Sensorimotor and proprioceptive exercise programs to improve balance in older adults: a systematic review with meta-analysis

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Abstract

The primary aim of this study was to systematically review and meta-analyze the impact of sensorimotor and proprioceptive exercises on balance in older adults. We also sought to define how researchers describe proprioceptive and sensory-motor training and their respective protocols. The review was conducted following the PRISMA guidelines, with searches performed in March 2023. Both authors carried out independent searches using the PubMed and PEDro databases. From a total of 320 identified records, 12 studies were deemed eligible for meta-analysis after screening and removal of duplicates. The average PEDro score was 5.11 ± 1.11 indicating overall fair quality of studies. Common outcome measures included the Berg balance scale, Timed up and go test, Tinetti balance scale, Functional reach test and various single-leg stance tests. All outcomes were significantly improved by the interventions (standard mean difference = 0.65 – 1.29), with little difference between proprioceptive and sensorimotor training. However, the quality of evidence ranged from “very low” to “low” based on GRADE guidelines, suggesting further high-quality studies are needed. This review underscores the potential benefits of sensorimotor and proprioceptive exercises for enhancing balance in older adults, while also highlighting the ambiguity and inconsistency regarding the usage of the terms proprioceptive and sensorimotor training.

Key Words: proprioception; elderly; postural control; risk of falls; fallers.

Eur J Transl Myol 34 (1) 12010, 2024 doi: 10.4081/ejtm.2024.12010

Older adults are growing in number, resulting in higher prevalence of musculoskeletal injuries. Age-associated functional declines in muscle strength and the sensory systems, along with other changes, contribute to reductions in balance and a consequent increase in fall risk.[1] A systematic literature review demonstrated that an increased risk of falls is associated with history of falls, being unstable while walking, cognitive disturbances, physical inactivity, antidepressant use, confusion, and urinary incontinence.[2] Vieira et al.[3] listed outside obstacles, vertigo, sleep disturbance, chronic illness, several medications, and need for personal assistance as risk factors for geriatric patient falls. Fall related injuries have medical, psychological and social implications and are associated with high medical costs. A need for prolonged treatment along with associated psychological and physical limitations may lead to loss of independence in activities of daily living.[4,5] Falls and associated injuries are common in older adults, with approximately 30% of adults 60 years of age or older experiencing a fall over a one-year period.[5,6] Falls are more common in elderly individuals who are physically weaker and those living in senior housing/facilities. Falls lead to soft-tissue injuries, bone fractures, subsequent difficulties with activities of daily living, and depression.[7]

Fall prevention strategies play an important role in reducing falls and their associated comorbidities.[8] Several studies have shown that exercise interventions including balance exercises and walking training are effective in mitigating the risk of falls.[9] Proprioceptive and sensory-motor training are two promising interventions for fall prevention and balance improvement.[10] Components of proprioceptive system are a foundational element of movement and play a key role in motor behavior.[11] Maintaining balance relies on efficient integration of sensory information from visual, vestibular and somatosensory systems.[12,13] During locomotion, sensory neurons provide important information about limb location and movement in space.[14] Elderly subjects are more dependent on visual information to ensure balance control, which is reflected in a more pronounced deterioration of balance when vision is removed.[15] Proprioceptive functions degenerate

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with age, which has been linked to balance deficits and increased risk of falling.[16] Proprioceptive training is an intervention aimed at improving proprioceptive function. It focuses on the use of proprioceptive signals, including kinesthetic and tactile-afferent senses, in the absence of information such as visual perception. The end-goal of such training is improvement and recovery of sensorimotor function.[17] Many studies also incorporate walking on uneven surfaces into proprioceptive training of lower limbs, which contributes to generation of movement responses and joint stability.[10]

Sensorimotor training is a similar approach, which by definition includes an accelerated input of somatosensory and proprioceptive stimuli, correcting muscle imbalance and ensuring a correct motor program at the central nervous system level.[18] The central nervous system integrates sensory and motor information to acquire skilled movements and respond to external perturbations through a process known as sensory-motor integration. The reciprocal interaction of the sensory and motor systems is a prerequisite for learning and performing skilled movement.[19] Simultaneous activity of both systems stimulates plasticity at their junction and is used to improve sensory and motor inputs in the sensorimotor integration centers. This is the process by which one senses one's own body and the surrounding environment in order to preform movement.[19] Researchers are finding that training interventions focusing on the execution of correct, rapid and well-directed steps may have a very valuable role in preventing falls. Training is particularly appropriate on uneven surfaces because it improves individual's cognitive perception and sensorimotor abilities.[20]

The primary aim of this paper was to conduct a systematic literature review and meta-analysis to determine the distinct effects of sensorimotor and proprioceptive exercise on balance in older adults. Unlike previous reviews, our work specifically compares these two types of exercises, addressing a gap in the literature. This paper stands out in its effort to clarify the overlapping and often ambiguous definitions of proprioceptive and sensorimotor training. Due to the ambiguous and versatile definitions of these terms across studies, a question arises whether they are truly two different approaches or simply two different terms describing the same approach.[21] Aman et al.[17] found that many studies use the term proprioception very loosely, frequently relying on tasks that include multimodal sensorimotor learning. Our analysis directly addresses this concern by critically examining the definitions and implementations in the included studies. We argue that distinguishing between sensorimotor and proprioceptive exercises is essential for scientific accuracy and clinical application. If we adopt the stance that any form of sensorimotor learning denotes proprioceptive exercise, the term itself carries little scientific meaning for the clinical community. If sensorimotor training is a form of unimodal sensory training or a form of specialized sensorimotor learning, this should be explicitly stated in order to avoid terminological unclarity and confusion.[21,22] Despite a large number of published studies about proprioceptive and sensorimotor exercises, there is a general lack of consensus on the exact meaning of these two terms, with different exercises being included in the training regimens. Consequently, the impact of proprioceptive and sensorimotor interventions on balance in elderly adults is unclear. Through our systematic approach, we provide insights into the distinct effects of these interventions, thereby contributing significantly to the field.

Materials and Methods

Search Strategy and inclusion criteria

The review was conducted according to PRISMA guidelines. The review was not prospectively registered, as the PROSPERO database only accepted COVID-19-related protocols at the time this review was initiated. The search was performed in March 2023. Both authors independently performed all search steps, and any disagreements were resolved by discussion. We searched the PubMed, Google Scholar and PEDro database. For PubMed, we used the following search string: (proprioceptive training OR proprioception training OR proprioception exercise OR sensorimotor training) AND (older adults OR eldery OR ageing). In the PEDro database, we used the simple search option and separately entered four individual combinations of words (i.e., "sensorimotor training elderly", "sensorimotor training older adults", "proprioception training elderly" and "proprioception training older adults" were used). In Google Scholar database, we used the simple search option and separately entered two individual combinations of words (i.e., "older adults proprioception training" and "older adults sensorimotor training" were used). In addition, we reviewed the reference lists of identified systematic reviews on the topic, and scrutinized reference lists of articles included in the first phase. The records were imported into Mendeley (version 1.19.8) to remove the duplicates, and then exported into Microsoft Excel software for further examination.

The inclusion criteria, structured according to the PICOS tool,[23] were determined as follows:

- P (population): Participants aged 55 years or more. Although older adults are typically classified as older than 65 years, balance deterioration may begin as early as after age 50. [4,25] Therefore, we decided to decrease the minimum participant age for 10 years. Studies were included if the participants were healthy or had chronic non-communicable diseases, with subgroup analysis attempts made where possible.
- I (Intervention): Exercise-based intervention, denominated as "sensorimotor" or "proprioceptive" training.

- C (Comparison): Control groups receiving no intervention, "usual care" intervention or education-based intervention.
- O (Outcome): Instrumented or field-based balance tests (posturography, single-leg stance test) or balance scales (e.g., Berg balance scale, Tinneti balance scale)
- S (Study design): Randomized and non-randomized controlled trials.

