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Review article

Impact of sensory afferences in postural control quantified by force platform in healthy older adults: Systematic review and meta-analysis

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ABSTRACT

Postural balance in older adults is a key research focus, as impaired balance significantly increases fall risk, potentially leading to severe injury or mortality. Given age-related sensory decline, force-platform posturography assessing sensory perturbation effects could elucidate postural control deficits in aging. This systematic review and meta-analysis examines older adults' ability to maintain quiet stance during sensory perturbations.

We searched 8 databases for studies evaluating older adults' balance under various sensory conditions.

We included 64 articles in this review, for a total number of 4481 subjects. Proprioceptive and visual afferences were the most explored. Meta-analyses were conducted when several studies shared similar procedures and domain analysis for older adults (OA), older fallers (OF), and young adults (YA). They showed a significant impact of visual deprivation on older adults' balance for positional, dynamic and frequential variables, while it was significant only in the positional and dynamic domains for younger adults. When proprioception was disturbed, all the meta-analyses showed a significant impact on older adults.

We concluded that positional and dynamic variables are sensitive to sensory perturbations and therefore could be useful in geriatric balance assessment. However, we emphasize the variability in methodological approaches and reporting standards, which constrains the broader applicability of these findings. We posit that posturographic research requires standardization and the establishment of an expert consensus regarding clinically relevant variables to facilitate the integration of posturography into geriatric fall risk assessment protocols, preventive programs and rehabilitation care.

1. Introduction

Healthy older adults' postural balance is a critical domain of research, and a key component of their quality of life, as balance deficit is an important risk factor for falls (Rubenstein, 2006). Individuals aged 60 and above constitute the most vulnerable population. Falls, ranking as the second leading cause of unintentional injury deaths, account for approximately 37.3 million severe incidents that require medical attention annually (World Health Organization, 2021). These incidents can lead to psychomotor and psychosocial disorders as well as reductions in physical activity, both nurturing the appearance of frailty or dependence (Baek et al., 2024). Consequently, the development of screening tools for balance capacities is crucial. Balance screening tools must have sufficient validity to identify people requiring individualized care. In addition, these tools must be able to quantify the sensory-motor abilities that are likely to increase or attenuate the risk of falling, which means they must have good sensitivity to intraindividual change. Equally imperative is the reliability of these screening tools, which means that the tools must provide repeatable, reproducible and sufficiently accurate measurements to be used repeatedly in daily care (Mokkink et al., 2023).

Correlation between age, balance, vision deficit and fall risk has been extensively established (Li et al., 2023). Maintaining balance involves an intricate interplay of various neurological mechanisms. The process

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encompasses afferent sensory systems, which include sensors and pathways for visual, somatosensory - i.e. tactile and proprioceptive -, and vestibular information. Additionally, central structures decode and contextualize this information at spinal and supraspinal levels (Forbes et al., 2018). Muscular efferents participate mainly through the coordinated response to destabilization (Horak, 2006). To recap, sensory integration at the level of the peripheral and central nervous systems induces a weighting of the information coming from the different sensory channels, then their contextualization. A motor response is eventually produced to induce a postural adjustment as well as a focal movement (Krishnamoorthy et al., 2005). This focal movement is compared to the desired movement thanks to feedback loops that are particularly effective in keeping one's balance (Takakusaki, 2017). Postural control is required in a static or steady-state balance, constituting the ability to sustain positions such as standing or sitting. This occurs through afferent and efferent pathways, alongside sensory-motor reflex capacities (Ivanenko and Gurfinkel, 2018).

Aging is characterized by progressive neurophysiological decline, including alterations in the central and peripheral nervous systems, leading to impaired sensorimotor integration, slower reaction times, and reduced muscle function (Peelle, 2020).

These age-related neurophysiological alterations are key pathogenic factors underlying impaired balance and increased fall risk in the elderly. The progressive loss of skeletal muscle mass and strength, which can lead to sarcopenia and/or cachexia, necessitate research and therapeutic development. However, the slow progression of muscle atrophy in humans and the ethical concerns surrounding such studies require the use of animal and in vitro muscle atrophy models. These models are crucial tools that allow for the investigation of complex biological processes, such as imbalances in protein metabolism, inflammatory responses, and changes in muscle fiber composition, which are fundamental to the compromised neuromuscular control underpinning balance impairment.

A comprehensive array of models ranging from natural aging models in rodents, which closely mimic human sarcopenia, to models induced by genetic editing, high-fat diets, hindlimb suspension (simulating disuse), and various chronic diseases are summarized in a review by Zhang et al. (2024). Each model, while valuable for specific research objectives (e.g., natural aging for primary sarcopenia versus tumor-induced models for cachexia), possesses inherent limitations, such as phenotypic discrepancies from human conditions or the difficulty of isolating specific mechanisms due to comorbidities. Therefore, the advancement of research into age-related neurophysiological decline, balance impairment, and fall risk relies on the selection and application of these models, allowing researchers to explore the underlying pathophysiological mechanisms, as well as functional exploration of balance in humans. These complementary approaches will allow researchers and clinicians to enhance risk stratification, enabling timely and targeted interventions aimed at preserving neuromuscular function and ultimately mitigating the substantial health and economic burdens associated with age-related balance impairment.

The complexity of postural control makes it difficult to assess it exhaustively, especially in a population where multimorbidity is common. The presence of multiple diseases or disorders requires clinician to develop specific tools. This is illustrated by the Comprehensive Geriatric Assessment (CGA), which is a systemic process used to assess health issues of older patients. The CGA includes methods to evaluate balance and sensory loss relevant to static balance, though they may lack the objectivity, sensitivity, and precision needed to quantify fall risk and postural compensations effectively (Bergquist et al., 2019). Observational methods, such as monitoring a patient's ability to stand from a seated position and assessing postural stability while standing, provide basic insights. Additionally, peripheral sensory testing evaluates proprioception in the feet, which is essential for balance. However, these methods offer limited quantifiable data on static balance and may not fully capture the subtle compensatory mechanisms older adults use to maintain stability, potentially underestimating their risk of falls (Beck Jepsen et al., 2022).

To enhance the evaluation of balance function, further exploration of neurological and sensory-motor systems is possible by suppressing or perturbing specific sensory inputs during assessments. For instance, the inability to maintain balance with closed eyes reveal an inability to rely on proprioceptive and vestibular pathways (Horlings et al., 2008). Similarly, subjects with visual or vestibular deficits, who are dependent on somatosensory input, will exhibit an excessive loss of balance when standing on a foam or unstable surface (Cohen and Sangi-Haghpeykar, 2020). Such evaluation protocols may be cheap, sometimes easy and quick to administer, but they exhibit limitations: ceiling effect, inter-rater reliability or insensitivity to change (Mancini and Horak, 2010).

Compared with clinical tests, computerized posturography from force platform therefore meets the need to numerized and quantify these potentially subtle and compensated postural deficits. This tool allows similar protocols as clinical tests, including complex manipulations of sensory conditions to explore a subject's ability to adapt to sensory perturbation or deprivation. This type of protocol was found to be valid and reliable to detect postural control changes in people with multiple sclerosis (Hebert and Manago, 2017) or to be able to differentiate people with Progressive Supranuclear Palsy, Parkinson's disease and healthy subjects (Ondo et al., 2000). However, this technology also has limitations: it requires more expensive materials than clinical balance scales, as well as trials to infer clinical information from posturographic features.The relevance of this tool for assessing fall risk in healthy older adults is therefore a topic for scientific research. Few systematic reviews focusing on follow-up studies using posturographic assessment to predict falls, Piirtola and Era (2006) and Pizzigalli et al. (2016) found several posturographic markers (i.e. Center of Pressure –CoP- features) derived from static balance associated with future falls across published studies. Regarding the methodology of the studies, the authors point out the variety of protocols and measurement methods, advocating for harmonization. Since these reviews, force platform have widely been used in clinical studies and many protocols and many features have been explored without consensus (Quijoux et al., 2021).

Given the impact of aging on sensory systems involved in balance, comprehensive posturographic protocols examining older adults' sensory organization and adaptation across varied conditions are crucial for delineating postural control alterations and assessing fall risk. The reviews cited previously, while identifying several posturographic features associated with deteriorated balance, failed to identify a definite posturographic protocol and marker that could classify a person as a future faller with sufficient reliability.

