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Review

Age-related modifications of muscle synergies during daily-living tasks: A scoping review

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ABSTRACT

Background: Aging is associated with changes in neuromuscular control that can lead to difficulties in performing daily living tasks. Muscle synergy analysis allows the assessment of neuromuscular control strategies and functional deficits. However, the age-related changes of muscle synergies during functional tasks are scattered throughout the literature. This review aimed to synthesize the existing literature on muscle synergies in elderly people during daily-living tasks and examine how they differ from those exhibited by young adults.

Methods: The Medline, CINAHL and Web of Science databases were searched. Studies were included if they focused on muscle synergies in elderly people during walking, sit-to-stand or stair ascent, and if muscle synergies were obtained by a matrix factorization algorithm.

Findings: Seventeen studies were included after the screening process. The muscle synergies of 295 elderly people and 182 young adults were reported, including 5 to 16 muscles per leg, or leg and trunk. Results suggest that: 1) elderly people and young adults retain similar muscle synergies' number, 2) elderly people have higher muscles weighting during walking, and 3) an increased inter and intra-subject temporal activation variability during specific tasks (i.e., walking and stair ascent, respectively) was reported in elderly people compared to young adults.

Interpretation: This review gives a comprehensive understanding of age-related changes in neuromuscular control during daily living tasks. Our findings suggested that although the number of synergies remains similar, metrics such as spatial and temporal structures of synergies are more suitable to identify neuromuscular control deficits between young adults and elderly people.

1. Introduction

Aging is associated with changes in neuromuscular control (Schmitz et al., 2009), which refers to the coordinated interaction between the nervous system and the muscles. These alterations can have a major impact on mobility capacities (Brown and Flood, 2013). The combination of motor and cognitive disorders is at the origin of an accelerated loss of independence and autonomy (Bimou et al., 2021; Sobral et al., 2018). Additionally, the aging process is often accompanied by degeneration of nerve and muscle tissues. As a result, the performance of daily tasks (e.g., walking, sit-to-stand and stair ascent) becomes increasingly challenging for elderly people (EP). Indeed, performing these tasks are considered complex considering multi-level joints coordination and the need to coordinate different agonist and antagonist muscles. However, daily-living tasks are necessary skills to maintain independence and autonomy (Merrilees, 2014).

Muscle synergy analysis is recognized as a useful tool to assess neuromuscular control strategies or to quantify functional deficits in

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pathologies (Turpin et al., 2021). The number of muscle synergies offers an indication of the complexity level of neuromuscular control an individual exhibits when performing a task (Turpin et al., 2021). Thus, a lower synergy number indicates a more simplified neuromuscular control, as observed in individuals with Parkinson (Falaki et al., 2016) or cerebral palsy (Bekius et al., 2020). Furthermore, a muscle synergy analysis gives an insight into the temporal and spatial structure of the muscles' coordination from the recorded muscle activity. So far, the most appropriate method to retrieve muscle synergies is by extracting muscle activity from electromyography (EMG) signals with the non-negative matrix factorization algorithm (NNMF) (Rabbi et al., 2020; Turpin et al., 2021). This method has been commonly used for assessing muscle synergies during daily-living tasks in various populations with neuromuscular control impairments (Cherni et al., 2021; Turpin et al., 2021). Indeed, neuromuscular control impairments during functional tasks assessed by muscle synergies may be relevant to develop training modalities that are specific to the impaired synergies, e.g. due to the merging of two synergies typically observed in intact leg or in healthy subject, especially in populations with deteriorating neuromuscular control (Ting et al., 2015).

The literature suggests that aging impacts how spinal circuits integrate peripheral afference and descending inputs, resulting in a change in final motor output (e.g., muscles synergies) in EP. For example, Baggen et al. (2020), found that neuromuscular control complexities and structures were affected by age during step ascent at different heights. Indeed, age was correlated with higher synergy complexity (Baggen et al., 2020). However, the authors reported higher synergies similarity in terms of spatiotemporal structure across step heights in the older compared to the young adults (YA) group (Baggen et al., 2020). On the other hand, Monaco et al. (Monaco et al., 2010) reported that the structures of muscle synergies and their temporal activations were similar between YA and EP during locomotion, while Kubota et al. (2021) reported a decreased synergy complexity in EP, compared to YA. The contradictory results of the above studies concerning the effect of age on synergies complexity show that it remains unclear whether the between-group neuromuscular differences are attributed to changes in specific muscle synergies, their temporal activities, or both. Indeed, the studies that have investigated the relationship between aging and changes in synergies during daily living tasks are scattered, and a scoping of the literature is necessary to provide a better understanding of the effect of aging on muscle synergies during common daily living tasks (i.e., walking, sit-to stand, stair ascent). This would help to guide interventions in aging populations and ultimately, lighten the decline in self-mobility and autonomy.

