Aging Brain 1 (2021) 100013

Contents lists available at ScienceDirect

Aging Brain

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

Muscular and cortical activation during dynamic and static balance in the elderly: A scoping review

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ARTICLE INFO

Article history:
Received 29 December 2020
Revised 17 March 2021
Accepted 18 March 2021

Keywords:
Electromyography
Electroencephalography
Balance
Older adults
Postural control

ABSTRACT

Falls due to balance impairment are a major cause of injury and disability in the elderly. The study of neurophysiological correlates during static and dynamic balance tasks is an emerging area of research that could lead to novel rehabilitation strategies and reduce fall risk.

This review aims to highlight key concepts and identify gaps in the current knowledge of balance control in the elderly that could be addressed by relying on surface electromyographic (EMG) and electroencephalographic (EEG) recordings. The neurophysiological hypotheses underlying balance studies in the elderly as well as the methodologies, findings, and limitations of prior work are herein addressed.

The literature shows: 1) a wide heterogeneity in the experimental procedures, protocols, and analyses; 2) a paucity of studies involving the investigation of cortical activity; 3) aging-related alterations of cortical activation during balance tasks characterized by lower cortico-muscular coherence and increased allocation of attentional control to postural tasks in the elderly; and 4) EMG patterns characterized by delayed onset after perturbations, increased levels of activity, and greater levels of muscle co-activation in the elderly compared to younger adults.

EMG and EEG recordings are valuable tools to monitor muscular and cortical activity during the performance of balance tasks. However, standardized protocols and analysis techniques should be agreed upon and shared by the scientific community to provide reliable and reproducible results. This will allow researchers to gain a comprehensive knowledge on the neurophysiological changes affecting static and dynamic balance in the elderly and will inform the design of rehabilitative and preventive interventions.

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https://doi.org/10.1016/j.nbas.2021.100013
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Introduction

Maintaining dynamic (as during walking) and static (e.g., standing posture) balance, which may seem effortless tasks, become demanding when diseases or physiological changes associated with aging take place [1]. In the elderly (age > 65 - years), balance impairments are among the main causes of falls, resulting in both morbidity and mortality [2]. Due to the *demographic transition* phenomenon, the cumulative decline of several physiological systems associated with vulnerability and adverse consequences represents a major health issue leading to high health care costs [3].

Postural control involves an organized network of interacting systems. The activity of muscles is controlled by the central nervous system (CNS) to maintain balance via integration of musculoskeletal, visual and vestibular system inputs [4]. Proprioception, which originates from muscles and cutaneous receptors, provides information about body position in the environment, as well as the relative position of the body segments. The visual system provides information about the external environment. Cerebellar control provides a feedback-feedforward control of muscle activation. Lastly, the vestibular system generates information, using specialized organs situated in the inner ear, that enable tracking angular acceleration by relying on the semicircular canals and linear acceleration by relying on the saccule and the utricle [5]. The redundancy of afferent information from the musculoskeletal system and from the vestibular and vision systems is essential to enable the CNS to generate correct responses when these systems receive conflicting stimuli.

Although the relevance of this information is well known, how the brain controls balance by integrating these inputs is still poorly understood. Several protocols have been proposed to measure postural sway to evaluate balance in older adults and in people with neurological disorders [6]. Reliable and quantifiable clinical measures rely on computerized dynamic posturography, force plates, and wearable sensors [7]. These methods have the important shortcoming of capturing solely the final output of a complex process taking place at the cortico-subcortical, spinal, and muscle level.

In light of the increasing threat posed by falls to an aging society [8], researchers and clinicians have displayed a growing interest for the study of balance impairments in the elderly and the development of new assistive and rehabilitative interventions. Identifying cortical activity and muscle activity patterns associated with effective balance control strategies could provide a benchmark to assess the efficacy of rehabilitative interventions or to determine the targets of neurostimulation-based interventions. Being non-invasive and relatively low-cost, the study of surface electromyographic (EMG) and electroencephalographic (EEG) data could provide a useful tool to investigate the neurophysiology of balance [9]. Surface EMG data can be looked upon as the superposition of the action potential waveforms that travel along its muscle fibers during a muscle contraction. The resulting electrical signal can be processed to estimate the timing and magnitude of muscle activation [10]. Its clinical utility has been proven [11–14].

EEG data enable the detection of motor planning and intention. EEG may also provide information on ongoing cognitive processes even in highly compromised people with weakness and abnormalities in muscle activation. EEG is a non-invasive low-cost imaging technique that allows clinicians and researchers to record the dynamics of brain activity (i.e., measures of voltage fluctuations collected on the scalp via non-invasive electrodes) with high temporal resolution (i.e., ms). Advances in hardware technology have allowed engineers to develop EEG wireless multi-channel systems [15]. Furthermore, advances in signal processing [16,17] have allowed source-resolved EEG dynamics during walking, thus promoting the development of Mobile Brain/Body Imaging (i.e., MoBI) [18].

Until now, the relevance of the muscular and cortical systems involvement and their functional modifications in both dynamic and static balance control have been primarily studied in pathological conditions [19–21] and in robot-assisted rehabilitation [22–24].

To more clearly observe balance control impairments in experimental settings, dual-task paradigms are often implemented. They consist of combining a static or dynamic balance task with a cognitively-demanding task, such as mental calculations, visual or auditory disturbances (as in oddball-based experimental paradigms) [25–27]. The rationale underlying the choice of combining tasks is to challenge competing resources. This experimental approach aims to highlight the major role played by the brain cortex.

A detailed knowledge of the cortical activity and of how the CNS controls muscles during the performance of static and dynamic tasks is not currently available. In contrast, extensive literature describes the role of muscle activity during the performance of both static and dynamic balance control tasks [28].

A previous review about neuroimaging in human balance control [29] provided evidence of an increase in brain activation during the performance of balance control tasks by healthy adults, regardless of mechanical, cognitive, or sensory challenges they experienced. In fact, this review focused only on brain activity during balance control tasks and did not attempt to analyze muscle activity. Analyzing both muscle and brain activity may provide additional insights into the mechanisms involved in balance control.