Hence, this systematic review will scrutinize studies investigating the elderly's ability to adapt to diverse sensory conditions during quiet stance through computerized posturography. An innovative methodology for meta-analyses will allow us to update and aggregate posturographic data from the literature, and explore them in domains of analysis rather than individual features.

2. Objectives

The primary question for this systematic review is:

- When exposed to sensory deprivation or perturbation during quiet stance, are healthy older adults able to maintain their balance or do they exhibit an increased instability compared with younger subjects? To answer this, we will analyze the variability of CoP features in different sensory conditions.

In order to better understand the relationships between the afferent systems and postural control, we set secondary research questions:

- What is the impact of experimental sensory conditions on the balance of healthy elderly subjects? For this question, we will compare the impact on CoP features of the perturbation or deprivation of each sensory channel.

- Which features of the stabilogram are used to assess the sensory organization of postural control during quiet stance in the healthy elderly ($\geq$ 60 years)? To address this question, we will extract the list of the CoP features assessed in each study included.

3. Methods

This literature search and analysis was designed according to the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) updated guidelines (Page et al., 2021).

3.1. Search strategy

Six databases were researched between February and July 2022 as sources for published articles: Medline (PubMed), Cochrane CENTRAL, ScienceDirect, Web of Science, Scopus, and BDSP to identify all articles published that include posturography during quiet stance under various sensory conditions in older adults. Two clinical trials registry platforms were also explored: ICTRP and ClinicalTrials.gov.

We previously published the protocol for this review and meta-analysis (Aflalo et al., 2022), where additionnal information can be found on the research and inclusion methodology, data extraction, analysis and synthesis as well as quality assessment.

In terms of the research area and methodology, we selected studies exploring older,adults' postural control with and without sensory deprivation or disturbance, but that seek a comparison between a control situation and a situation with altered sensory afferences (i.e. not a comparison between features or a pre-post intervention effect). This therefore includes studies that explore balance through a force platform with the addition of a sensory altering tool or condition such as eye closure, a blindfold or a foam device added to the platform.

3.2. Paper review process

Eligible studies were screened by two authors independently (LG and JA) based on title, abstract and full text. The intervention of a third reviewer wasn't needed during the process. Articles were imported into the Zotero® bibliographic database (Corporation for Digital Scholarship and the Roy Rosenzweig Center for History and New Media, USA) before screening so that all articles could be reviewed from the same source and then assessed for risk of bias.

Following Cochrane's handbook guidelines (Chandler et al., 2017), an individual quality/risk of bias assessment was performed with a 27-item checklist (see Appendix A) based on the Single-Case Reporting Guideline In BEhavioural Interventions (Tate et al., 2016). More details about the construction of this checklist can be found in the protocol published previously (Aflalo et al., 2022).

The data extraction was performed and verified by two authors (LG and JA) and included study identification, demographic and biometric data such as participants' gender, age and specific profile (i.e. frailty, fall or cognitive status). When present, the data from a younger control group was also extracted. Quiet standing test parameters included conditions of the procedure such as the foot and body position (comfortable or standardized), the number and duration of trials, posturographic materials and settings in order to evaluate the diversity of protocols and potential bias in results. We then extracted data for every posturographic feature for each sensory condition tested (e.g., varying visual surrounding, type of standing surface, with or without tactile or vestibular stimulation). When comparing different sensory conditions, if no information was provided regarding a sensory channel, we considered it as standard/baseline settings. For example, if perturbed somatosensation is tested and referred to as “foam condition” with no details regarding the visual afference, we labeled it as “foam and eyes open”.

3.3. Data synthesis

Data were included in a meta-analysis when they explored the same sensory perturbation on a similar group (i.e. healthy older adults –OA-, older fallers –OF- or younger adults control participants –YA-) with a posturographic feature from the same domain. We defined 4 domains based on Quijoux et al. (2021): positional, dynamic, frequential and stochastic. An extension of the classification already available with Chiari et al. (2002), who discussed the importance of analysing COP variables from different domains. Positional variables assess the dispersion of the two-dimensional trajectory and the positional preferences of the COP, such as the mean distance of the COP from the center of its trajectory, which might reflect the general stability of the body (Prieto et al., 1996). Dynamic variables examine the temporal aspects of COP movement, such as the mean velocity, which are intended to measure the speed and magnitude of the postural adjustments required to maintain balance (Maki et al., 1994; Prieto et al., 1996). Frequential variables focus on the frequency decomposition of the COP signal, such as total power, which quantifies the energy of postural oscillations across different frequencies. This approach provides insight into the rhythms of postural control and can detect subtle changes that may not be evident in temporal analyses (Loughlin and Redfern, 2001). Finally, stochastic variables model the COP as a random process, for example, the mean square displacement, which describes how the COP disperses over time under perturbations, thereby capturing the complexity and relative unpredictability of balance strategies (Collins and De Luca, 1993).

Variables from each domain were aggregated using correlation matrices based on Nicolaï (2021), as presented in Fig. 1. The correlation coefficients were calculated using a public data set of posturographic evaluations published by Santos and Duarte (2016).

Means and standard deviations of measures, as well as the number of participants per group were used to compare the effect size of each condition on the postural stability for each group. The results are illustrated with forest plots, funnels plots and I^2 was used to assess publication bias and heterogeneity respectively.

For each study, effect sizes were calculated by comparing posturographic features between the two sensory conditions (e.g. eyes open vs eyes closed for visual afferents). The standardized effect size d was calculated as follows:

$$d = \frac{\overline{X}_{altered} - \overline{X}_{control}}{S_p}$$

Where $\overline{X}_{altered}$ and $\overline{X}_{control}$ represent the means of the posturographic variables in the altered and control conditions, respectively. The combined standard deviation S_p was calculated according to the eq. (1).

$$S_p = \sqrt{\frac{(n_{altered} - 1).S^2_{altered} + (n_{control} - 1).S^2_{control}}{(n_{altered} + n_{control} - 2)}} \quad (1)$$

These effect sizes were calculated for each domain of posturographic features (positional, dynamic, frequential, stochastic) as a function of the specific sensory conditions. Variables from the same study are correlated because they are measured on the same individuals. To aggregate them, we need to consider their correlations; otherwise, we would overestimate the precision and the contribution of the summary effect for positively correlated features. One approach, described by (Borenstein (2009), is to create a composite variable, e.g., the positional variable, whose value is the mean of variables that belong to the positional group and whose variance is the average of each variance, multiplied by a so-called Variance Inflation Factor that depends on the correlations. The actual correlation values are taken from the study of Nicolaï (2021). The composite variables are treated as regular outcomes using the statistical meta-analysis methodology (Borenstein, 2009).