Data extraction

The data extraction was performed by both authors and disagreements were resolved through additional discussion. The following data was extracted: (a) baseline, post-intervention and follow-up data (means and standard deviations) for all outcome measures for experimental and control groups; changes (in %) were considered instead of pre-post data when available (b) baseline demographics of participants (sex, age, body height, body mass, body mass index); (c) intervention characteristics (duration of the intervention, weekly frequency, volume (number of exercises, sets, and repetitions), inclusion if resistance exercise, breaks, and supervision). Data were carefully collected into Microsoft Excel 2016 (Microsoft, Redmond, WA, USA). If the data were presented in a graphical format, we used GetGraphDataDigitalizer software (version 2.26.0.20) to accurately determined the means and standard deviations. In case of missing data, the authors of the articles were contacted by e-mail A reminder was sent after 14 days, and if no reply was received, the data was considered irretrievable.

Study quality assessment

Both authors evaluated the risk of bias of the included studies using the PEDro scale which assesses study quality based on a 10 items.[26] Potential disagreements between the reviewers were resolved by discussion. Studies scoring from 9 to 10 were considered as "excellent," 6 to 8 as "good," 4 to 5 as "fair," and <4 as "poor" quality. The PEDro scale was selected because it was specifically developed to evaluate the quality of clinical trial studies investigating physical therapy interventions.[27]

Certainty of evidence assessment

The certainty of evidence was assessed according to GRADE guidelines.[28] GRADE guidelines encompass 5 main domains (risk of bias, precision, consistency, directness, and publication bias) to categorize evidence quality. The comparisons were classified as representing either high, moderate, low or very low quality of evidence. Each study score started as "high quality", and the level of evidence was downgraded if: a) there was a substantial heterogeneity among the studies (I2 > 50 % or statistically significant heterogeneity test (inconsistency); b) more than 25 % of studies were classified as fair or poor quality (risk of bias); c) the studies assessed the effects of the intervention indirectly (e.g., population, intervention or outcome not being representative of the research question) (indirectness), d) when a large CI was observed, or when the total number of participants was <200 (imprecision) e) when the study results provided differed from the original protocol or study objectives (publication bias).[29]

Data analysis

The meta-analysis was done in Review Manager software (Version 5.3, Copenhagen: The Nordic Cochrane Center, The Cochrane Collaboration, London, UK). Although there has been consensus on the minimum number of studies required for a meta-analysis [30], we decided to performed the analyses when three or more studies could be included. Before the results were entered into the meta-analysis software, the pre-post differences were calculated by subtracting baseline values from post-intervention values. In addition, standard deviations of the pre-post difference were calculated according to the following formula SD = √[(SD2pre + SD2post) – (2 × r × SDpre × SDpost). The correction value (r), which represents the pre-test–post-test correlation of outcome measures, was conservatively set at 0.70. The meta-analyses were done using continuous outcomes module, with a random-effects model and inverse variance method. The pooled effect sizes were expressed as standardized mean difference (SMD), with 95 % confidence intervals (CI) reported alongside to provide the precision of the overall effect estimate.[31] Absolute mean difference (MD) was also reported to provide a more tangible and practically useful estimate of the intervention effects. Statistical heterogeneity among studies was determined with the I2 statistics. According to Cochrane guidelines, the I2 statistics of 0% to 30% might not be important, 30 to 60% may represent moderate heterogeneity, 50–90% may represent substantial heterogeneity, and 75–100% indicates considerable heterogeneity. In case of substantial heterogeneity between the studies, a subgroup analysis was performed to examine the effect of moderator variables such as participants characteristics (e.g., patients vs. healthy) and intervention (e.g., sensorimotor vs. proprioceptive training, weekly frequency).

To elucidate the distinctions and similarities between proprioceptive and sensorimotor training approaches, we conducted a systematic analysis of the exercise variables employed in the included studies. This analysis encompassed the duration and frequency of the interventions, session lengths, types of exercises, implementation of gait training, the use of equipment, and the inclusion of cognitive tasks.

Results

General overview of the search results

We identified 155 records through a database search and 165 records through an additional search of the reference lists. After duplicates were removed, 135 records were screened. In a next step, 26 articles were screened for eligibility. A total of 12 studies were eligible for meta-

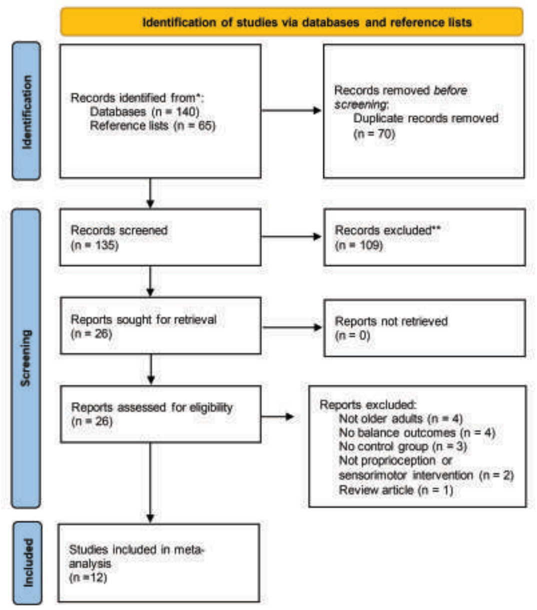

Fig 1. *PRISMA Diagram*

analysis. The detailed summary of the search process is shown in Figure 1.

Detailed characteristics of included studies (participants, intervention type, control group, outcome measures, main findings) are also presented in Supplementary Materials Table 1. Both men and women participated in 10 studies, in a study by Teixeira et al.[32] there were only women and in the study by Salah et al.[33] had only male subjects. In most studies, the participants were adults (range of means for age: 60,6 to 83,2 years), except in the study by Da Silva et al.[34] which examined older adults (57,9 ± 8.50 years). This study was the only one where the subjects were on average younger than 60 years old. Across studies, weekly frequency ranged from 2 to 3 and session durations ranged from 30 to 60 minutes. In most studies, the control groups performed education only or usual care. In one study, the participants in the control group did perform the physiotherapy.[35] The most common outcome measures were the Berg balance scale (9 studies), the Timed up and go test (7 studies), the Tinetti balance scale (5 studies), single-leg stance test with eyes open (4 studies), single-leg stance test with eyes closed (3 studies) and the functional reach test (2 studies). Proprioceptive training was defined in 9 studies, in 3 studies the authors defined the intervention as sensorimotor training.

Comparison between the content of proprioceptive and sensorimotor training

The detailed intervention descriptions are shown in Supplementary Materials Table 2. We observed that while the overall duration (8 to 16 weeks) and frequency (2 to 3 times weekly) of these training programs were similar. Proprioceptive training primarily included exercises aimed at enhancing the body's internal sense of position, such as balance and gait training on uneven surfaces. In contrast, sensorimotor training often incorporated a broader range of activities, integrating physical exercises with cognitive challenges to stimulate both motor and cognitive functions. A key difference was noted in the use of gait training and equipment. Gait training was more prevalent in proprioceptive exercises, whereas sensorimotor training displayed a greater diversity in equipment, including technology-enhanced tools. The inclusion of cognitive tasks was another distinguishing feature of sensorimotor training, contrasting with the predominantly physical focus of proprioceptive exercises. This analysis reveals that despite shared goals in improving balance, proprioceptive and sensorimotor training approaches exhibit distinct methodologies and emphases in their implementation, highlighting the need for clear definitions and standardized protocols in future research.