The aim of this review is to summarize currently available data on the characteristics of muscular and cortical activation patterns during static and dynamic balance tasks in the elderly as derived by relying on EMG and EEG recordings. Furthermore, this review highlights gaps in the available knowledge of the neurophysiological mechanisms underlying the control of balance in the elderly, identifies potential biomarkers to be used in the design of intervention strategies, and suggests future research directions in this research field of growing interest.

Material and methods

Inclusion criteria

Only studies evaluating the following were considered in this review: healthy elderly (>60 y), or involving both elderly and young participants, without diagnosed neurological, cardiovascular, vestibular, musculoskeletal or any other systemic disorder; dynamic or static balance and EEG or EMG recordings.

Dynamic balance studies were considered if related to: 1) walking, either overground or on a treadmill; 2) any other dynamic action such as step-initiation, physical exercises/tests, slip-induced trials, etc. and 3) any physical functional balance assessment. Static balance studies were considered if assessing individuals during upright stance, with or without perturbations.

Case reports, clinical trials, clinical studies, comparative studies and methodological papers were included, whereas reviews, commentaries, editorials, conference abstracts or communication papers were excluded.

Database searches

The following databases were used: Scopus, Web of Science, PubMed, Cochrane library, IEEEXplore and Science Direct. Only search results written in English and published in the last ten years (from 2010 to April 2020) were considered. The search string was composed as follows: the search categories - i.e., motor task, balance condition, measurement and target population - were linked using the AND Boolean operator, which corresponds to the algebraic intersection, and the words describing each category were linked using the OR Boolean operator, which corresponds to the algebraic union:

(walk OR "upright stance") AND (balance OR balanced OR balancing OR "dynamic balance" OR "static balance" OR stability OR "dynamic stability") AND (aged OR elderly OR elderlies OR "older adults") AND ((electroencephalography OR EEG) OR (electromyography OR EMG)).

The search string and databases used in the study were chosen with help from an expert librarian and agreed among the authors.

Fig. 1 shows a schematic representation of the database search. From a total of 953 papers published between 2010

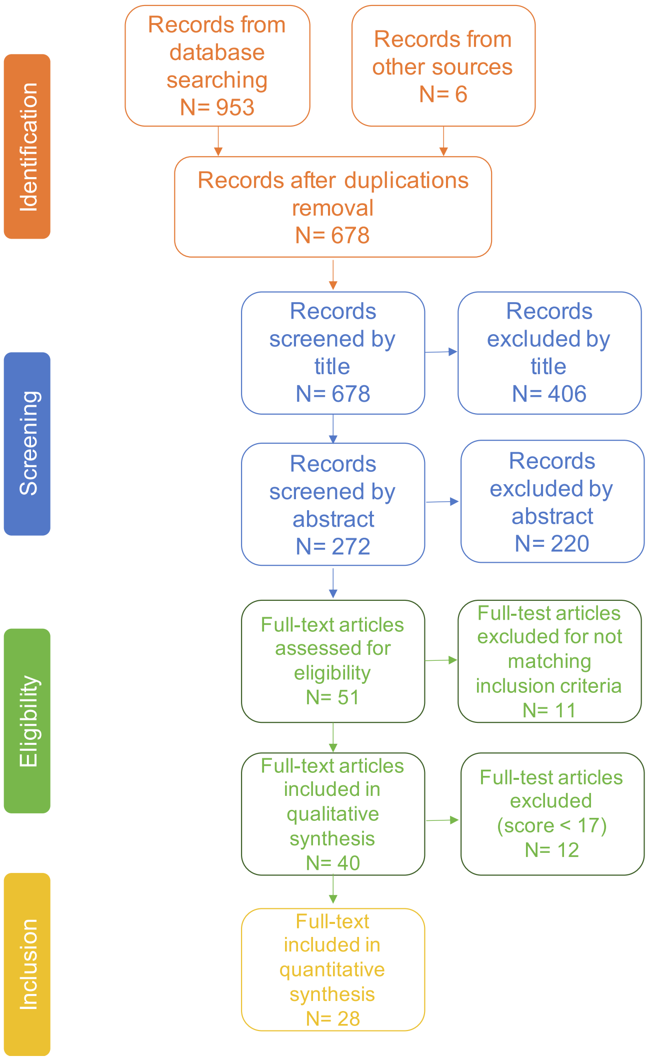

Fig. 1. PRISMA-flow of the articles selection process.

and 2020, identified following the Preferred Reporting Items for Systematic Review and Meta-Analysis (PRISMA statement) [30], 6 papers were added searching among the references of the selected studies. Duplicates were removed using the Mendeley software: 678 articles remained for further screening. Then a title screening was carried out, i.e., articles were excluded from further consideration if they revealed to be out of topic or to not meet the selection criteria. After title screening, 278 articles underwent an abstract screening. Fifty-two papers remained for full-text analysis. During both title and abstract screening, if all the investigators did not agree about the inclusion/exclusion decision, the record was moved to the next stage (Fig. 1: identification, screening, eligibility). This procedure was performed by one investigator (MZ) and cross-checked by two experienced researchers (MR, RDM). A fourth reviewer (EF) screened the papers in case of discordance among the others.

In light of the high heterogeneity of the experimental setups and protocols, and of the analysis methods utilized to study the neurophysiological signals collected during the selected studies, we decided to carry out a scoping review [31].

Articles selection

Quality assessment

The quality of the papers was independently evaluated by three reviewers (MZ, MR, RDM). Fourteen criteria, adapted from two systematic reviews [32,33], were assessed for each paper, belonging to the following seven sections: 1) aim of the work, 2) inclusion criteria (selection bias), 3) data collection and processing (performance bias), 4) data loss (attrition bias), 5) outcomes (detection bias), 6) presentation of the results, and 7) statistical approach.