Once d is calculated, the variance V_i associated with this effect size

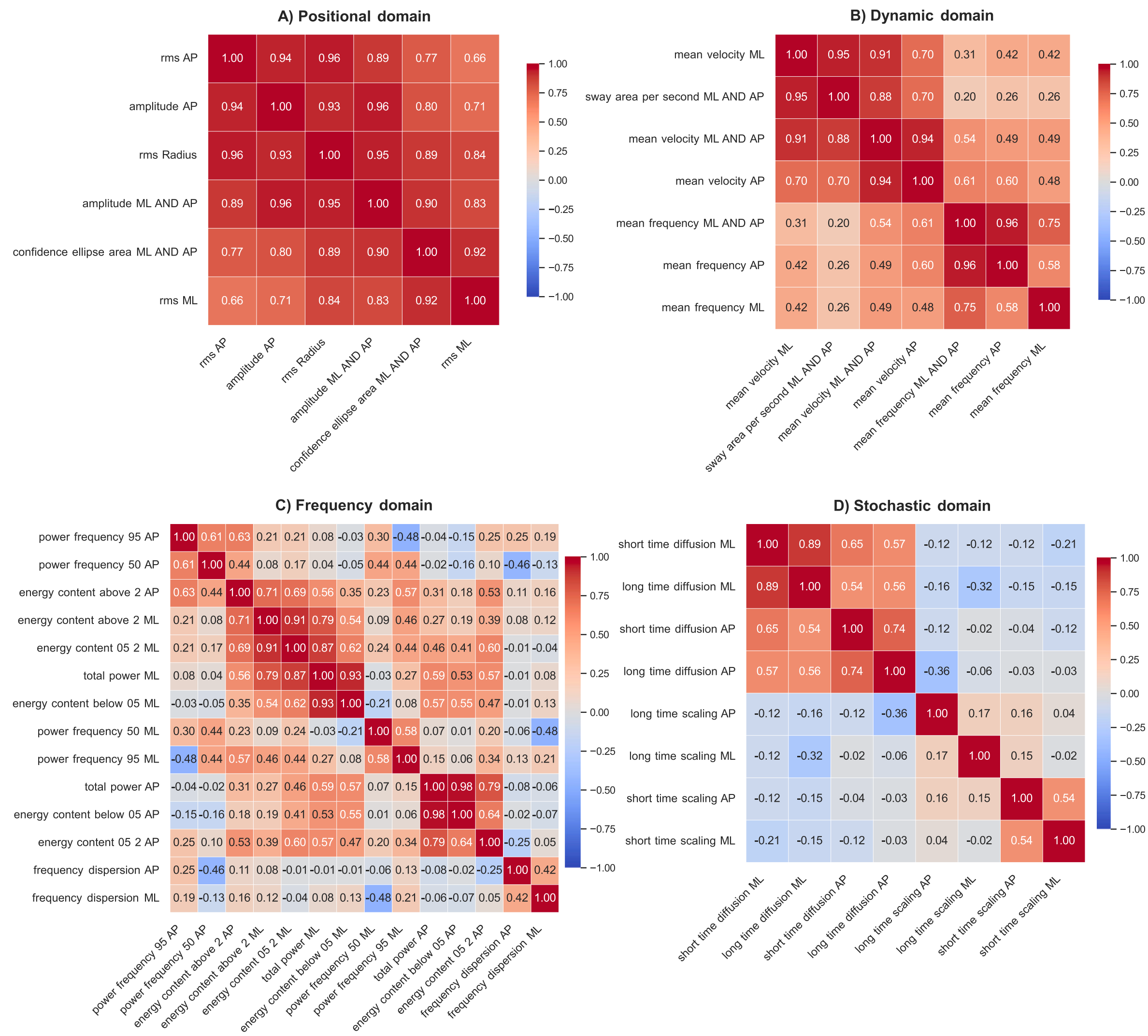

Fig. 1. Correlation matrices for positional (A), dynamic (B), frequential (C) and stochastic (D) variables used for meta-analyses.

for a given study was determined with eq. (2).

$$V_i = \frac{n_{altered} + n_{control}}{n_{altered} . n_{control}} + \frac{d^2}{2(n_{altered} + n_{control})} \tag{2}$$

The combined effect size variance ($V_{combined}$) was adjusted for these correlations using the eq. (3).

$$V_{combined} = \frac{1}{k^2}\left(\sum_{i=1}^{k} V_i + 2\sum_{i<j} R_{ij}\sqrt{V_i V_j}\right) \tag{3}$$

where k is the number of correlated variables, V_i is the variance of effect size i, and R_{ij} represents the correlation between effect sizes i and j (based on the correlation matrices per posturographic domain). This approach allows effect sizes to be combined while taking into account interdependencies between measurements, thus ensuring a more accurate estimate of the overall effect of perturbed sensory conditions on postural control. When two features are perfectly anti-correlated ($R = -1$), meaning an increase in one is systematically associated with a decrease in the other, the combined overall size effect tends to cancel out, reducing the variance of the overall estimate. This reduction in variance can lead to a more accurate estimate of the overall effect, but also to greater sensitivity to variations between studies. On the other hand, when the posturographic features show no correlation ($R = 0$), they are considered to be independent, the contribution of the individual effect size variances to the combined variance is additive. The combined variance in this case is simply the usual average of the individual variances.

To compare subgroups, p-values returned by the meta-analysis were adjusted with Bonferroni correction given the large number of comparisons between sensory conditions (Armstrong, 2014).

For data that cannot be aggregated into a meta-analysis, a "best evidence synthesis" method was preferred, evaluating the strength of the studies' evidence in regard to their score in the risk of bias assessment, with particular attention on the methodological quality of the studies.

4. Results

4.1. General results

We identified 1607 records across the 8 databases searched, and included 64 studies in our review for a total of 4481 participants (3122 older adults, 472 older fallers and 887 younger adults). Details on the inclusion process are shown in the flowchart (Fig. 2). The most explored sensory channel was vision with 55 studies testing balance with eyes opened versus eyes closed. Other visual perturbations were tested such as blurring glasses, moving scenes or optocinetic stimulation. Foam was used to disturb proprioceptive feedback by 17 studies, other protocols

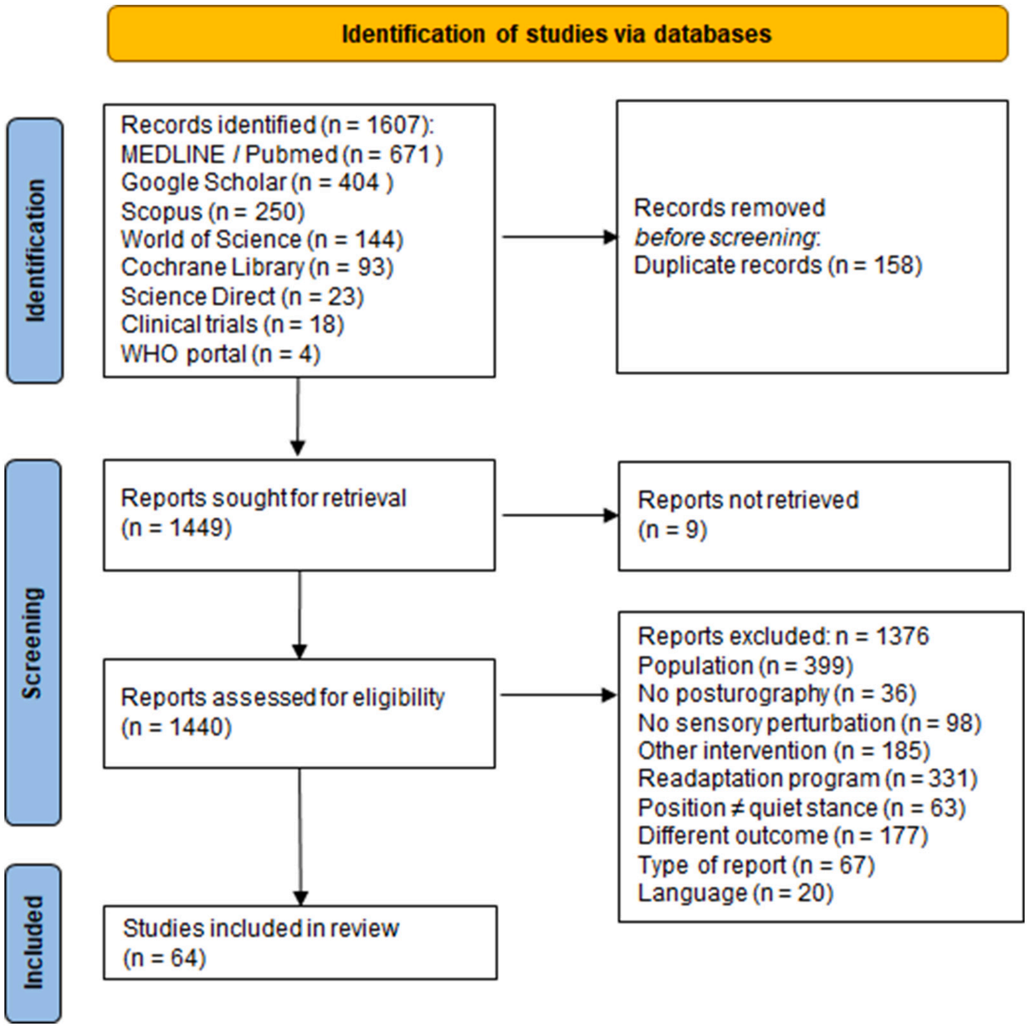

Fig. 2. Studies inclusion's flowchart for the literature review.

consisted of vibrating stimulation on the lower limb or neck, use of vibrating shoes and feet immersion in ice. Vestibular perturbance was the less common but was present in 2 studies (Anand et al., 2003; Buckley et al., 2005). The participants were instructed to maintain a 45° head extension or rotation during the balance recording. The majority reported the impact of the combination of conditions affecting several sensory channels, most commonly eyes closed and foam, with some specific individual protocols such as foam and head extension (Anand et al., 2003), or eyes closed and calf vibration (Kristinsdottir et al., 2001). One study (Freeman et al., 2009) explored the impact of olfactory perturbation with black pepper scent. Although this sensory channel is not typically included in models describing balance function, we included this study in our review as it gave us additional information on a sensory perturbance rarely explored in the literature (See Fig. 3).