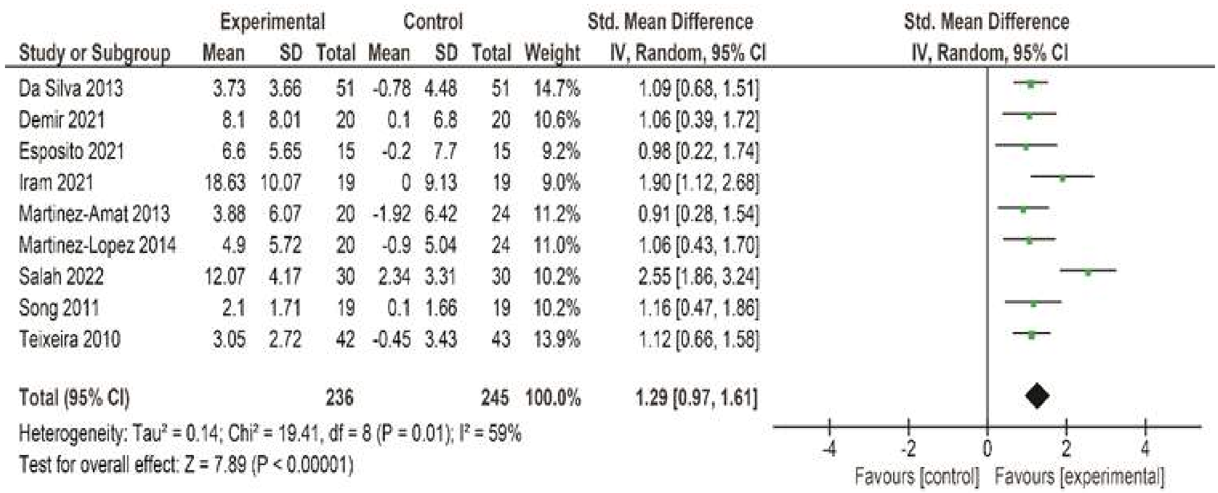

Fig 2. *Meta-analysis for Berg balance scale*

Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Da Silva 2013	2.31	3.5	51	-0.37	3.99	51	38.7%	0.71 [0.31, 1.11]
Demir 2021	4.7	4.54	20	-0.15	5.14	20	14.3%	0.98 [0.32, 1.64]
Espejo-Antunez 2020	1.58	2.09	21	-0.84	2.2	21	14.5%	1.11 [0.45, 1.76]
Martinez-Amat 2013	3.59	5.22	20	-0.34	7.88	24	16.9%	0.57 [-0.04, 1.17]
Martinez-Lopez 2014	3.4	2.68	20	-0.4	4.45	24	15.6%	0.99 [0.36, 1.63]
Total (95% CI)			**132**			**140**	**100.0%**	**0.83 [0.58, 1.08]**

Heterogeneity: Tau² = 0.00; Chi² = 2.22, df = 4 (P = 0.70); I² = 0%
Test for overall effect: Z = 6.49 (P < 0.00001)

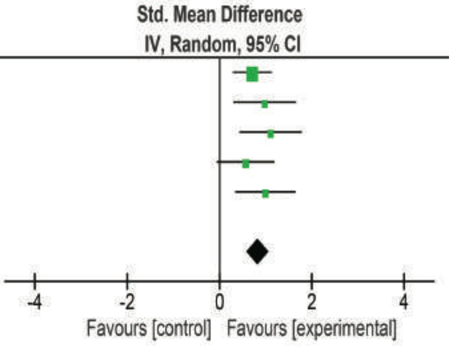

Fig 3. *Meta-analysis for Tinneti balance scale.*

Assessment of study quality

The assessment of study quality according to Pedro Scale is shown in Supplementary Materials Table 3. Four studies were of good quality and eight studies were of fair quality. The average score was 5.11 ± 1.11 (median = 5), indicating overall fair quality of evidence.

Effects on Berg balance scale

In total, 9 studies included BBS as an outcome measure (236 and 245 participants in experimental and control groups, respectively). There was low-quality evidence that interventions had statistically significant and large effect on BBS score (SMD = 1.29; [CI: 0.97 – 1.61]; p < 0.001; I2 = 59 %). In absolute terms, the BBS score was increased by 6.50 units [CI: 4.20 – 8.79] (Figure 2). Subgroup analyses indicted no difference (p = 0.120) in the overall effects between studies conducted with healthy participants (SMD = 1.03; [CI: 0.75 – 1.32]) and patients (SMD = 1.53; [CI: 0.97 – 2.09]). All studies but one termed their intervention as sensorimotor training, therefore, no subgroup comparison was made between proprioceptive and sensorimotor training.

Effects on Tinetti balance scale

In total, 5 studies included Tinneti balance scale as an outcome measure (132 and 140 participants in experimental and control groups, respectively). There was low-quality evidence that the interventions had statistically significant and large effect on Tinneti balance scale score (SMD = 0.83; [CI: 0.58 – 1.08]; p < 0.001; I2 = 0 %) (Figure 3). In absolute terms, the Tinneti balance scale score was increased by 2.96 units [CI: 2.14 – 3.79]. Three studies involved proprioceptive training and two used sensorimotor training. As the study effects were very homogenous (I2 = 0 %), no subgroup analyses were performed.

Effects on Timed up and Go test

In total, 9 studies included TUGT as an outcome measure (179 and 177 participants in experimental and control groups, respectively). Very low-quality evidence suggests that the interventions had statistically significant and large effect on TUGT score (SMD = 1.03; [CI: 0.59 – 1.64]; p < 0.001; I2 = 70 %). In absolute terms, the TUGT time was reduced for 2.33 seconds [CI: 1.02 – 3.64]. Four studies involved proprioceptive training and three used sensorimotor training. Subgroup analyses indicted a potential difference between the intervention types (p = 0.07), with proprioceptive training studies showing larger effect (SMD = 1.32; [CI: 0.59 – 1.91]) compared to sensorimotor training studies (SMD = 0.70; [CI: 0.37 – 1.03]). All studies but one termed their intervention as sensorimotor training, therefore, no

Study or Subgroup	Experimental Mean	Experimental SD	Experimental Total	Control Mean	Control SD	Control Total	Weight	Std. Mean Difference IV, Random, 95% CI
Ahmad 2019	-1.78	1.69	12	-0.68	1.76	9	11.2%	-0.61 [-1.50, 0.27]
Da Silva 2013	-2.72	2.02	51	0.09	4.3	51	17.8%	-0.83 [-1.24, -0.43]
Espejo-Antunez 2020	-4.94	5.41	21	0.33	8.34	21	14.6%	-0.74 [-1.36, -0.11]
Iram 2021	-3.69	1.57	19	-0.26	2.31	19	12.9%	-1.70 [-2.45, -0.95]
Morat 2019	-0.1	0.58	15	0.2	1.04	15	13.3%	-0.35 [-1.07, 0.38]
Song 2011	-1.7	1.71	19	-0.1	1.7	19	14.0%	-0.92 [-1.59, -0.25]
Teixeira 2010	-3.84	1.65	42	-0.2	2.12	43	16.2%	-1.90 [-2.41, -1.38]
Total (95% CI)			**179**			**177**	**100.0%**	**-1.03 [-1.46, -0.59]**

Heterogeneity: Tau² = 0.23; Chi² = 20.02, df = 6 (P = 0.003); I² = 70%
Test for overall effect: Z = 4.66 (P < 0.00001)