Each item listed in Table 1, was scored from 0 to 2 by each reviewer, considering if the goals were not met (0), partially met (1), or fully met (2). Then the individual criteria scores were summed and averaged among reviewers. An article was included if the final score exceeded 60% of the maximum score (>17).

Table 1
Quality check items.

Aim of the work	
1	Description of a specific, clearly stated purpose
2	The research question is scientifically relevant
Inclusion criteria (selection bias)	
3	Description of inclusion and/or exclusion criteria
Data collection & processing (performance bias)	
4	Data collection is clearly described and reliable
5	Data processing is clearly described and reliable
6	Algorithms are clearly described and referenced
Data loss (attrition bias)	
7	Drop-outs < 20%
Outcomes (detection bias)	
8	Outcomes are topic relevant
9	The work answers the scientific question stated in the aim
Presentation of the results	
10	Presentation of the results is sufficient to assess the adequacy of the analysis
11	The main findings are clearly described
Statistical approach	
12	Appropriate statistical analysis techniques
13	Clearly states the statistical test used
14	Actual probability values reported for the main outcomes

Data extraction form

A standardized form was created to extract data from the eligible papers. The following data were included in the extraction form: 1) first author and year of publication, 2) participant characteristics, 3) balance condition, 4) procedures, 5) signal analysis pipeline and 6) outcomes. EMG and EEG patterns reported by these studies were analyzed in a detailed manner for each manuscript and included in the final step of the literature review.

An example of the data extraction form is provided in Table 2.

Results

From the 51 papers selected for full-text analysis, 11 did not meet the inclusion criteria and were excluded. Among the remaining 40 full-papers, 28 (27 journal papers and 1 paper published in conference proceedings) received a score higher than 17. In scoring these papers, there was general agreement among the three raters as computed using the Fleiss' kappa [34], as shown in Table 3. Among those included, 23 papers were EMG-based studies, 3 were EEG-based studies, and in 2 papers both techniques were used. In these studies, participants were considered as older adults if their average age ranged between 65 and 83 y (with only one study including 60 year-old participants [26], and another one including participants with an average age of 61.9 y [35]). When a comparison with results obtained from a control population was carried out (i.e., 21 papers out of 28), young participants had an average age ranging between 18 and 36 y. It is worth considering that in some cases the small sample size considered for both elderly and younger participants might have negatively affected the relevance of the results. Indeed, the median sample size for the elderly population was 16 participants (ranging from 8 [35] to 70 [36]), and 10 for the younger controls (ranging from 8 [35] to 30 [37]). Fig. 2 provides additional details about the age and sample size of the elderly and younger adult groups recruited in the studies considered in this review.

Different experimental protocols were utilized to evaluate balance performance in the elderly. Participants were asked to: 1) walk overground or on a treadmill (e.g., [38]); walk on a slippery surface (e.g., [39]), or step over an obstacle (e.g., [35]); 2) maintain the upright stance with either their eyes opened or their eyes closed (e.g., [40]), on a swaying platform (e.g., [41]), while performing the Functional Reach test (i.e., extending the arms as far forward as possible without moving the feet) (e.g., [42]), holding a load (e.g., [37]), performing a verbal or an arithmetic task (i.e., cognitive dual-task paradigm) (e.g., [43]).

The Supplementary Materials section includes a table showing the number and age of the participants in the 28 studies considered in this review, the experimental conditions in which the data were collected (i.e., balance task/s

Table 2
Data extraction form.

Organizational aspects		
Reviewer	*Date*	*Checked by*
List of authors	*Year of Publication*	*Journal/Source*
Publication type:	Conference abstract/Conference paper/Full paper	Other
Fate:	Decision Pending	EX/IN-cluding
Notes/Short description		
Aim		
Results in brief		
Reasons for Exclusion		
Participants:	Not healthy (>60) and without control group	Healthy (<60)
Instrumentation:	Neither EEG nor EMG	
Task:	Imagined	Passive
Other:	Duplicate	Other:
Study description		
Participants:	Number/Sex	Age interval
Disease:	None	Other
Balance condition:	Upright stance	Walking
	Static balance	Dynamic balance
Balance perturbation:	Expected	Unexpected
Visual	Cognitive	Other
Instrumentation:	EEG	List of electrodes/sample frequency
	EMG	List of muscles/sample frequency
	Additional investigation	
EEG analysis:	Protocol	
EMG analysis:	Protocol	
Other analysis:	Protocol	
Main outcomes		
Confounders:	Same setting/operator	Statistic correction

and perturbation conditions), the overall aim of each study, and their main outcomes.

Cognition, physical activity and executive functions

Cognitive and physical status were considered as covariates in the majority of the studies. In particular, to assess potential cognitive impairments, the Mini Mental State Examination test was used in [44–48], the Mental Status Questionnaire was used in [37], the Rapid Dementia Screening Test was used in [36], the Montreal Cognitive Assessment Questionnaire was used in [43], and the Cambridge Neuropsychological Test Automated Battery and Stanford Sleepiness Scale were used in [49].

The following tests were utilized to assess executive functions: the Trail Making Tests A and B were used in [25–27], the Stroop Interference Test and Digital Symbol Substitution test were used in [26], and the Binocular Visual Acuity was used in [49].

Many studies quantified also the physical performance using the International Physical Activity Questionnaire [49–51], the Berg Balance Scale [27,46,52], and the Timed Up-and-Go test [36,37,43]. Other assessment tests used in these studies were the Fried's Criteria for frailty syndrome [50], the One Leg Standing test [37], the Chinese version of the Fall Efficacy Scale and of the Movement Specific Reinvestment Scale [45], the Four Square Step Test [53], and the Activities Specific Balance Confidence Scale [27,43]. Test side dominance was also checked using the Edinburgh Handedness Inventory [43]; and Waterloo Footedness Questionnaire [49].