Table 1 summarizes the key informations of the studies included in this review, such as: study identification, date, population, sensory protocol(s), posturographic domain(s) analyzed, duration of the posturographic examination and if they were included in a meta-analysis.

4.2. Individual risk of bias assessment

Using our modified checklist to assess risk of bias, with a maximum score of 27, we found a mean score of 18.8, ranging from 14 to 22 points across all studies. Some items were scored positively for all studies (e.g. describing the study design or discussing main findings). We found no protocol published beforehand to describe the authors' methodology and allow us to verify if procedural changes were made. Similarly, only half of the studies reported adverse events or disclosed their funding. Regarding the specific subject of posturography, most authors described their materials and sensory conditions, but only half of them described the data pre-processing or the exact posturographic features used. Only 11 studies gave an exact definition and calculation for the CoP variable.

4.3. Quantitative analysis

We identified 112 different posturographic features across all 4 domains. Table 2 summurizes all possible meta-analyses, and the level of significance for the meta-analyses we were able to conduct.

Positional and dynamic features were the most prevalent while stochastic parameters were rare but included Detrended Fluctuation Analysis (DFA), Recurrence quantification analysis (RQA) and Local Dynamic Stability (LDS) analyses as well as fractal dimensions. We were able to aggregate the results for 3 domains: positional, dynamic and frequential. While stochastic features were present in some studies, each one used a different method and we could not perform a meta-analysis due to differences in their sensory conditions.

Meta-analyses for visual perturbation were performed in positional and dynamic domains across all 3 groups: Older Adults (OA), Older Fallers (OF) and Young adults (YA). In the frequency domain, only one study had a younger control group, therefore we only performed meta-analyses for OA and OF. Regarding proprioceptive afferences, we could only perform 2 meta-analyses: positional and dynamic for OA.

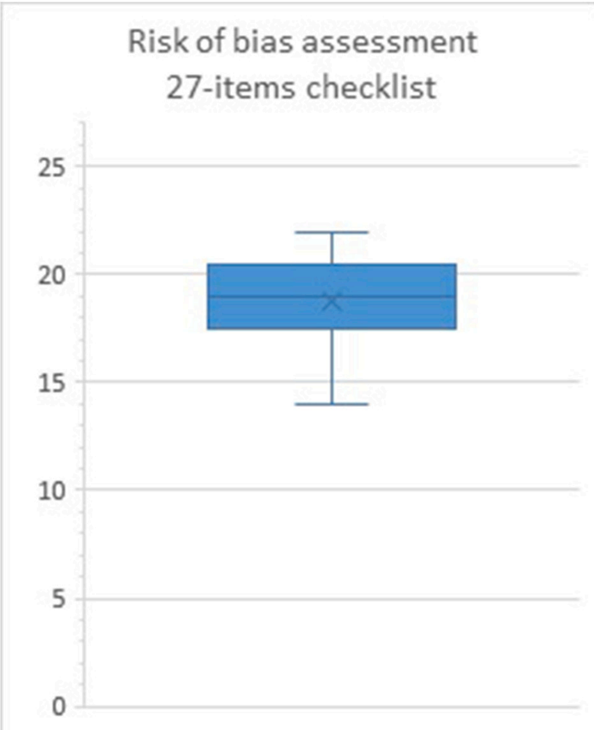

Fig. 3. Boxplot of studies' risk of bias assessment scores, on a 27 maximum points checklist.

4.3.1. Meta-analyses for visual conditions

Eight meta-analyses were performed for visual conditions (eyes open versus eyes closed) in 3 domains: positional, dynamic and frequential. All forest plots are presented in Fig. 4 for positional, Fig. 5 for dynamic and Fig. 6 for frequency.

4.3.1.1. Positional. The results from 16 studies exploring visual perturbations showed a significant impact, with a deterioration of balance parameters in all 3 groups: Older Adults, Older Fallers and Young Adults. The effect size was the largest in the YA group ($g = -1.07$ $[-1.91; -0.24]$; $p < 0.02$) with a large variance. The results for the OA and OF groups were respectively $g = -0.83$ $[-1.18; -0.47]$; $p < 0.001$ and $g = -0.54$ $[-0.87; -0.21]$; $p < 0.001$. The heterogeneity was very high ($I^2 > 85$ %) in the OA and YA groups, while it was slightly lower in the OF group ($I^2 = 69.1$ %).

4.3.1.2. Dynamic. Dynamic features were used by 17 studies to explore the impact of visual perturbations. The results of the meta-analyses showed a significant effect on all 3 adults groups. The effect sizes were of the same order in OA ($g = -0.84$ $[-1.16; -0.52]$; $p < 0.001$) and OF ($g = -0.86$ $[-1.28; -0.44]$; $p < 0.001$); in YA the effect size was larger ($g = -1.54$ $[-2.78; -0.30]$; $p < 0.02$) but again with an important confidence interval due to the smaller number of studies. In addition, the heterogeneity was comparable to the results of the positional meta-analyses: $I^2 = 76.2$ % for OF; $I^2 = 86.5$ % for OA and $I^2 = 79.8$ % for YA.

4.3.1.3. Frequential. Four studies used frequency analyses and 2 of them had an OF group. None of the meta-analyses showed significant results. Effect sizes were $g = -0.50$ $[-1.38; 0.38]$, $p > 0.2$ and $g = -0.66$ $[-3.88; 2.57]$, $p > 0.6$ for OA and OF respectively.

Only one study had a YA group and found no significant effect either.

4.3.2. Meta-analyses for proprioceptive conditions

We found 5 studies exploring proprioceptive perturbation with similar protocols (stable platform versus platform with foam) and domains of analysis, allowing us to perform 2 meta-analyses for OA only. The forest plots for proprioceptive meta-analyses are shown in Fig. 7.

4.3.2.1. Positional. We found 5 studies exploring the impact of a compliant surface (foam) on positional features and could aggregate their results for the OA group. The effect was significant ($g = -2.80$ $[-3.54; -2.05]$; $p < 0.001$ with a high heterogeneity ($I^2 = 89.2$ %).

4.3.2.2. Dynamic. Three studies used dynamic features while comparing a stable platform versus one with foam, for OA. The effect was significant ($g = -1.10$ $[-1.26; -0.94]$; $p < 0.001$) with no heterogeneity ($I^2 = 0$ %).

4.4. Best evidence synthesis

4.4.1. Visual – stochastic

Due to the variety of stochastic analysis, we couldn't perform a meta-analysis on the data, however, 6 studies provided such analyses, showing a significant impact of visual perturbation on stochastic features for OA and OF, with a moderate level of evidence. Scores for the 6 studies ranged from 16 to 21 with a mean score of 19. Only one study (Seigle et al., 2009) had a YA group, reporting a significant difference between older and younger adults in both eyes open and eyes closed conditions, with RQA analysis.

4.4.2. Proprioceptive – frequential, stochastic

Studies exploring proprioceptive perturbation are less common. Most of them used foam or a compliant platform, others used vibration (TENS) on the lower limb during the posturographic examination. Regarding the frequential analysis, only one study (Maranesi et al., 2016) provided raw data, reporting no significant difference between OA and OF, with a moderate level of evidence. Three studies used stochastic analyses (with risk of bias scores of 19; 20 and 21), and 2 of them provided raw data, however none of them compared older adults with a different group.

4.4.3. Vestibular - positional, dynamic, frequential, stochastic

Vestibular afferences are more difficult to disrupt during a posturographic examination, hence the reduced number of studies included in this review. The protocols found in the literature included head extension, flexion and neck vibration (TENS). (Anand et al., 2003) explored the impact of head extension, but we could not draw conclusions considering it was only in combination with other sensory perturbations. (Buckley et al., 2005) explored head extension as well as flexion in OA, reporting significant impact on a positional feature only for the head flexion.

In summary, the studies included in the review that could not be added to the meta-analyses offered an insight on the diversity of sensory protocols used to explore the contribution of each sensory channel to maintain balance, as well as the impact of sensory afferences usually not explored when evaluating balance: auditory and olfactive stimuli (Freeman et al., 2009).