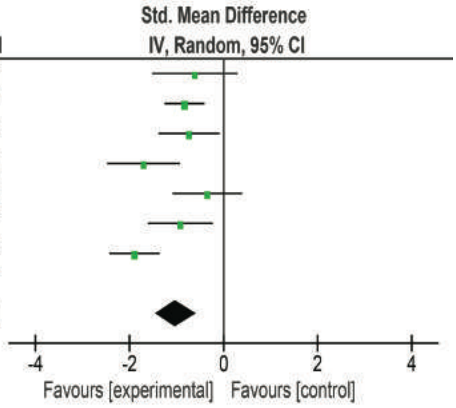

Fig 4. *Meta-analysis for Timed up and go test.*

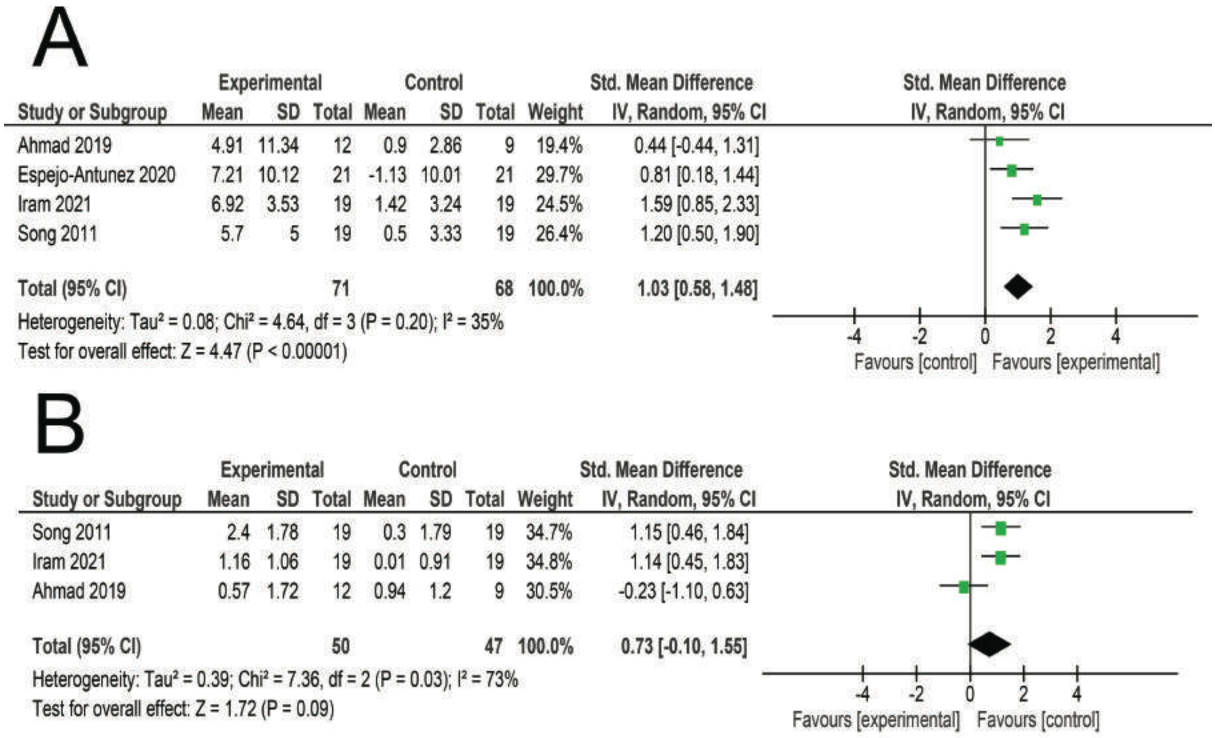

Fig 5. *Meta-analysis for single-leg stance test with eyes open (A) and eyes closed (B).*

subgroup comparison was made between proprioceptive and sensorimotor training.

Effects on single-leg stance

In total, 4 studies included single-leg stance test (eyes open) as an outcome measure (71 and 68 participants in experimental and control groups, respectively). Very low-quality evidence suggests that interventions had statistically significant and large effect on single-leg test time (SMD = 1.03; [CI: 0.58 – 1.48]; p < 0.001; I2 = 35 %) (Figure 5A). In absolute terms, the single-leg test time score was increased by 5.51 seconds [CI: 3.93 – 7.08]. Three studies involved proprioceptive training and one used sensorimotor training. Given the low number of studies and small heterogeneity between them, no subgroup analyses were performed.

In addition, three studies included single-leg test with eyes closed (50 and 47 participants in experimental and control groups, respectively). Very low-quality evidence suggests that interventions showed a moderate effect which was not statistically significant (SMD = 0.73; [CI: –0.10 – 1.48]; p < 0.090; I2 = 73 %) (Figure 5B). In absolute terms, the effect indicated an increase for 1.01 seconds [CI: –0.10 – 2.17]. Two studies involved proprioceptive training and one used sensorimotor training.

Effects on functional reach test

In addition, 2 studies included FRT as an outcome measure (31 and 28 participants in experimental and control groups, respectively). Very low-quality evidence suggests that interventions had statistically significant

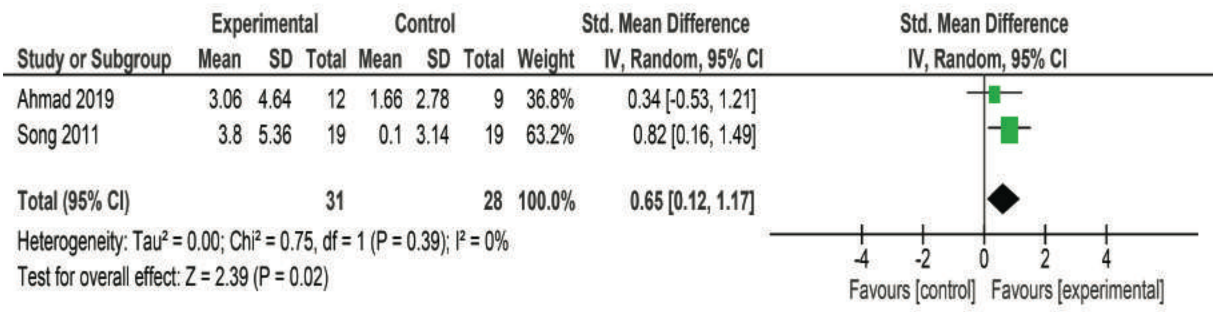

Fig 6. *Meta-analysis for functional reach test.*

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and moderate effect on FRT distance (SMD = 0.65; [CI: 0.12 – 1.17]; $p < 0.021$; I2 = 0 %) (Figure 6). In absolute terms, the FRT score was increased by 2.69 cm [CI: 0.45 – 4.92]. One study used proprioceptive training and one used sensorimotor training.

Discussion

The primary objective of this paper is to perform a systematic literature review and meta-analysis to assess the impact of sensorimotor and proprioceptive exercises on balance in older adults. Additionally, we sought to define, through qualitative analysis, how researchers describe proprioceptive and sensory-motor training and their respective protocols. We also aimed to evaluate the effectiveness of these training regimens on balance and other motor skills in older individuals via a meta-analysis. In the reviewed literature, eight studies labeled the exercise as "proprioceptive" while three termed it "sensory-motor" (refer to Supplementary Materials Table 1). Overall, older participants who underwent proprioceptive and sensorimotor training exhibited notable enhancements in most baseline measurements when compared with control groups. For most outcome measures, the evidence, albeit of very low quality, indicated that the interventions significantly improved the outcomes. Notably, the FRT outcome measure showed the interventions led to a statistically significant, moderate effect (as seen in Figure 6). Conversely, the one-leg stand test (with eyes closed) demonstrated a moderate but not statistically significant improvement due to the interventions (refer to Figure 5). One study reported no improvement in balance in the one-leg stand test (with eyes closed) following an 8-week sensory-motor training period. When considering the TUGT outcome measure, subgroup analyses revealed that studies focusing on proprioceptive exercises yielded a more pronounced effect than those involving sensorimotor exercises (see Figure 4). For the BBS outcome measure, there was no discernible difference in the overall effects between studies that focused on healthy participants versus those that focused on patients (refer to Figure 2). The findings from our literature

Fig 7. *An example set of "proprioceptive" exercises on a balance foam pad.*

review therefore indicate that both proprioceptive and sensory-motor training yield similar beneficial outcomes on balance in the elderly. The studies encompassed in our meta-analysis suggest that training regimens spanning 8 to 18 weeks (averaging 12 weeks), conducted 2 to 3 times weekly and lasting 30 to 60 minutes per session (with an average duration of 45 minutes), are efficacious.