The following sections describe the protocols and data analysis pipelines used to extract the key features of balance control in the elderly, with specific reference to EMG and EEG recordings. The papers were then divided in two categories: those investigating static balance and those investigating dynamic balance. Studies were subsequently subdivided accordingly to the recorded neurophysiological signal: i.e., *EMG-based studies*, *EEG-based studies* and *EEG-EMG-based studies.*

Data acquisition and data analysis procedures

Notwithstanding the common aim of investigating how aging affects the mechanisms underlying static and dynamic balance control in different conditions of mechanical or cognitive load, the papers selected in this review displayed high heterogeneity in the methodologies utilized across studies. On average, people ranging between 65 and 83 y of age were considered in the group of older adults. Younger individuals were recruited in some studies. People 60 + years-old were considered eligible to participate in the study as older adults in [26] and an average age of 61.9 y (standard deviation of 2.9 y) marked the group of older adults in [35]. Results obtained in the elderly group were compared to the results in a control population of younger adults (age range of 18–36 y) in 21 of the 28 papers herein considered. In five papers, gender differences were detected as the studies focused on mechanisms hypothesized to affect in a distinct manner female [46,50,54,55] or male subjects [51].

Table 3
Quality assessment: inter-rater reliability.

Fleiss' kappa	Error	Confidence Interval	Agreement	z	*p*-value
0.76893	0.091287	0.72238–0.81549	Substantial	8.4233	<0.001
Reject null hypothesis: Observed agreement is not accidental					

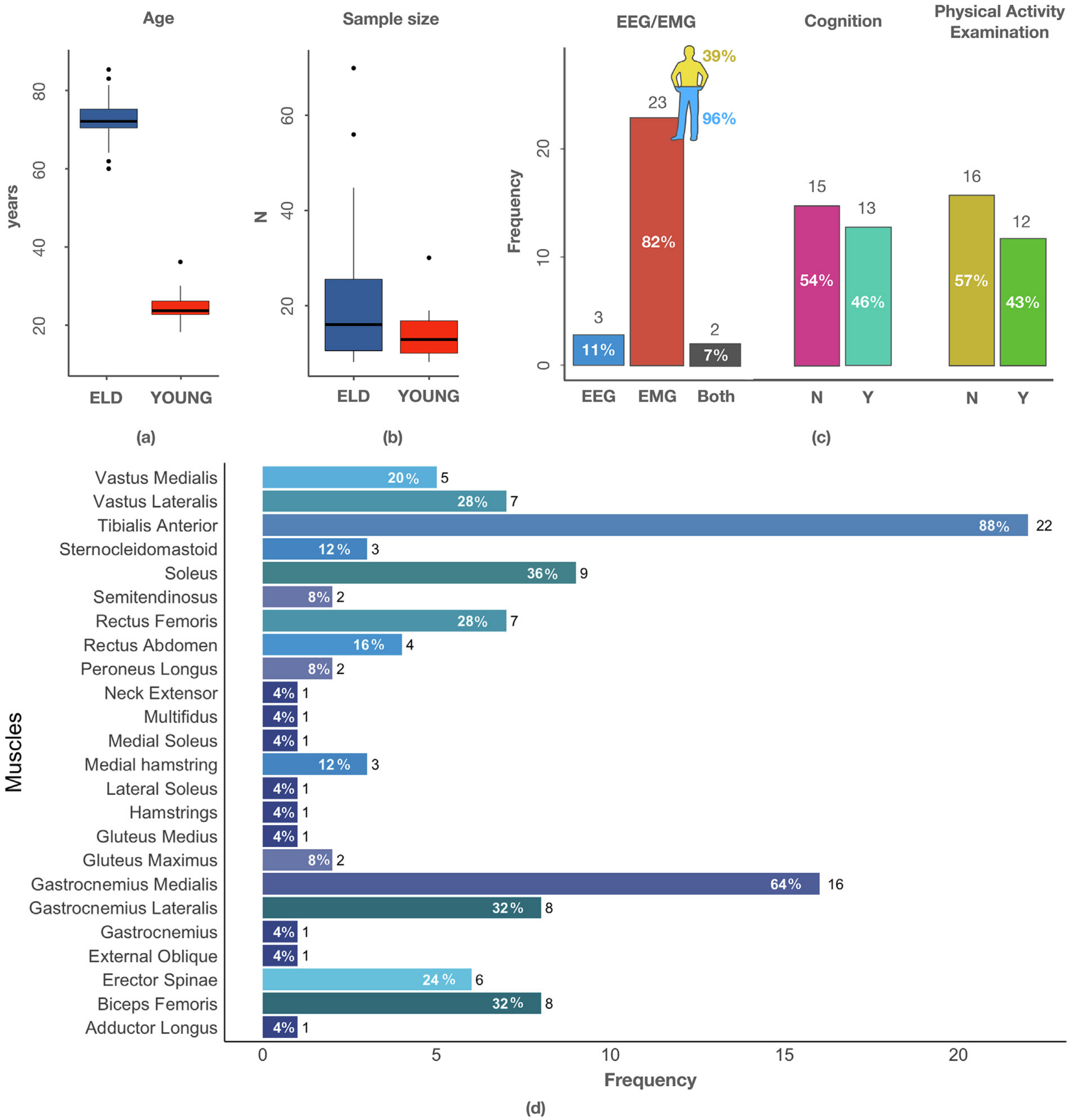

Fig. 2. Details about the included papers: (a) age of included participants for both elderly (ELD) and younger adult (YOUNG) groups; (b) sample size; (c) number of papers including EEG or EMG (for EMG, relative frequencies of papers investigating lower and upper body are also provided), number of papers investigating cognition and physical activity; (d) frequency bar plots of the muscles analyzed in the papers (relative frequencies are given close to each bar).

EMG-based studies

The majority of papers included EMG recordings (25 out of 28) as a tool to investigate balance control under different conditions. The EMG data were typically collected at a sampling rate of 1 kHz or higher (except for [56], in which a sampling rate of 600 Hz was used). Five studies collected data only from two muscles [27,36,37,49,57]. Electrode arrays were used in [51] to investigate the spatial distribution of the muscular activity in older women. Twenty-two studies investigated the activity of lower limb muscles and only 9 studies targeted trunk or neck muscles.