5. Discussion

The findings from this systematic review and meta-analysis provide important insights into the ability of older adults to maintain balance when exposed to sensory deprivation or perturbation during quiet stance. We included 64 studies in this review, with a total of 3979 participants. Studies were published from 1990 (Pyykko et al., 1990) to 2021 (Nishino et al., 2021; Perucca et al., 2021; Strandkvist et al., 2021). The evolution of posturographic materials as well as analyses is important to take into consideration, explaining the disparity in risk of bias assessment scores, and offering new opportunities to explore

Table 1
Details of studies included in the literature review. Groups: Older Adults (OA); Older Fallers (OF); Younger Adults (YA).

Study ID	Groups (n)	Feature(s) domain(s)	Sensory condition(s)	Duration (s)	Included in meta-analysis
Anand et al., 2003	OA (15)	Positional	Visual / Proprioceptive / Vestibular	30	No
Aufauvre et al., 2005	OA (15) OF (15)	Positional Dynamic Frequential	Visual	51,2	Yes
Baloh et al., 1994	OA (82) YA (30)	Dynamic	Visual	10	No
Baloh et al., 1995	OA (70)	Dynamic	Visual / Proprioceptive	10	No
Baloh et al., 1998a	OA (72)	Positional Dynamic	Visual	10	No
Baloh et al., 1998b	OA (72) YA (30)	Dynamic	Visual	10	No
Baracat and De Sá Ferreira, 2013	OA (38) YA (35)	Positional Dynamic	Visual	60	No
Bauer et al., 2010	OA (30)	Frequential	Visual	25,6	Yes
Bekkers et al., 2014	OF (13)	Positional	Visual / Proprioceptive	4 x 20s	No
Ben Achour Lebib et al., 2006	OA (30) OF (30)	Dynamic	Visual / Proprioceptive	3 x 10s	No
Benjuya et al., 2004	OA (32) YA (20)	Positional	Visual	20	Yes
Bird et al., 2013	OA (69)	Positional	Visual / Proprioceptive	30	No
Brika et al., 2021	OA (33)	Positional Dynamic	Visual / Proprioceptive	15	Yes
Buatois et al., 2006	OA (132) OF (57)	Positional	Visual	20	Yes
Buckley et al., 2005	OA (12)	Positional	Visual / Vestibular	30	No
Cabral et al., 2020	OF (124)	Positional Dynamic	Visual	60	Yes
Deschamps et al., 2014	OA (50)	Positional Dynamic	Visual	2 × 51.2 s	Yes
Earles et al., 2000	OA (10) YA (12)	Positional	Visual / Proprioceptive	No info	No
Eikema et al., 2012	OA (16) YA (20)	Dynamic	Visual / Proprioceptive	60	No
Eikema et al., 2013	OA (12) YA (12)	Dynamic	Visual / Proprioceptive	60	No
Freeman et al., 2009	OA (17)	Positional Dynamic	Visual / Olfactive	60	Yes
Haibach et al., 2008	OA (15) YA (15)	Positional	Visual	25	No
Haibach et al., 2009	OA (15) YA (15)	Positional Frequential	Visual	3 x 20s	No
High et al., 2018	OA (10) OF (9)	Positional Dynamic Stochastic	Visual / Proprioceptive	30	Yes
Howcroft et al., 2017	OA (76) OF (24)	Positional Dynamic	Visual	30	Yes
Johannsen et al., 2009	OA (10)	Positional	Visual	No info	No
Kim et al., 2008	OA (16) YA (16)	Positional Dynamic Frequential Stochastic	Visual / Proprioceptive	3 x 60s	No
Kinsella-Shaw et al., 2006	OA (12) YA (12)	Positional Stochastic	Visual	8 x 30s	No
Kristinsdottir et al., 2001	OA (40) YA (10)	Positional Frequential	Visual / Proprioceptive	235	No
Lion et al., 2014	OA (128)	Positional	Visual / Proprioceptive	25,6	Yes
Loughlin and Redfern, 2001	OA (16) YA (13)	Frequential	Visual	30	No
Machado et al., 2017	OA (19) YA (19)	Positional Dynamic	Visual	3 x 30s	No
Maranesi et al., 2016	OA (67) OF (63)	Positional Dynamic Frequential	Visual / Proprioceptive	30	Yes
Marques et al., 2019	OA (60)	Dynamic	Visual / Proprioceptive	30	Yes
Melzer et al., 2004	OF (19)	Positional Dynamic	Visual / Proprioceptive	20	Yes
Melzer et al., 2010	OA (69) OF (29)	Positional Dynamic Stochastic	Visual	No info	No
Merlo et al., 2012	OA (67) OF (63)	Positional Dynamic	Visual / Proprioceptive	30	Yes
Moghadam et al., 2011	OA (16)	Positional Dynamic	Visual	30	Yes

(continued on next page)

Table 1 (*continued*)

Study ID	Groups (n)	Feature(s) domain(s)	Sensory condition(s)	Duration (s)	Included in meta-analysis
Nagy et al., 2007	OA (19) YA (11)	Positional Frequential	Visual	No info	No
Nishino et al., 2021	OA (156) YA (141)	Positional	Visual / Proprioceptive	No info	Yes
Özkal et al., 2019	OA (68) YA (68)	Positional	Visual	10	No
Palazzo et al., 2015	OA (40)	Positional Dynamic	Visual / Proprioceptive	2 x 20s	No
Patel et al., 2009	OA (16) YA (25)	Positional	Visual / Proprioceptive	235	No
Pauelsen et al., 2020	OA (45)	Frequential	Visual	30	No
Perrin et al., 1997	OA (50) YA (41)	Positional Dynamic	Visual	20	No
Perucca et al., 2021	OA (53)	Positional	Visual / Proprioceptive	20	No
Prieto et al., 1996	OA (20) YA (20)	Positional Dynamic Frequential	Visual	30	Yes
Pyykko et al., 1990	OA (17) YA (100)	Dynamic	Visual / Proprioceptive	30	No
Quek et al., 2014	OA (20)	Positional Dynamic Frequential Stochastic	Visual	30	Yes
Redfern et al., 1997	OA (8) YA (8)	Positional Dynamic	Visual / Proprioceptive	30	No
Redfern et al., 2009	OA (22) YA (24)	Positional	Visual / Proprioceptive	3 × 180 s	No
Redfern et al., 2018	OA (31) YA (24)	Positional	Visual / Proprioceptive	180	No
Rugelj et al., 2014	OA (26) YA (18)	Positional Dynamic	Visual	70	Yes
Rugelj et al., 2020	OA (19)	Positional Dynamic Frequential	Visual / Proprioceptive	60	Yes
Schülein et al., 2020	OA (123) YA (35)	Positional Dynamic	Visual	3x30s + 1x60s	Yes
Seigle et al., 2009	OA (12) YA (11)	Positional Stochastic	Visual	51,2	Yes
Shin et al., 2018	OA (20)	Positional Dynamic	Visual	30	No
Strandkvist et al., 2021	OA (45)	Positional Dynamic	Visual / Proprioceptive	30	Yes
Suarez et al., 2013	OA (8)	Frequential	Visual / Proprioceptive	No info	No
Van Impe et al., 2012	OA (36) YA (31)	Positional	Visual / Proprioceptive	3 x 20s	No
Wade et al., 1995	OA (23) YA (21)	Positional	Visual	4	No
Wang et al., 2019	OF (26) YA (16)	Stochastic	Proprioceptive	65	No
Whipple et al., 1993	OA (239) YA (34)	Positional	Visual / Proprioceptive	1 or 3 x 20s	No
(Yeh et al., 2014)	OA (9)	Positional	Visual / Proprioceptive	3 x 30s	No

perturbations that would specifically influence more recent and complex domains of analysis.

Regarding the importance of sensory feedback for balance, we found that both afferences explored in the meta-analyses, visual and proprioceptive, had an impact on younger and older adults. This result mitigates theories on older adults' visual (Barela et al., 2013) or proprioceptive (Wiesmeier et al., 2015) dependance with aging, as a cause for instability and falls. While this dependency could appear in subgroups, based on individual sensory alterations or medical conditions, our results suggest that older adults' balance is deteriorated by all perturbations. Hence, a possible cause could be a difficulty to integrate all afferences to adapt to missing informations.