Previous literature reviews complemented with meta-analyses have already explored the effects of different fall prevention programs for older adults.[36,37] From these reviews, it is clear that balance training is recommended to decrease both the risk and incidence of falls in this age group. Despite variations in proprioceptive training protocols, the results consistently show that they are similarly effective in improving both static and dynamic balance. Balance control in individuals relies heavily on the interplay of the visual, vestibular, and proprioceptive systems. Previous studies have indicated that older individuals might experience a decline in balance control.[38] In light of this, previous studies have designed their training to channel sensory information to the central nervous system using proprioceptive and kinesthetic inputs, particularly during specific postures and while moving dynamically. Their training approach includes exercises that are performed with both open and closed eyes. This method is believed to help focus attention on body movements and position, integrating this awareness into the central nervous system through the development of new synaptic connections.[35] Additionally, some researchers highlight the benefits of stepping training. This training is seen as a means to help individuals make precise, rapid, and directed steps, which are essential for preventing falls. It is particularly effective in unstable conditions, as it enhances the individual's neuromuscular, psychological, and sensory-motor capabilities.[20]

Many studies have incorporated the use of an unstable surface in proprioception training for the legs. This approach stimulates the proprioceptive system, playing a pivotal role in generating movement responses and stabilizing the joints.[10] The researchers conducted proprioceptive training on such unstable surfaces using a

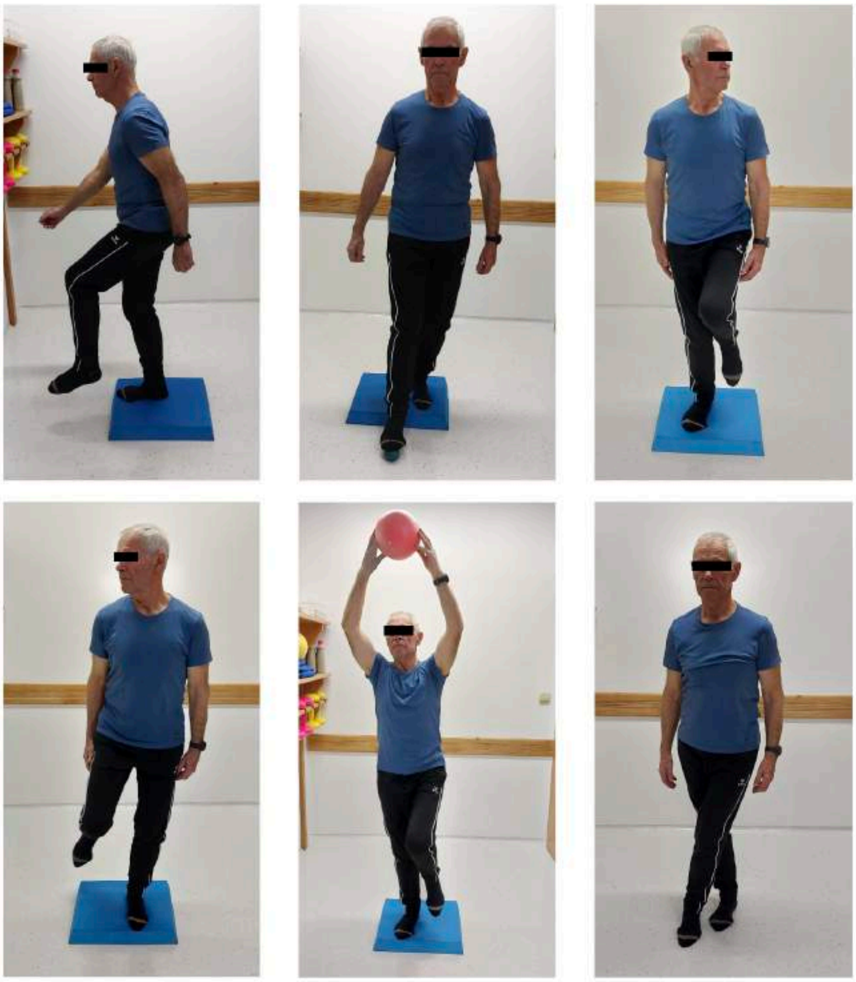

Fig 8. *An example set of "sensorimotor" exercises on a balance foam pad.*

variety of equipment to induce instability. These included a Swiss ball, a soft ball (BOSU), various balance foam cushions, and trampolines. The devised training regimen was usually comprehensive, involving a series of specific proprioceptive exercises. An example of such set of exercises, using a balance foam mat, is shown in Figure 7.

These were executed under both static and dynamic conditions. The participants engaged in a mix of standing, seated, kneeling, and lying postures. Regardless of the position, they always interacted with the training equipment, which provided an element of unstable support. Typically, the training process was segmented into three distinct phases: initial, intermediate, and advanced. This structure ensured a gradual increase in the complexity and challenge of the exercises. For instance, participants were subjected to decreasing hand support during standing, deeper hip and knee bends during squatting exercises, and transitioned from training with eyes open to training with eyes closed.[10,39] Interestingly, in the three proprioceptive training studies considered for the meta-analysis, gait training was not included.[33,40,41] In two studies focused on proprioceptive training, exercises were performed exclusively with eyes open.[33,42] Additional studies,[35,43] incorporated exercises like rolling a ball with one foot while standing and standing on a foam cushion with the alternate foot. The variations in methodologies and exercises across these studies underscore the ambiguity surrounding the definition of proprioceptive training. Such discrepancies emphasize the need for a more standardized and clear understanding of what truly constitutes proprioceptive training. This would ensure consistency in research and application, providing clearer insights into its benefits and best practices.

Sensorimotor training is often discussed in the context of sensory-motor integration. This integration is facilitated by the central nervous system, which merges sensory and motor information to produce skillful and coordinated bodily movements.[44,45] A harmonious interaction between the sensory and motor systems is essential for acquiring and executing coordinated movements. Ahmad et al.[18] suggested that sensorimotor training focuses on enhancing the assimilation of somatosensory and proprioceptive stimuli, reducing muscle imbalances, and instituting an accurate motor program within the central nervous system. Their training regimen included balance exercises on unstable surfaces, trunk muscle strengthening, and gait training. Specific exercises included back-sliding squats on vertical surfaces, unilateral standing exercises, and toe and heel stepping on a balance mat. Additionally, exercises targeting trunk muscle strengthening and various walking patterns were incorporated. Da Silva et al.[34] adopted a similar approach, employing a circuit training model. Their sensory-motor exercises were diverse, being executed on both stable and unstable platforms. Participants trained with both eyes open and closed, and exercises were designed for dual-leg and alternating single-leg stances. Training also encompassed walking in various directions: forward, backward, sideways, over obstacles, and upstairs. Additionally, participants adapted their walking based on auditory cues from researchers. Morat et al.[46] emphasized that sensorimotor marching exercises are more tailored for enhancing balance and preventing falls when compared to traditional balance-enhancing exercises, such as postural holds. In their study, participants engaged in a controlled exercise regimen, focusing on a specific protocol of marching exercises in both stable and unstable settings. The training was conducted on an advanced exercise platform equipped with force sensors and a display (Dividat Senso). This platform facilitates diverse training, honing both cognitive and motor skills. The intervention encompassed 11 distinct marching tasks executed using Exergames (including Targete, Divided, Simon, Flexi, Snake, Tetris, Habitats, Birds, and Hexagon). While two tasks (Ski and Rocket) were devoid of additional cognitive challenges, the remaining games were instrumental in stimulating cognitive abilities in participants. This was achieved through exercises targeting divided and selective attention, visual-spatial working memory, mental rotation, and cognitive flexibility. Overall, the sensorimotor training content partially overlapped with proprioceptive exercise. Figure 8 shows examples of exercises found within papers investigating sensorimotor training.