Despite the need to use standardized protocols for skin preparation, electrode placement, data collection, quality check, and signal processing [13,58], only seven research articles included a statement concerning the standardized protocol utilized in the study. Five of these articles referred to the SENIAM protocol [25,42,50,52,59], and two of them to other protocols [38,46].

Muscular activity was normalized using different methods: 1) using data collected during a control condition, 2) using the maximum signal amplitude, 3) by subtracting the mean and dividing by the standard deviation of the time series, 4) using data collected during a maximum voluntary contraction (MVC) (this was the case for 18 out of 28 papers), and 5) by normalizing the EMG time series using a reference value derived from data collected within the time interval corresponding to a cycle of the movement of interest, such as a gait cycle (this was the case for 7 out of 28 papers). Almost all the papers considered indices designed to compare the activity of agonist and antagonist muscles.

These indices were used as a measure of co-activation/co-contraction (e.g., ratio of signal amplitudes and ratio of the integrals of antagonist and total signals) [60], timing of activity onset and amplitude as derived from filtered EMG signals. Three papers suggested an alternative processing approach based on applying a data reduction algorithm to obtain the muscle synergies [35,56,61], which have been interpreted as spinal modules used by the nervous system to generate patterns of motion. The use of muscle synergies by the CNS is interpreted as a strategy to reduce the complexity of the neuromuscular control [56].

EEG-based studies

Five papers included the collection of EEG data. EEG data were collected at a sampling frequency ranging between 256 [49] and 1000 Hz [41,48]. Data were gathered using 3 [45], 64 [41,48,49] or 72 electrodes [47]. The EEG data were filtered with a minimum high-pass cut-off frequency of 0.1 Hz [41,48] and a maximum low-pass cut-off frequency of 80 Hz [49]. Despite the use of high-density electrode arrays, none of the studies herein reviewed relied on reconstructed EEG waveforms (estimated using EEG data recorded from the scalp) to determine cortical sources. All EEG channels from the peripheral and temporal sites were rejected a priori in [41]. The analysis of task-evoked N200/P300 components was limited to data collected from the fronto-central scalp sites (i.e., the three midline sites: FCz, Cz and CPz) in [47]. Also, the analysis was limited to data collected from Cz in [49] as the authors explored the coherence between EEG signals and EMG data collected from the tibialis anterior muscle. The coherence function can be looked upon as a measure of correlation between the frequency content of two signals. The authors used this function in an attempt to assess if the recruitment of muscle motor units and the modulation of their firing rate could be accounted for by the modulation of specific frequency components of the EEG data [49].

Static balance

EMG-based studies

Static balance was evaluated during upright stance and static conditions in 11 papers, with the aim of investigating the effect of aging on: 1) the activity of muscles controlling ankle movements [40,50,51] and potential differences in EMG activity in fallers vs. non-fallers [44], 2) the patterns of co-contraction of muscles controlling ankle movements [36,57] in fallers vs. non-fallers [53], and 3) the control of balance during experiments carried out using a dual-task paradigm (either cognitive or manual extra load) [35,37,61]. Additionally, a new predictive data-driven model of the CNS mechanisms underlying postural control was developed and experimentally validated in [59].

Higher amplitude in the EMG activity of the muscles controlling ankle movements during quiet standing with eyes open and eyes closed was reported in the elderly compared to younger participants in [40,50,51]. The same findings marked the results in [44], where the authors investigated amplitude differences in plantar- vs. dorsi-flexor muscles in fallers vs. non-fallers, and observed a greater contribution to postural control of plantar-flexor muscles vs. dorsi-flexor muscles in the elderly compared to younger adults and in those with a history of falls compared to non-fallers.

Muscle co-contraction is the mechanism used to increase joint stiffness and is often associated with the performance of small postural adjustments during the performance of challenging motor tasks. Hence, the presence of co-contractions was looked upon by several researchers as a proxy for "postural instability", as patterns of co-contraction lead to the loss of degrees of freedom that might be important in generating an appropriate response to an external perturbation. Indeed, higher co-contraction levels were observed in the elderly vs. younger adults when comparing the activity of individual muscles [50,57] as well as when researchers investigated the characteristics of muscle synergies [35]. Moreover, in [53], the authors found a positive correlation between the level of co-contraction of the tibialis anterior and gastrocnemius muscles and fall reports, thus highlighting the potential use of metrics capturing the severity of co-contractions as proxy for fall risk. This finding is also supported by [44], where the authors observed an elevated level of muscle activity in the muscles controlling ankle movements in older adults with history of falls, which they suggested to be associated with greater postural sway. When studying postural control using a dual-task paradigm (i.e., holding a glass full of sand/water or performing a cognitive task) [37], a decrease in the activity of the tibialis anterior and gastrocnemius muscles was observed in older adults undergoing testing using a dual-task experimental paradigm (i.e., performing a cognitive task during quiet standing) when compared to the other conditions.

EEG- and EEG-EMG-based studies

In [45], the correlation between fear of falling - quantified using the movement specific reinvestment scale (MSRS) - and scalp EEG activity was investigated in the elderly. Results showed that higher MSRS scores (i.e., higher fear of falling) was associated with lower T3-Fz coherence.

In [41], EEG activity in the elderly and younger participants was recorded during postural tasks including quiet standing and standing on a swaying platform, as well as during dual-task experiments. Results showed: 1) an increase in delta activity (i.e., in the 1–4 Hz range) in both groups under challenging postural conditions, 2) a theta activity (i.e., in the 4–7 Hz range) response to an increase in cognitive requirements, and notably 3) an increase in gamma activity (i.e., in the 30–50 Hz range) in the elderly compared to younger participants.