Another factor for balance deficits and fall risk in the older population is the neurophysiological changes in muscle mass and function. While this aspect was not explored in the present review, the relationship between these age-related deficits and balance abilities is well established in animal models (Zhang et al., 2024). However, these models while informative, do not completely explain fall risk in humans because they often lack the complexity and multifaceted nature of human aging and disease, and contain phenotypic and temporal dynamics discrepancies. Nonetheless, we reckon that deficits in muscle mass and function, while more complex and difficult to study in humans, contributes to balance deficits and that the intrication of neuro-muscular and sensorial changes in the elderly exacerbate fall risk.

A key focus of the literature has been examining how disruptions to different sensory modalities (visual, somatosensory, vestibular) impact postural control in older adults. While the effects of visual deprivation (eyes closed) and somatosensory perturbation (e.g. platform with foam) have been well studied and allowed us to perform meta-analyses, assessing the vestibular system remains technically challenging. This is an important limitation, as age-related vestibular dysfunction is a major contributor to balance impairments in older adults (Horak et al., 1990).

An interesting observation from the review was the wide range of CoP features used across the included studies to assess sensory organization and postural control during quiet stance. This highlights the lack of consensus regarding the most sensitive and meaningful

Table 2
Results of meta-analyses by sensory perturbation, domains, and groups.

		*Young Adults	Older Adults	Older Fallers
Visual (eyes open vs. eyes closed)	Positional	**	***	***
	Dynamic	**	***	***
	Frequential	X	NS	NS
	Stochastic	X	X	X
Proprioceptive (stable platform vs. foam pad)	Positional	X	***	X
	Dynamic	X	***	X
	Frequential	X	X	X
	Stochastic	X	X	X
Vestibular	Positional	X	X	X
	Dynamic	X	X	X
	Frequential	X	X	X
	Stochastic	X	X	X

X: Not enough data to conduct a meta-analysis.
NS: not significant.
* $p < 0,05$.
** $p < 0,01$.
*** $p < 0,001$.

posturographic markers for evaluating balance in this population. This diversity was previously raised by Chiari et al. (2002) as a potential source of variability between participants and protocols.

Another level of complexity is the intricating way sensorial afferences affect balance, leading researchers to test protocols with combinations of perturbations such as standing quiet on foam with eyes closed, blurring glasses or optokinetic lights. This complexity makes it difficult to aggregate data and draw conclusions on the simultaneous effect of perturbations and their clinical implications. Most studies included lack of description in their protocols, data pre-processing and reporting, and calculation of features is an important negative factor for reproducibility, hence fell the risk of bias evaluation.

As suggested in a previous paper (Quijoux et al., 2021), future research would benefit from an expert consensus on experimental posturographic protocols including sensory perturbations as well as other relevant conditions (e.g. dynamic evaluation, motor or cognitive double-task), signal processing, variables interpretation and cut-off scores, to allow for more meaningful comparisons across studies. Regarding posturographic variables and clinical interpretation, the next key step forward is identifying a core set of CoP features that best capture age-related changes and their relationship to sensory function, motor skills or fall risk, or use a domain analysis with aggregated features as presented in this paper, to reduce the complexity of analyses.

While an expert consensus on posturographic evaluation necessitates rigorous methodological guidelines, implementing posturographic evaluation with older people, particularly in nursing homes, presents significant challenges for clinicians. The primary difficulty lies in the complexity and resource intensity of the current technology and protocols, coupled with the functional limitations of the patient population. For example, the instructions can be difficult to implement due to cognitive impairments (patient moving or talking during examination thus introducing bias); or neuromuscular/motor disabilities preventing standardization in the body or feet position, as well as sensory perturbations.

The best evidence analyses of outlier protocols and features delved deeper into the impact of specific sensory manipulations on balance in older adults. By examining the effects on CoP features, the review was able to highlight the role of proprioceptive and vestibular afferences in maintaining balance, even though most protocols in the literature solely test visual deprivation.

The lack of vestibular perturbations in the studies can be explained by the difficulty of manipulating that afference and test it with a

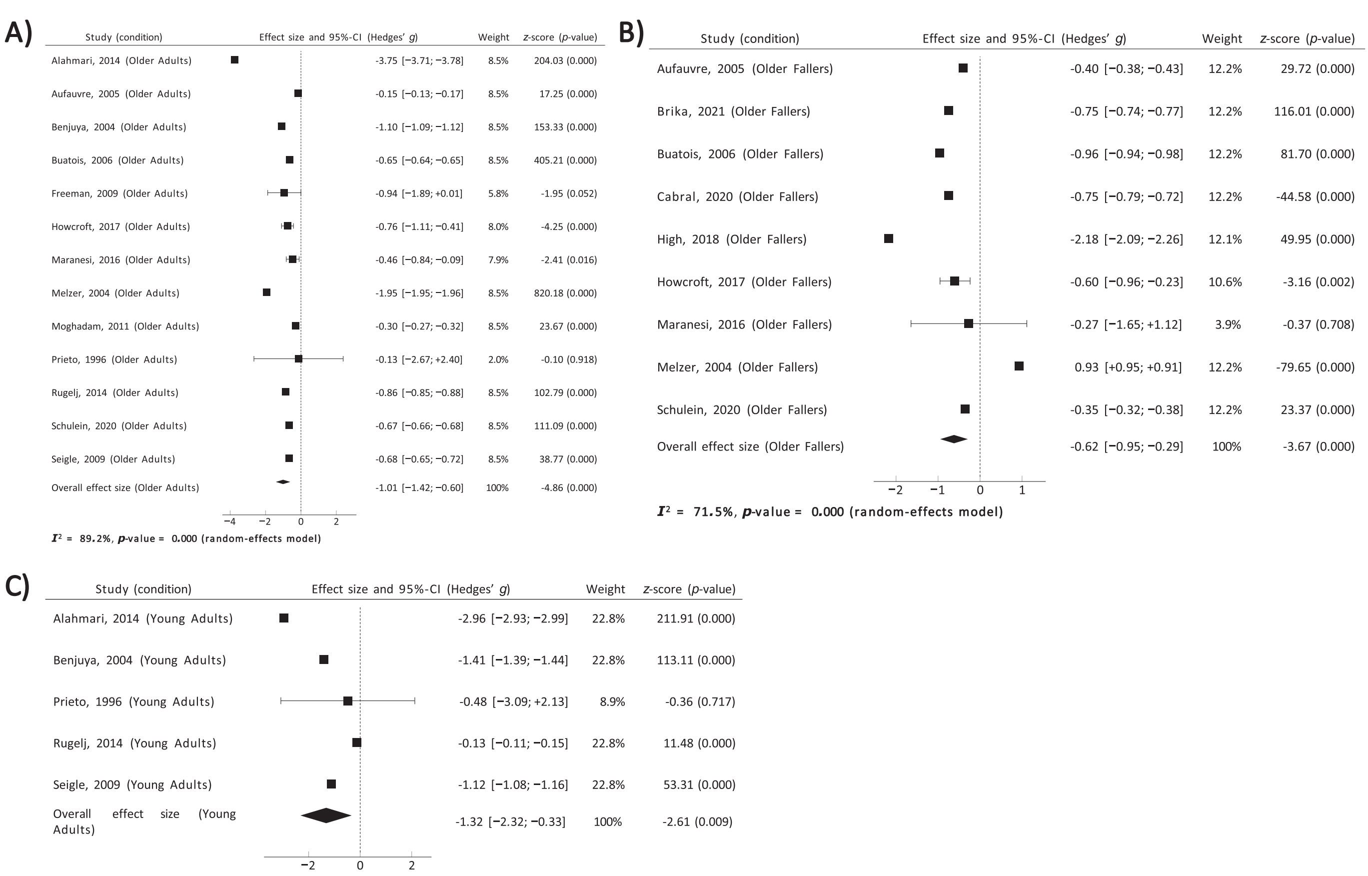

Fig. 4. Forest plots comparing balance with eyes open and closed with positional features in Older Adults (A), Older Fallers (B) and Young Adults (C).

