, improves balance in those with significant sensory losses [44]. Sensitivity-enhancing interventions also improve postural control, suggesting they may be promising for balance and sensory improvement in diabetics/DPN patients in some (not all) variables. Hence, enhanced standardization and increased research efforts are essential.

Instability in aging and neurological patients is not only due to reduced plantar cutaneous or proprioceptive inputs. Other factors, like skin and structural changes (e.g., foot deformities and joint stiffness), can mask the causal link between proprioception and skin sensitivity in postural control. To comprehend the role of plantar sensitivity and proprioception in postural control, researchers manipulated afferent information in healthy participants and found changes. Ischemic, hypothermic, and anaesthetic methods aim to reduce afferent inputs, while hyperthermic inductions, electrical, or mechanical stimulations are employed to increase afferent inputs. Seven interventions were performed in studies on sub-question three to improve the mentioned parameters. Long-term training, such as proprioceptive training (eight weeks, three times a week) and Tai Chi, was shown to enhance reflex responses, proprioception, and balance [28,53].

Acute manipulations/interventions, such as warm-up exercises and kinesiology tape, also improved balance and proprioception [23,54]. Whole-body vibration enhances balance in aging individuals, but not in young adults [56]. Two studies on warming protocols found varying results: for older participants, warming the entire foot improved cutaneous sensitivity, but no balance improvements were found [24]. Younger participants experienced improvements in cutaneous foot sensitivity and some balance parameters [58]. Both long-term and acute interventions consistently showed positive effects, though outcomes varied depending on methodological aspects (e.g., age and intervention type). Enhancing technology for both acute and chronic somatosensory manipulations could improve the quality of life for those with postural instability.

The remaining studies regard manipulations/interventions that aim to deteriorate proprioception and skin sensitivity. Five cooling studies showed differing results. Two studies found cryotherapy did not alter balance, despite reducing proprioception [22] and vibration sensitivity [62]. Two other investigations showed plantar hypothermia negatively affected balance and vibratory sensitivity [26,57], raising questions about the adequacy of the methods employed in altering balance. They also suggest a reweighting process by other sensory systems to maintain balance. Three studies found the factors noxious heat stimuli [25], ischemic blocks [59], and alcohol intoxication [61] to negatively impact the sensory system but not balance, though alcohol generally impairs postural control. Finally, orthoses with high pressure negatively affect proprioception [55]. Both interventions (reducing/improving performance) generally contribute to understanding the relationship between postural control and sensitivity due to mostly consistent findings, encouraging the exploration of alternative interventions. The failure to consider interactions between postural biomechanics and sensory information may introduce bias in participant recruitment for standing studies.

Limitations

There are some limitations in our review. We selected three postural tasks and populations, but further research on other tasks and populations is needed. When assessing proprioception, particularly joint position sense, measurement precision and resolution are crucial. Differences may be as small as 1.52º [29], but not all studies provided detailed information. Validated devices and repeatability data are essential. We also noted considerable variability in CoP measurements, such as an extremely small sway area of approximately 0.50 cm² using a BalanSensTM device [29]. Similar data variations in the somatosensory domain complicate identifying effects or correlations. Limited technical knowledge in biomechanics and/or neurophysiological measures raises concerns about the validity of studies combining these approaches

CONCLUSION

This review highlights the crucial role of foot and ankle somatosensory inputs, particularly proprioception and cutaneous sensation, in postural control, with a focus on aging, neuropathy, and sensory interventions. A major limitation across studies is the inconsistent use of neurophysiological measures, which hampers a full understanding of foot and ankle sensory contributions to balance. Although CoP analysis is common, assessments of proprioception and cutaneous function vary greatly, especially in foot and ankle research. Furthermore, the strength of this relationship depends on the population and methods used.

Clinically, standardizing sensory assessments could improve early identification of balance impairments, particularly in populations at high risk of falls. Incorporating foot and ankle proprioceptive and cutaneous evaluations into routine practice and targeting these functions through interventions may enhance balance and fall prevention. Such integration allows the development of more effective strategies for improving postural control in vulnerable groups.

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