In [48], not only EEG activity, but also EMG activity was recorded in the elderly and younger participants during quiet upright standing and after a perturbation induced by a platform translation or rotation. These experiments were carried out with eyes open and eyes closed. Gamma activity increased in the elderly in the eyes closed condition, whereas delta activity was higher in younger participants than in the elderly over the central and central parietal cortices. In the analysis of cortico-muscular coherence after balance perturbations, a higher coherence between C1 and the activity of the rectus femoris muscle was found in the elderly, whereas higher C1-tibialis anterior coherence was observed in younger participants. Post-perturbation potentials (PEP) were also analyzed showing that older participants displayed longer latency compared to younger adults. Interestingly, the delay in muscle activity onset in the elderly compared to younger adults ranged on average between 20 and 60 ms, the same delay observed between the groups for the N1 component of the PEP (i.e., the first EEG voltage deflection elicited by visual stimuli).

Dynamic balance

EMG-based studies

EMG recordings were used to investigate the effect of aging on muscle activity and postural control during dynamic balance tasks in 17 of the 28 papers considered in this review. This was sometimes done while asking subjects to simultaneously perform a cognitive task. In some studies, participants were asked to walk (either overground [27] or on a treadmill [25,26,46]) while doing arithmetic calculations [26,27,43]. In others, obstacles were positioned on the subjects' walking path [46] or displayed in a virtual reality environment to challenge their balance [25]. The results of these studies demonstrated that an increase in cognitive load was significantly associated with an increase in the level of muscle co-contractions, as well as with motor and cognitive performance [27], with the latter not being affected by dual-tasks [26] and with no sizable effect on onset latencies and signal amplitude [43]. Apprehensive gait was marked by a greater level of activation of thigh muscles both in the elderly and in younger participants [46]. However, an increase in the level of co-contraction of agonist and antagonist muscles was observed only in the elderly population [27,46]. An increase in muscle onset latency was observed in older adults in response to a perturbation when researchers analyzed the data of individual EMG channels [43] as well as when muscle synergies were examined [35,56,61] and when the activity of upper body muscles was studied [54]. Differences in motor performance were observed in terms of higher muscular activity for the elderly than their younger counterparts, especially when the activity of the hamstrings was examined [26] and the co-activation of agonist/antagonist muscles was considered [25]. Moreover, a greater level of co-contraction was observed in the elderly [27] when delivering visual stimuli [25].

In [36,42], muscle activity in the elderly was monitored during a functional reaching test consisting of instructing subjects to maintain a fixed base of support while extending their arms as far forward as possible without moving their feet. In these conditions, the authors observed a temporal ordered muscle activation following a caudo-cranial pattern in the anterior muscles (i.e., tibialis anterior, rectus femoris, rectus abdominis, sternocleidomastoid), with subsequent activation of the posterior muscles (i.e., soleus, hamstring, erector spinae). The same activation pattern and two different balance strategies (hip and mixed) were observed during all the trials.

The impact of aging on muscle recruitment during the performance of demanding tasks, such as uphill and downhill walking, was investigated in [38]. Similar muscle activation patterns were observed when testing subjects while walking on a treadmill at different inclinations thus simulating uphill and downhill walking [38]. An increase in muscle activity level was observed in both the elderly and younger study participants with steeper inclinations, but a greater level of activity of the gluteus maximus and the gastrocnemius muscles was observed in the elderly group during uphill walking. Also, older adults exhibited greater muscle co-activation levels of leg muscles in all conditions. Higher muscle activation levels were generally observed in the elderly, with a significant correlation between age and level of muscle activation of trunk and lower limb muscles [52]. The same study highlighted a decrease in the activity of the rectus abdominis and gastrocnemius muscles during the stance phase of the gait cycle [52].

In [39], older adults with history of falls were trained on a slipping platform to identify the biomechanical and neuromuscular changes that such training induces, and to test for an improvement in balance control possibly associated with improvements in recovery reaction time. Results showed that the training group reduced the probability of falling by using a motor strategy marked by early activation of the hamstrings and tibialis anterior muscles and by a decrease in the level of muscle co-activation compared to the control group (which did not receive any training).

The effect of aging on muscle recruitment and activation patterns was also investigated and assessed via the analysis of muscle synergies based on data collected during step initiation and induced slip while walking [35,61], and comparing the characteristics of muscle synergies in those who fell and those who recovered after the perturbation [56]. A less complex muscle response was observed in the group of those who maintained their balance, whereas a delayed activity onset (especially in the knee flexors/extensors of the slipping leg) and the recruitment of fewer muscle synergies was observed in participants who fell

[56]. This finding was confirmed by [35,61], which also highlighted that fallers displayed muscle synergies marked by more prominent levels of co-contraction of agonist/antagonist muscles, thus compromising their ability to respond to perturbations by exploiting "unused" degrees of freedom.

Despite the relevance of the vestibular system in maintaining balance control and the fact that it is part of the inner ear, the postural control of the head and upper body has not been extensively investigated. Specifically, the activity of muscles of the upper body was investigated to understand the mechanisms that support head stabilization during gait initiation [54] and during planned gait termination [55]. The activity of trunk muscles was analyzed during gait initiation, revealing a delayed onset of the activity of the sternocleidomastoid muscle paralleled by higher head angular displacement in the elderly. The delayed activation of muscles appeared to affect the ability to attenuate acceleration patterns originating from the trunk and transmitted to the head in the antero-posterior direction [54]. When examining gait termination instead, the sternocleidomastoid muscle activity appeared constant in both the elderly and younger adults in the first phase of gait termination, while it decreased during the end of the task only in the younger population, thus suggesting that a less stable mechanism of coordination between trunk and head movements would potentially lead to poor balance control [55].