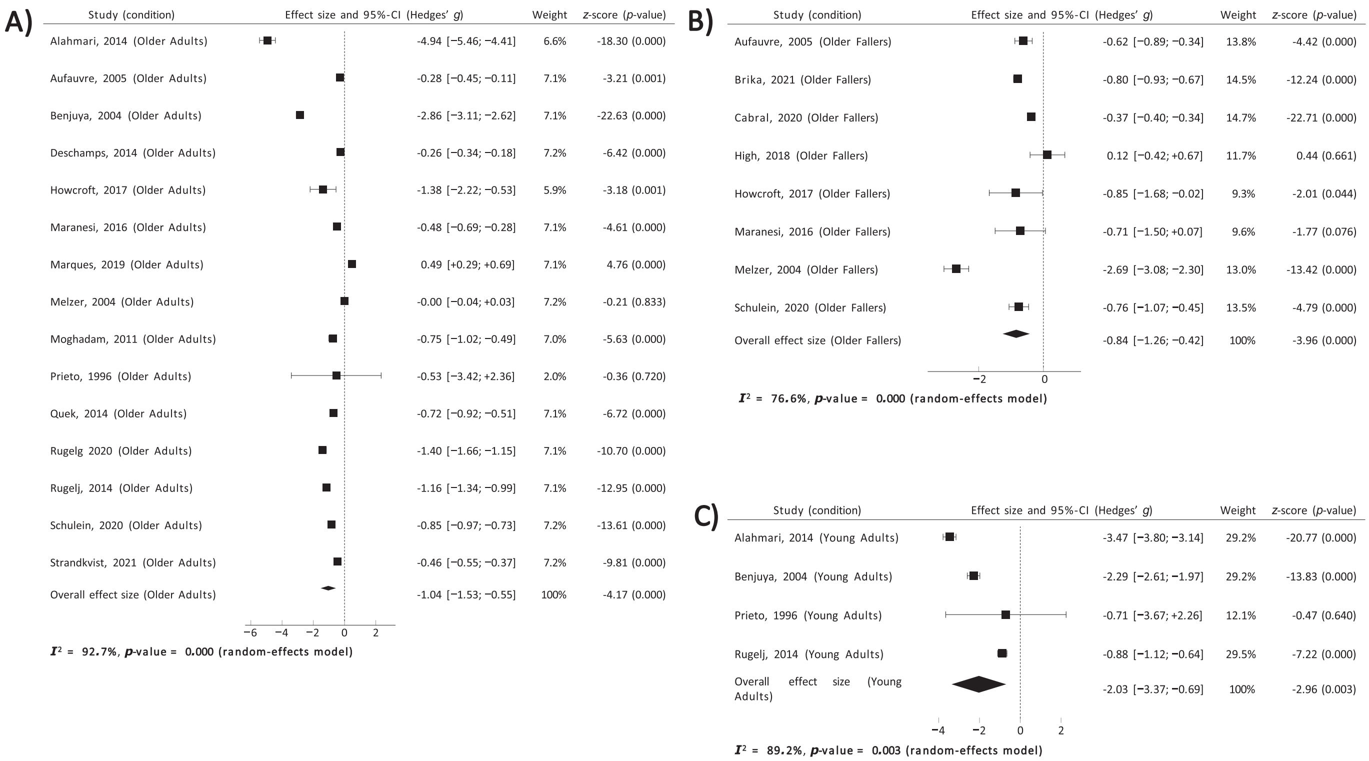

Fig. 5. Forest plots comparing balance with eyes open and closed with dynamic features in Older Adults (A), Older Fallers (B) and Young Adults (C).

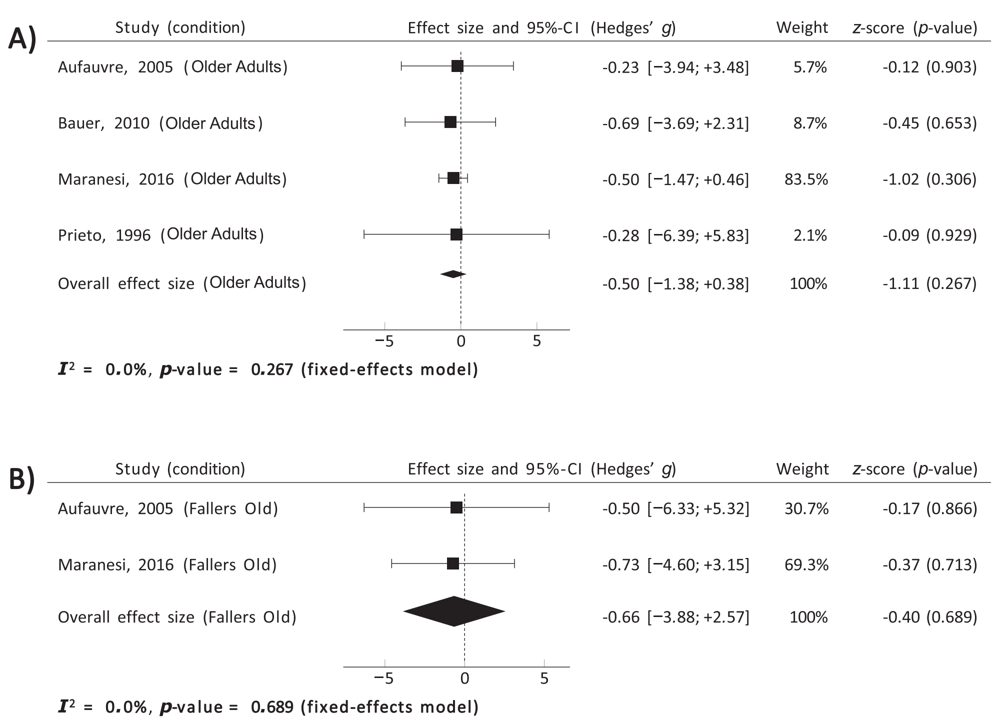

Fig. 6. Forest plots comparing balance with eyes open and closed with frequential features in Older Adults (A) and Older Fallers (B).

population at fall risk. However, Anand et al. (2003) and Buckley et al. (2005) were able to test it with head extension during quiet stance, which suggest more studies could be conducted with similar protocol in order to add more data to aggregate in a future meta-analysis.

Positional and dynamic domains showed better significance than frequency features to detect a change in balance due to sensory perturbation, across all groups. The dynamic domain was explored for OA in proprioceptive and visual perturbations. Proprioceptive interference seemed to induce a larger deterioration in balance than visual deprivation, based on respective effect sizes. Theses analyses revealed that older adults exhibited increased postural instability, as measured by greater effect sizes in CoP features under challenging sensory conditions, but younger adults exhibited similar behavior. While the balance of both young and older adults is impacted by sensory perturbation, fall risk is

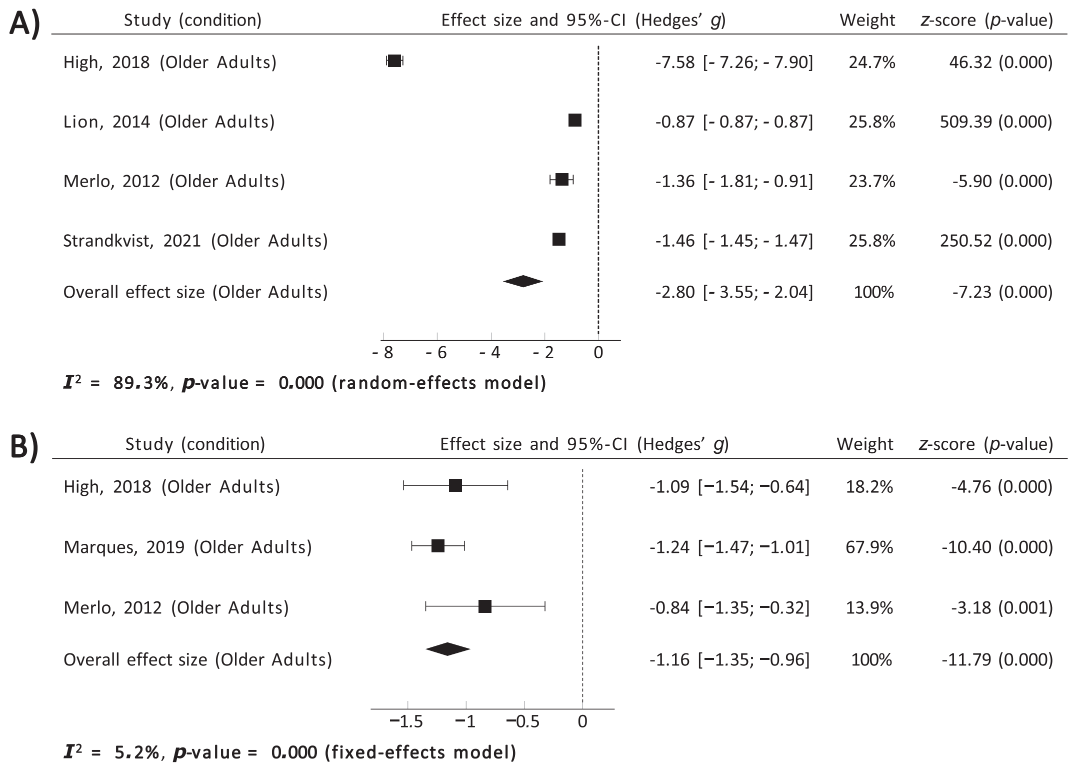

Fig. 7. Forest plots comparing balance of Older Adults on a stable platform or on foam with positional (A) and dynamic (B) features.

significantly higher in the older population (World Health Organization, 2021). This suggests that age-related declines in sensory integration and processing may impair the ability of older adults to effectively adapt their postural control and motor strategies to compensate for disruptions in afferent feedback, as previously established by Osaba et al. (2020) while studying gait. This finding also questions the impact of individual deficits or dysfunction in sensory afferences, revealing the importance of these protocols to detect underlying sensory conditions which could induce a sensory preference or dependence, preventing the individual to adapt in a challenging environment.