Limitations and future perspectives

One of the significant limitations of this study is the grouping of studies in the meta-analyses. We included studies that focused on elderly people of both sexes, as well as studies that exclusively targeted elderly men or elderly women. While this was done in light of low number of available studies, we have to admit that by integrating these distinct studies, there is a potential risk of introducing additional heterogeneity that compromises the specificity of our findings.

Recognizing this, it is essential for future meta-analyses in this domain to adopt a more discerning approach, possibly through stratified analyses based on gender, to ensure more robust and nuanced conclusions. Another constraint we faced was the limited number of studies included in the meta-analysis, preventing subgroup analyses for most outcomes. Furthermore, it is crucial to recognize that the outcomes derived from our meta-analysis reflect only short-term effects. The lack of long-term follow-up on subjects means that the long-term impacts of the protocols remain unknown. Notwithstanding the plethora of studies on proprioceptive and sensory-motor training, a definitive understanding of these terms, their encompassed interventions, and their specific impacts on the balance of older individuals remains elusive. When evaluating the training interventions detailed in the various studies, it became apparent that there is inconsistent and, at times, incorrect usage of the terms 'proprioceptive' and 'sensory-motor' by some authors. To illustrate, when reviewing

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studies not included in our meta-analysis, we found that two studies described identical training interventions but labeled them differently - one as proprioceptive and the other as sensorimotor. For instance, one study classified their home-based training as sensory-motor.[47] Yet, this training was identical to that another study,[9] where it was labeled proprioceptive.

The prevalent, casual usage of "proprioception" in many studies is a cause for concern. Often, this term is used in contexts that refer to multi-modal sensory-motor learning tasks. Accepting a broad view that equates all forms of sensory-motor learning to proprioceptive training renders the term virtually meaningless to both the scientific and clinical realms. If a study posits proprioceptive training as a unique form of sensory training or specialized sensory-motor learning, it is imperative for clarity's sake to state this distinction explicitly. This would mitigate the potential for terminological confusion and ambiguity.[17] Consequently, some researchers advocate for eschewing the term 'proprioceptive training' when referencing training types known to boost motor function but not proven to enhance proprioceptive function .[21,22]

In this systematic review and meta-analysis, we assessed the impact of sensorimotor and proprioceptive exercises on balance in older adults. The majority of the studies included both male and female participants with ages spanning from middle-aged to elderly. The interventions varied in frequency and duration, but consistently showed potential benefits for improving balance. Common outcome measures underscored the significance of exercises in enhancing balance, mobility, and overall proprioceptive function. The study quality was predominantly good to fair, reinforcing the validity of the findings. Overall, the evidence suggests that sensorimotor and proprioceptive exercises play a pivotal role in promoting balance and reducing fall risk in older adults. This highlights the importance of integrating such exercises into regular therapeutic and fitness regimens for the elderly population. We also observed an ambiguity and inconsistency regarding the usage of the terms proprioceptive and sensorimotor training, which should be addressed in the future.

List of acronyms

CI – confidence interval
FRT – functional reach test
SMD – standardized mean difference
SD – standard deviation
TUGT – timed up and go test

Contributions of Authors

Both authors conceptualized the paper and performed the literature review. Both authors worked on analyzing the literature and writing the manuscript. Both authors read and approved the final manuscript.

Acknowledgments

None.

Funding

The study was supported by the Slovenian Research Agency through the research program KINSPO - Kinesiology for the effectiveness and prevention of musculoskeletal injuries in sports (P5-0443).

Conflict of Interest

The authors declare they have no financial, personal, or other conflicts of interest.

Ethical Publication Statement

We confirm that we have read the Journal's position on issues involved in ethical publication and affirm that this report is consistent with those guidelines.

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Submission: October 20, 2023
Revision received: November 20, 2023
Accepted for publication: November 20, 2023

SUPPLEMENTARY MATERIALS

Table 1. Characteristics of included studies.

Study	Participants				Intervention training type	Control group	Outcomes	Results/Conclusions
	Sample size	Age (years) mean ± SD	Gender	Inclusion criteria				
Demir 2021	n = 40 EG: 20 CG: 20	EG: 73.50 ± 7.08 CG: 72.45 ± 7.25	M: 26 F: 14	Age of 65 and over, to be able to walk independently or with the support of assistant equipment, to have Type 2 diabetes at least for 2 years.	Proprioception training.	Education only.	Tinetti balance scale, Berg balance scale, Gait test.	Study group demonstrated significant differences in Berg Balance Scale and Tinetti Balance and Gait Test scores. Active matching movement and tactile sensory of the sole showed statistically improvement in the study group.
Espejo-Antunez 2020	n = 42 EG: 21 CG: 21	EG: 83,21 ± 6.59 CG: 82.72 ± 6,40	M: 13 F: 29	Adults older than 65 years old, who were living in an institutionalized setting, who were participating voluntarily in the study who had experienced a fall in the past year and who had a physician prescription that the rehabilitation intervention would be appropriate and potentially beneficial.	Proprioception training.	Physiotherapy.	TUTG, Tinetti balance scale. Cooper, 1-leg stance, and the MFS	A proprioceptive exercise program demonstrated significant improvements compared with the control group in areas such as functional mobility, musculoskeletal endurance, balance, gait, and risk of falls in institutionalized older adults. This study may help to enhance our understanding of the impact of a specific protocol for a proprioceptive rehabilitation program.
Esposito 2021	n = 30 EG: 15 CG: 15	EG: 71.00 ± 4.90 CG: 71.00 ± 4.90	M: 12 F: 18	Inclusion criteria were to have experienced at least one non-debilitating fall, to be able to perform the tests proposed in this study and to be mostly sedentary	Proprioception on training.	Usual care.	Berg balance test, four square step test, a questionnaire to assess confidence and fear of falling.	The results showed that 12 weeks of proprioceptive training effectively improved dynamic and static balance in older adults. The perceptions of the experimental group were more positive than the other one, in terms of the importance of physical activity to prevent the risk of falls, fear of falling again, and experience of falls during the last 12 weeks..
Iram 2021	n = 38 EG: 19 CG: 19	EG: 64.00 ± 7.78 CG: 63.00 ± 8.25	M: 22 F: 16	Patients of type 2 diabetes and distal symmetrical polyneuropathy, a velocity of 39m/s of the Michigan Neuropathy Screening Instrument checked for any variation in latency and amplitude of sural, peroneal and tibial nerves, no contraindications for osteoarthritis, SBP >200	Proprioception training.	Foot care lectures.	TUGT, Berg balance scale, one leg standing test with EO and EC.	Proprioception training exercises were found to be effective in improving balance among patients with diabetic neuropathy. The one leg standing score with eyes open improved significantly, but the difference was non-significant with eyes closed.