EEG and EEG-EMG based studies

In [47], a cognitive dual-task (i.e., go-no-go task) during walking and a control task were performed by both the elderly and younger participants. Only the group of older adults showed a decrease in cognitive performance in the dual-task experimental condition compared to the control task. In addition, EEG activity was measured during both the dual-task and the control task conditions. Event related potentials (ERP) were calculated by identifying changes in N2 and P3 components. The N2 component, which displayed an earlier onset in younger participants compared to the elderly, showed a decrease in younger adults during the dual-task trials. However, no difference in this component was observed in older adults during the dual-task condition vs. the control condition. The group did not show any modulation in P3 latency, but exhibited a walking-related increase in P3 amplitude.

In [49], EEG and EMG activity was recorded during normal and visually-guided walking in the elderly and in younger participants to measure cortico-muscular and inter-muscular coherence. Results demonstrated that younger participants had higher cortico-muscular (considering EEG beta and gamma frequency bands) and inter-muscular coherence compared to the elderly. In fact, the magnitude of the coherence function increased in both groups during visually-guided walking.

Discussion

This review aimed to summarize current knowledge on the neuromuscular control of static and dynamic balance in the elderly. The paucity of studies investigating cortical activity showed that available knowledge concerning the CNS control of balance in healthy elderly is still insufficient [41,45,48]. This is not surprising, given that even in healthy young subjects the mechanisms underlying cortical control of postural stability are not fully understood [62,63]. In light of the CNS changes induced by aging, the need for investigating its role in balance control in the elderly is of paramount importance.

Recent studies have demonstrated that EEG frequency rhythms, in particular in the delta and gamma EEG frequency bands, play a key role in maintaining posture in both static and dynamic tasks in the elderly (Fig. 3) [41,45,48]. Although the role of delta rhythm has not been fully understood from a neurophysiological point of view, an increase in the power spectral density function in the delta frequency range has been detected in data collected from older adults during dual-task experiments [41,48]. It is possible that an elevated power in the delta frequency band might reflect an active cognitive task to help maintaining postural stability in the elderly. Beside the higher values in the delta frequency band, gamma rhythms in the frontal areas of the brain cortex appear to be involved in both cognitive processes and postural control, not only in the elderly but also in younger adults [64]. Perturbation-evoked cortical response in younger adults showed: 1) a scalp distribution of power in the delta, theta, alpha, and beta frequency range that increased at fronto-central midline electrode sites and 2) a significant synchronization of delta, theta, alpha, and beta activity [65]. To disentangle if cortical differences among healthy elderly and younger adults are due either to impairments in the balance control system (vestibular, musculoskeletal, visual) or to physiological changes that mark the aging brain, studies focusing on balance function in elderly fallers and non-fallers are needed to better understand postural control mechanisms in individuals prone to falls.

In healthy aging, structural [66] and functional [67] brain changes occur. As a result, the increased allocation of attentional resources to handle a challenging postural task may cause an increased recruitment of cortical areas. These different activation patterns highlight the increased cognitive load observed in older adults and point to the "frailty" of the system even in healthy aging. The interference of cognitive tasks with motor tasks is confirmed by data from the few EEG studies we identified in this review, which reported an increase during balance tasks in EEG band primarily associated with cognition (i.e., gamma) in the elderly [41,48]. EEG findings are paralleled by EMG results showing delayed motor activations, a behavior consistent with the observation that cortical potentials in the elderly appear with a longer time lag compared to younger individuals. The identification of these EEG characteristics (e.g., power spectral changes in different frequency bands) in association with the performance of challenging postural control tasks suggests their potential use to achieve: 1) early detection of postural instability [63], 2) tracking functional recovery during rehabilitation, and 3) the development of new rehabilitative treatments tailored according to the physiological patterns observed on a subject-by-subject basis (Table 4). To accomplish these three goals,

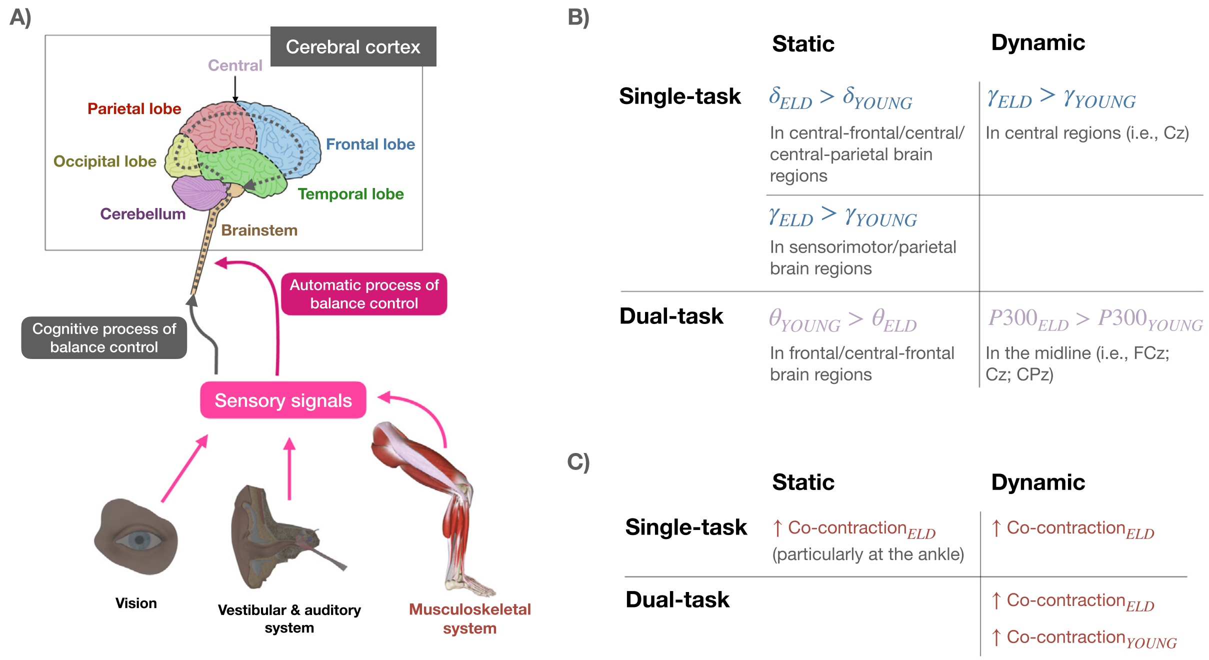

Fig. 3. Summary: A) the network of balance control with and without the involvement of cognitive process of sensory signals; B) main observed differences in the cortical signals recorded from the elderly vs younger study participants – power bands are highlighted with the color of the relevant cortical area as in A); C) main observed differences on muscular activity between the elderly and younger study participants.

further interventional studies are needed to relate changes in postural behavior and cortical electrophysiology data recorded after the intervention.