Regarding the greater effect sizes in visual conditions for younger adults compared to older ones, a possible explanation for this result could be underlying balance disorders of older adults leading to instability in the control condition, thus reducing the difference between conditions for this group.

Another finding was the non-significance of the frequency meta-analyses, in contradiction with the literature suggesting frequency features could especially highlight instability related to sensory perturbation (Jurkojć et al., 2021). Previous studies suggested that frequency analysis, and the identification of certain bandwidth in particular, could be relevant for exploring balance adaptation in elderly people. Baloh et al. (1994) were able to discriminate younger and older adults based on the ratio of high frequency energy content over low frequency ratio, and Sullivan et al. (2006) suggested that this ratio could be useful to evaluate balance instability due to neurological disorders and sensory perturbations.

While our findings do not support the above, it is important to note that we only included 4 and 2 studies respectively for OA and OF in our meta-analyses for frequency features. The aggregation of frequency indicators into a single domain does not allow us to specifically explore a feature on a particular bandwidth, as does the lack of data in the literature. For this reason, and because of the lack of physiological interpretability of these indicators, further research is needed, while explicitly specifying the feature calculation methods, material sample frequency and posturographic signal pre-processing steps that have a major impact on the results of the domain frequential variables (Quijoux et al., 2021).

The development of stochastic analyses in posturography is recent, hence the few number of studies and the variety of methods, with no consensus on their relevance. However, the individual results suggest they could be interesting to explore with more protocols and participants as they could enlight us on more complex postural control strategies and dynamics. For example, various authors suggested that features derived from Stabilogram Diffusion Analysis (SDA) could reflect specific phenomena contributing to balance. Collins and De Luca (1993) theorized that two complementary systems (closed and open loops) regulated postural balance based on time scale, while Peterka (2000) proposed a model with a continuous closed-loop regulation. Other models based on a Langevin equation try to parallel the parameters of the model to biomechanical systems and forces. They describe the center of pressure trajectory as a result of brownian motion with one or several parameters interpreted as a recall force, a corrective joint movement or a stiffness constant (Nicolaï, 2021).

Further investigations are needed to understand the physiological phenomena adjusting balance in human, but we suggest that stochastic analyses could provide a better insight of these underlying mechanisms than positional or dynamic features which reflect the consequences of these adjustments.

In summary, there is a need to reduce the number of posturographic features used in the literature by selecting the relevant ones or aggregating them in domains as described in this review. Furthermore, we reckon that positional, dynamic, frequential and stochastic domains are complementary and offer a different insight into postural balance. Stochastic analyses model the systems aiming at pulling the center of mass back to a reference position, while frequency analyses reveal the forces acting at different time scales to achieve this objective. Finally, positional and dynamic analyses offer a visualization of the consequences on postural control, by describing the trajectory of the center of pressure.

These findings have important clinical implications, as they could inform the development of targeted evaluations and interventions to improve balance and reduce fall risk in older adults by addressing specific sensory deficits and adapt their environment. A systematic review from Zhang et al. (2021), as well as a more recent study (Ni et al., 2024) reported balance improvement after a sensory-based training program. We suggest that posturographic evaluation with sensory conditions could be used to personalize such programs, rendering them more efficient.

6. Limitations

A key limitation of this review is the variable quality of the included studies, with many lacking important details about participant characteristics, experimental protocols, and data analysis procedures. Furthermore, many studies did not include raw data, despite the authors being contacted, not allowing us to include their work in the meta-analyses. These factors make it challenging to critically evaluate the findings and draw robust conclusions, and may have contributed to the substantial heterogeneity observed in the meta-analyses, limiting the strength of the conclusions that can be drawn. Additionally, the proliferation of diverse postural control features across studies, often with inconsistent terminology, hinders the ability to synthesize results and establish a consensus on the most sensitive markers of age-related changes in sensory-motor function.

A common limitation also noted across the literature is the non-representative nature of the participant samples, with many studies excluding older adults with common pathologies or impairments (e.g. dementia, Parkinson's disease, cognitive impairment). This reduces the generalizability of the findings, as the samples may not reflect the true diversity of the older adult population, especially for 80+ years old. Future research should aim to include a more representative sample of community-dwelling older adults, including those with mild to moderate sensory, cognitive or mobility deficits. While studies on a more vulnerable population are needed, it also presents challenges, since most protocols perturbing proprioceptive and vestibular afferences are not feasible for many frail, disabled or cognitive impaired older adults.

The quality assessment of the synthesized literature revealed several persistent methodological shortcomings that introduced substantial variability and weakened the cumulative strength of the evidence. These limitations included the frequent reliance on small sample sizes across studies, which restricts statistical power and limits the generalizability of the findings. Furthermore, there was inconsistent and often insufficient reporting of key participant characteristics and a lack of standardization in the specific posturographic variables and protocols utilise. These inconsistencies contributed directly to the significant heterogeneity observed in the meta-analyses, thereby impeding the ability to draw robust, definitive conclusions regarding the magnitude and mechanisms of age-related balance deficits during sensory perturbations. Nonetheless, the overall body of evidence supports the notion that older adults demonstrate greater postural instability when faced with sensory challenges compared to younger adults.

Regarding the meta-analyses, the methodology for aggregation rely on estimated correlations between features, based on a different dataset than the studies included. While these correlations could vary with a different dataset, we chose to base our calculations on an publicly available dataset with exhaustive description of protocols and population (Santos and Duarte, 2016). We suggest that future studies systematically explore features correlations for their protocols and population to help identify redundant features, and thus relevant ones.

7. Conclusion

This systematic review allowed us to highlight the importance of sensory feedback for balance, confirming the need for evaluation, targeted interventions and adaptations to prevent falls in challenging situations such as unstable ground or diminished luminosity, based on the patient's posturographic test and sensory dysfunction. As we previously stated, individual systems can be evaluated, with visual, proprioceptive and vestibular examinations. We suggest that when confronted with postural instability or falls, a combination of sensory examinations and posturography could help clinicians have a more detailed and comprehensive understanding of the patient's fall risk as well as the underlying cause(s).

The methodology of the meta-analyses, aggregating posturographic features with correlation matrices was introduced in response to the diversity of variables in the literature and allowed us to synthetize results in spite of it. This lack of harmonization, in addition to the vast number of sensory protocols (sensory conditions, position, duration), leads us to suggest a consensus should be discussed and published by experts in the near future, with recommendations on protocols, data preprocessing and analysis, to help aggregate future results and draw more robust conclusions.

CRediT authorship contribution statement

J. Aflalo: Writing – review & editing, Writing – original draft, Methodology, Formal analysis, Data curation, Conceptualization. **C. Truong:** Writing – review & editing, Methodology, Formal analysis. **A. Nicolaï:** Methodology. **L. Gouzer:** Writing – original draft, Data curation. **B. Morisset:** Writing – original draft, Data curation. **F. Bertin-Hugault:** Validation, Supervision, Methodology, Funding acquisition, Conceptualization. **D. Ricard:** Validation, Supervision, Methodology, Funding acquisition, Conceptualization. **F. Quijoux:** Writing – review & editing, Validation, Supervision, Methodology, Funding acquisition, Conceptualization.

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Declaration of competing interest

The authors declare that they have no competing interests.

Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.exger.2025.112976.

Data availability

No data was used for the research described in the article.

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