				mmHg, DBP >110 mmHg, patients with ability to walk independently, lower limb muscles in grade 3 on manual muscle testing.				
Martinez -Amat 2013	n = 44 EG: 20 CG: 24	EG: 77.00 ± 6.90 CG: 79.35 ± 7,42	M: 25 F: 29	65 years of age or older and able to follow simple directions (left, right, up or down).	Proprioception training.	Education only.	TUGT, Tinetti balance scale, Romberg quotient.	Proprioceptive training program is associated with significant improvements in static posturography and functional balance, and it can reduce the risk of falling in people aged 65 years and older. Leads to positive effects on lateral and anterior-posterior stability in older adults. There were also significant improvements in the surface and speed of the center of pressure (Romberg test) but not in the distance.
Martinez -Lopez 2014	n = 44 EG: 20 CG: 24	EG: 79.35 ± 7.42 CG: 77.00 ± 6.90	M: 25 F: 19	65 years or older and able to follow simple directions (left, right, up and down).	Proprioception training.	Usual care.	Berg balance scale, Tinetti balance scale.	Proprioception program intervention significantly improves flexibility, balance, and lumbar strength in older adults. Hip-joint mobility, dynamic balance, and lumbar strength are positively associated to balance ability and to fall risk in older adults. This proprioceptive training does not cause significant improvement in hip-joint mobility and static balance.
Salah 2022	n = 60 EG: 30 CG: 30	EG: 60.60 ± 3.32 CG: 59.83 ± 3.25	M: 60 F: /	COPD patients, age ranged from 55 to 65 years, BMI ranged from 25 to 29.9 kg/m2, clinically and medically stable, patients with good cognition to understand the requirements of the study, conscious patient and respond to verbal command, patients with grade 3 muscle test. To maintain 45 seconds Timed unipedal stance test, >45 scores on Berg balance scale, > 50% functioning level on Activities specific balance confidence scale.	Proprioception training.	Usual care.	Berg balance scale, Activities-specific balance confidence scale (ABC).	At the end of the study, there were a significant increase in BBS, ABC in both groups post treatment compared with that pretreatment. It was concluded that adding proprioceptive training with muscle strengthening exercises to pulmonary rehabilitation program was more effective in improving postural balance control inpatients with COPD.
Song 2011	n = 38 EG: 19 CG: 19	EG: 72.90 ± 5.60 CG: 73.20 ± 5.40	M: 15 F: 23	Diabetes patients with diabetic peripheral neuropathies diagnosed older adults.	Proprioception training.	Education only.	TUTG, Berg balance scale, FRT, Single leg stance with EO and EC. and 10-m walking test	The balance exercise program improved balance and trunk proprioception. These results suggested that a balance exercise is suitable for individuals with diabetic neuropathy.

Teixeira 2010	n = 85 EG: 42 CG: 43	EG: 63.10 ± 4.53 CG: 62.78 ± 4.87	M: / F: 85	A bone mineral density T-score of -2.5 standard deviation in lumbar spine, femoral neck, or total femur region were included.	Proprioception training.	Usual care.	TUTG, Berg balance scale SF 36 questionnaire.	The association of progressive strength training for the quadriceps and the proprioceptive training is effective for the prevention of falls, increasing the muscle power, the static and dynamic balance and increasing the speed of the motor responses, therefore improving the performance of daily activities.
Ahmad 2019	n = 21 EG: 12 CG:9	EG: 66.75 ± 4.15 CG: 64.77 ± 6.06	M: 14 F: 7	Diabetes > 7 years, BMI 18.5-29.9 kg/m2, > 2 diabetic peripheral neuropathy symptoms, scored > 2/13 MNSI questionnaire and scored > 1/10 on physical assessment including impaired vibration perception.	Sensorimotor training.	Education only.	TUGT, FRT, Single leg stance EO and EC, Berg balance scale, Tinetti balance scale.	Sensorimotor training improved static and dynamic balance as well as proprioception measures after eight weeks of exercise intervention. Static balance showed greater improvement in the middle-aged than older aged adults, while dynamic balance and proprioception showed similar results for both.
Da Silva 2013	n = 102 EG: 51 CG: 51	EG: 57.90 ± 8.50 CG: 58.37 ± 8.11	M: 11 F: 91	Patients with Rheumatoid arthritis, patients who were not participating in exercise program for 3 months prior to the study, patients aged 40 and older.	Sensorimotor training.	Usual care.	TUTG, Berg balance scale and Tinetti balance scale, short form health survey SF-36, Health assessment questionnaire (HAQ).	Statistically significant improvement was found in all variables assessed in the sensorimotor group in comparison with the baseline evaluation and control group. No significant difference was found related to the pre- and post-evaluation in the control group. Therefore, the sensorimotor training is effective in the improvement of the functional capacity and quality of life of patients with rheumatoid arthritis.
Morat 2019	n = 45 EG1: 15 EG2: 15 CG: 15	EG1: 67.50 ± 5.10 EG2: 69.70 ± 6.20 CG: 71.10 ± 5.20	M: 17 F: 28	Older than 60 years, retired and community-dwelling, blood pressure had to be medically adjusted if necessary.	Sensorimotor training.	Maintain physical activity.	TUGT, Y balance test.	Unstable volitional stepping seems to be superior in improving reactive balance and functional mobility under dual-task conditions. It appears that the volitional stepping under unstable conditions requires motor skills relevant for preventing falls since it is more tasks specific when compared to volitional stepping under stable conditions.

EG: experimental group; CG: control group; n: numerus; M: male; F: female; BMI: body mass index; MNSI: Michigan neuropathy screening instrument; TUGT: The timed up and go test; FRT: Functional reach test; EO: eyes open; EC: eyes closed; MFS: Morse fall scale; HAQ: Health assessment questionnaire; SF 36: Short form questionnaire; ABC scale: Activities-specific balance confidence scale; COPD: Chronic obstructive pulmonary disease.

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Table 2. The analysis of the content of sensorimotor and proprioceptive interventions used in included studies.

Study	Intervention type	Exercise variables	The content of the intervention and examples of exercises
Demir 2021	Proprioception training	8 weeks, 3 sessions per week (24 sessions in total), 45 min per session. 8 exercises, including unstable surfaces (with eyes open and closed). Gait training included.	Lower extremity proprioceptive exercise program was arranged according to condition of the patient, consisted of the following: ball rolling under foot, standing on one leg, activities which includes taking steps on Bosu ball, antero-posterior and medio-lateral weight transfer on Bosu, star excursion gait and balance exercises such as walking without support consisting of different grounds, heel to toe walking, side walking, cross walking exercises were chosen and applied. Sessions progressed from supported to unsupported exercise and from eyes open to eyes closed exercises.
Espejo-Antunez 2020	Proprioception training	12 weeks, 3 sessions per week (36 sessions in total), 55 min per session. 12 exercises, training without unstable surfaces with eyes open and closed. Gait training included.	The proprioceptive training program comprised six specific exercises, each five minutes long, which were conducted in static and dynamic positions. These exercises were performed using a one-legged stance, sitting in a chair, and bipedal support, and were performed either with eyes open or closed. The remaining exercises were walking 30 steps in a straight line. Walking 15 steps in each direction. Standing in couples for a maximum of 30 s. Standing with both feet on the ground in front of a chair placed 1 meter away with the shoulders slightly flexed and elbows straight arms directed toward the back of the chair while keeping the feet still and only moving the upper body the participant must attempt to touch the back of the chair a maximum of 10 times. Exercises using balloons and balls.
Esposito 2021	Proprioception training	12 weeks, 2 sessions per week (24 sessions in total), 60 min per session. 5 exercises, including unstable surfaces (with eyes open). Gait training included.	The experimental group followed a proprioceptive training protocol for 12-week intending to improve static and dynamic balance. The proposed exercises were adapted for each older adult and included proprioceptive exercises requiring instability management and postural exercises. The methodology used in the central phase was the functional circuit, repeated three times. Warm-up was performed for 13 minutes. Main part of the session: Balance on one leg (stork position), getting up from a 60 cm highchair, walking on a proprioceptive pad, walk-in a straight line of 10 meters and throw softballs towards a wall 10 feet away. Cool down: Walking, breathing exercises ang stretching 15 minutes.
Iram 2021	Proprioception training	8 weeks, 2 sessions per week (16 sessions in total), 60 min per session. 5 exercises, including unstable surfaces (with eyes open and closed). Gait training not included.	Proprioception training program was based on earlier studies. It started with 10 minutes of warm-up activities when the subjects were advised to do light manual stretches and to step up and down on foam to get their body warmed up to have improve muscular flexibility. This was followed by 30 minutes of proprioceptive exercises targeting lower extremities. Proprioceptive exercises were divided into three components. The first component comprised standing on foam with eyes open and eyes closed and passing any object from one subject to the other for 10 minutes. the second component consisted of activity that was performed in groups of two. Throwing and catching a ball was performed while standing on foam for additional 10 minutes. The third component, throwing and catching a ball, was performed on trampoline to further challenge the balance system. After each set of 10-minute exercise, the subjects were given two-minute resting periods. In the end, 10 minutes were given for cooling down in which deep breathing exercises and static back extensor stretching exercises.