The analysis of muscle activity patterns has allowed researchers to study balance control strategies in healthy aging. Longer EMG latencies, higher amplitude levels, and more prominent muscle co-contractions were observed in the elderly compared to younger participants in the majority of the studies examined in this review [25,35,38,46,50,57]. An increase in the activation of antagonist muscles (associated with an increase in the energy cost of maintaining balance) has been suggested to be part of physiological aging [68]. Of interest, challenging motor tasks in the elderly produces a further increase in the co-contraction levels [25,38], which is most likely due to older adults perceiving static and dynamic tasks as more demanding than their younger counterparts. Conversely, during dual-task tests (either cognitive or based on motor tasks not strictly associated with balance - e.g., holding a glass of water [37]), younger adults increase the level of co-contraction, whereas the elderly display a deterioration in their motor performance, with what appears to be a decrease in muscle activity aimed to favor achieving a cognitive task [26,41,57]. Muscular activity in the elderly was higher than in younger adults, even under dual-task conditions [37]. Moreover, muscle synergies appear to be altered in the elderly and in a more prominent way in individuals reporting frequent falls. This knowledge based on EMG analyses may guide rehabilitative interventions, considering the age of the subject, both by: 1) addressing joint control and motor strategies that is important to focus on and 2) selecting the muscles to be targeted by strengthening interventions (Table 4).

When EEG and EMG data were simultaneously recorded, analyses focused on cortico-muscular coherence [48], which is generally reduced in the elderly, highlighted the decreased reactivity of the muscular and nervous systems with advancing age.

Overall, standardized protocols are needed to produce reliable and reproducible results that enable comparisons across studies. Future research would need to: 1) assess and include cognitive performance capacity of study participants as a covariate in the proposed statistical analyses, 2) use shared and validated protocols for muscle electrode positioning and analysis of EMG activity, 3) apply shared EEG signal analysis protocols, and 4) use high spatial resolution EEG systems to estimate EEG source waveform activity. Appendix A and B contains further details/discussion on papers limitations.

Table 4
Discussion Summary.

Tool	Information provided	Possible translational implication
EEG	Balance cortical correlates	Early detectors of instability; Trackers of recovery; Drivers of new rehabilitative treatments
EMG	Balance control strategy Muscle synergies	Targeted rehabilitation programs; Non-voluntary movement control restoration

A potential limitation of our literature review is the lack of systematic sub-grouping of the elderly to account for some of the pathologies that affect this population. Our decision of including only studies on healthy participants and thus without neurological, cardiovascular, vestibular, musculoskeletal or any other systemic disorders was driven by our aim to study the effects of healthy aging on balance control and not the effects of specific pathologies.

Conclusions

The present review on muscular and cortical control during static and dynamic balance highlights the need to further investigate the CNS many contributions to assure postural stability. This holds particularly true when this topic is investigated in the elderly, a population at high risk of falls due to balance impairments. Despite being interesting and promising, the results of the studies herein reviewed leave significant gaps in our understanding of balance control in the elderly. This review highlights the urgent need to share protocols and data analysis pipelines to tackle a pressing demand in our ageing societies: to understand the neurophysiological basis of postural control and thus develop preventive and rehabilitative measures for the elderly that are consistent with the mechanisms underlying balance control impairments in this population.

Declaration of Competing Interest

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

Acknowledgements

This work was supported by the Italian Ministry for Foreign Affairs under the call "Progetti di Grande Rilevanza Internazionale" (PGR-01045 - SoftAct).

Appendix A. . Limitations of EMG-based studies

Only five of the studies herein reviewed [25,42,50,52,59], which reported EMG data, utilized the SENIAM guidelines to assure reproducibility of electrode placement [58]. Different studies showed significant heterogeneity in the selection of muscles to record EMG data during dynamic balance tests with no clear rationale supporting their choice (Fig. 2d), except for upright stance studies where authors recorded the activity of muscles controlling ankle movements based on the hypothesis of a prevalent ankle strategy to maintain balance, specifically, in response to perturbations.

Appendix B. . Limitations of EEG-based studies

In the five papers where EEG data were collected [41,45,47–49]; despite in four out of five studies, a high-density EEG set-up was exploited in data recordings, the processing was limited to a small sub-set of EEG channels. This limitation in the reported spatial resolution of the EEG results may be due to challenges encountered by researchers as they attempted to remove motion artifacts such as those associated with head movements during locomotion. In the last decades, many effective methods have been suggested, e.g., based on blind source separation [69] or adaptive filtering [70], but their computational complexity may not be suitable for online applications. To achieve real-time removal of non-cyclical movement artifacts, many trials are needed for the creation of an appropriate set of artifact templates and movement-related kinematic signals [16]. Contrary to prior claims [71], recent findings accurately quantify the extent to which head motion-related artifacts contaminate the EEG signal, showing that they are not as dominant relative to the actual cortical signal recorded by the EEG at slow to moderate walking speeds [72].

The work of Whitham et al. (2007) [73], showing that the main part of the EEG gamma signal disappears with temporary muscle paralysis, has challenged the assumption that EEG gamma bands could be recorded. A novel approach [74] has been proposed to reduce the effect of scalp and neck EMG, observing that scalp and neck muscle spikes had specific waveforms in the time domain which allowed researchers to separate them from the EEG gamma rhythms.

Appendix C. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.nbas.2021.100013.

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