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Martinez-Amat 2013	Proprioception training	12 weeks, 2 sessions per week (24 sessions in total), 50 min per session. 6 exercises, including unstable surfaces (with eyes open and closed). Gait training included.	The proprioceptive training program comprised six specific proprioceptive exercises, each five minutes long, which were conducted in static and dynamic positions. The training was structured into three progressive phases according to the type of exercise. The initial phase comprised weeks 1-5, the intermediate phase weeks 5-8, and the advanced phase weeks 8-12. Training on Swiss ball-4 exercises: sitting, wall squat, glute bridge, back extension. Training on Bosu ball-2 exercises: stepping up and down on the Bosu ball, standing on the Bosu ball.
Martinez-Lopez 2014	Proprioception training	16 weeks, 2 sessions per week (24 sessions in total), 50 min per session. 6 exercises, including unstable surfaces (with eyes open and closed). Gait training included.	The training program comprised six specific proprioceptive exercises, each five minutes long, which were conducted in static and dynamic positions for a period of 30 minutes. The training was structured into two or three progressive phases according to the type of exercise (the initial phase, the intermediate phase and the advanced phase). Training on Swiss ball-4 exercises: knee flexion-extension, hips flexion extension, hip and knee flexion-extension with the ball between the back and wall, trunk extension and flexion on the Swiss ball. Training on Bosu ball-2 exercises: stepping up and down on the Bosu ball, standing on the Bosu ball.
Salah 2022	Proprioception training	12 weeks, 3 sessions per week (36 sessions in total), 30 min per session. 5 exercises, including unstable surfaces (with eyes open). Gait training not included.	This program training consisted of proprioceptive exercises using Swiss ball and BOSU ball, which were conducted in static and dynamic positions for a period of 30 minutes. The exercise consisted of 2 sets of 10-15 repetitions with 1 minute of rest between sets and include alternate knee flexion-extension with extended trunk posture, Hip and knee flexion-extension with the Swiss ball between back and wall, hip raises lying their back on the floor with both legs on the Swiss ball and standing on the BOSU ball.
Song 2011	Proprioception training	8 weeks, 2 sessions per week (16 sessions in total), 60 min per session. 5 exercises, including unstable surfaces (with eyes open and closed). Gait was training not included.	Balance exercises consisted of three parts. The first and second part comprised two sets of 4 min each, with eyes opened and eyes closed, respectively. In particular, while performing the second set, subjects were paired for their safety, and they performed it in turns. The third part included three activities to challenge and increase their balance. In the first activity, the subjects were asked to stand in a circle on foam and pass doughnuts from themselves to the next subject in the circle. The donuts were passed with the help of a straw in their mouths. The second activity was performed in pairs and comprised catching and throwing a ball while standing on the foam. The third activity was performed in a similar way but on a trampoline instead of on foam to challenge balance strategies. The size of the ball, the number of repetitions, and the distance between subjects were increased progressively as the patients' balance responses improved.
Teixeira 2010	Proprioception training	18 weeks, 2 sessions per week (36 sessions in total), 50 min per session. 8 exercises, including unstable surfaces (with eyes open and closed). Gait was training included.	The functional exercises (proprioception and balance) were performed in a routine that followed a progressive order beginning with stable surface and changing to unstable surfaces, gait training without obstacles and then performance of gait training with obstacles, exercises first with eyes opened and then eyes closed, first low-speed exercises and according to the patient performance high-speed exercises, bipedal training and then unipedal, also using resources such as balance, trampoline, and proprioceptive boards always using the same progressive order.

Ahmad 2019	Sensorimotor training	8 weeks, 3 sessions per week (24 sessions in total), 60 min per session. 10 exercises, including unstable surfaces (with eyes open). Gait training included.	Each session comprised of 10-min warm-up, followed by 50–60 min of exercise, followed by 5–10 min of cool-down. Sensorimotor training comprised wall slides, core exercises, balance exercises on unstable surface (Thera band stability trainer), and gait training (different patterns of walking). Cool-down exercises included deep breathing, abdominal breathing and mild stretching. Exercise participation was modified, postponed, or stopped based on the current guidelines of American Diabetes Association. The volume of exercise was increased after three sessions. In addition to this, the exercise level was increased after every two weeks if tolerated.
Da Silva 2013	Sensorimotor training	16 weeks, 2 sessions per week (32 sessions in total), 40 min per session. 7 exercises, including unstable surfaces (with eyes open and closed). Gait training included.	Sensorimotor exercises progressed from stable surfaces to unstable surfaces, training gait in a line (tandem walk or walking straight) followed by gait including change in directions, gait without obstacles to gait with obstacles, change in the support base (feet apart and then together), physical exercises with eyes opened and closed, always respecting the functional capacity of each patient and progressively increasing the difficulty of each exercise. To help the training, cones, balance board, bars, mats and a minitrampoline were used. According to the patient progress, the exercises were combined, generating circuits.
Morat 2019	Sensorimotor training	8 weeks, 3 sessions per week (24 sessions in total), 40 min per session. 10 exercises, including unstable surfaces (with eyes open and closed). Gait training included.	Supervised step training with specific training protocol (volitional stepping exergames under stable and unstable conditions). For a diverse training of cognitive and motor abilities, eleven stepping exergames were part of the training intervention. In nine of eleven exergames ("Targets", "Divided", "Simon", "Flexi", "Snake", "Tetris", "Habitats", "Birds" and "Hexagon"), stepping was the major motor task and the following cognitive abilities were additionally addressed through the different games: divided and selective attention, visuospatial working memory, mental rotation and cognitive flexibility. Two games ("Ski" and "Rocket") had no additional cognitive task and addressed weight shifting and endurance as a major motor task respectively.

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Table 3. Assessment of study quality with Pedro Scale.

	TOTAL SCORE	Eligibility criteria	Random allocation	Concealed allocation	Baseline comparability	Blind subjects	Blind therapists	Blind assessors	Adequate follow-up	Intention-to-treat analysis	Between-group comparisons	Point estimates and variability
Demir 2021	5	1	1	0	1	0	0	0	1	0	1	1
Espejo-Antunez 2020	6	1	1	0	1	0	0	1	1	0	1	1
Esposito 2021	4	1	1	0	1	0	0	0	1	0	1	0
Iram 2021	5	1	0	0	1	0	0	1	1	0	1	1
Martinez-Amat 2013	4	1	0	0	1	0	0	0	1	0	1	1
Martinez-Lopez 2014	4	1	0	0	1	0	0	0	1	0	1	1
Salah 2022	6	1	0	1	1	0	0	1	1	0	1	1
Song 2011	5	1	1	0	1	0	0	0	1	0	1	1
Teixeira 2010	7	1	1	1	1	0	0	1	1	0	1	1
Ahmad 2019	4	1	1	0	1	0	0	0	0	0	1	1
Da Silva 2013	7	1	1	1	1	0	0	0	1	1	1	1
Morat 2019	5	1	1	0	1	0	0	0	1	0	1	1