This scoping review aims to give an overview of the existing studies investigating lower limb muscle synergies in EP during daily living tasks such as walking, sit-to-stand task and stair ascent. The primary aim is to examine how muscle synergies in EP differ from those exhibited by YA during walking, stair ascent, and sit-to-stand tasks by investigating the quantification and structure of synergies, and the variability of synergies between and within EP.

2. Methods

2.1. Data source and literature source

A science librarian was consulted for the initial development of the search protocol. Studies were identified by searching Medline, CINAHL and Web of Science from inception to October 2022. The search strategy was based on three main concepts: "muscle synergy," "elder, and "daily living tasks". More details concerning search strategy and the key words used are reported in Appendix as a supplementary material. The current review follows the Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) checklist (Tricco et al., 2018) and was registered on the OSF platform (ID: osf.io/e3bzv).

2.2. Eligibility criteria

The included studies met the following inclusion criteria: (1) performing on a group of adults with a mean age of 60 years or older (as defined by the United Nations); without a history of major physical or psychiatric condition likely to affect gait, and in case of a mixed population: the majority of the investigated population older than 60; (2) focused on muscle synergies of the lower limb during walking, sit-to-stand task or stair ascent; (3) based on NNMF synergy extraction method and; (4) study published in French or English. Studies were excluded if they: (1) was performed on a population other than elder; (2) focused on muscle synergies of the upper limb; and (3) was not original research, such as letters to editor, conference abstracts and commentaries.

2.3. Studies screening

Titles and abstracts of the identified studies were screened independently by two of the authors (YC and SH) to identify those that potentially met inclusion criteria. A full review of those studies was then performed independently by the same authors. In the case of any unresolvable disagreement related to the studies eligibility, a third author (FM) performed the screening to reach consensus.

2.4. Methodological quality and risk of bias

Two authors independently (YC and SH) rated the overall quality of each included study, using the modified version of the Downs and Black checklist (Connor Gorber et al., 2007; Downs and Black, 1998). Out of 27 Items, fourteen Items were identified as relevant by the authors which allows to evaluate overall reporting bias (items 1, 2, 3, 4, 5, 6, 7, 10), external validity (items 11 and 12), internal validity bias (items 15, 16, 18, 20), internal validity confounding (items 21, 22, 25), and power (item 27) of the included studies. The maximum total consists of 19 points per study. Each study was assigned a score of "high" ($\geq$75%), "moderate" (60–74%), "low" ($\leq$60%) (Desmyttere et al., 2018). For the assessment procedures, a calibration meeting was initially performed with five studies, to ensure a clear understanding of each criterion and thus standardization and reliability of assessments. A second meeting was held to discuss the criteria for each study included, until a consensus was reached for a score. In the case of any unresolvable disagreement, a third author (FM) performed the assessment to reach consensus.

2.5. Data charting process

Data including study design, quality assessment, subject characteristics (age, sex), study methods (number of cycles analyzed, number and name of muscles recorded, EMG pre-processing methods), and synergy outcomes (muscle synergies in EP, and differences with YA), was extracted by one author (CDP), and validated by a second author (YC). Descriptive and numerical analyses were used to summarize the literature for each functional task (i.e., walking, sit-to stand, stair ascent). The main outcome measures discussed in this review were: (1) quantification of muscle synergies such as total number of synergies, the spatial (i.e., muscle weighting/relative contribution) and temporal (i.e., relative temporal activation) structure of muscle synergies (Safavynia et al., 2011), and the variability accounted for (VAF). The spatial and temporal structure of muscle synergies were reported as mentioned in the original article by the authors or extracted from the article graphics. If extracted from graphics, muscles with the highest weight and the most significant timing were reported to define the spatial and temporal structure, respectively. The VAF was defined by the uncentered Pearson correlation coefficient between weight x coefficient, and the EMG amplitude time series (Torres-Oviedo et al., 2006). Effect sizes were reported for each significant synergy difference between group (EP vs YA). If the original study does not provide the effect size, it was calculated from mean and standard deviation data. The authors were contacted if mean and standard deviation were not available. Cohen's d effect size (d) or Glass's delta effect size (△) was calculated if the study used parametric tests or non-parametric, respectively (Cohen, 1977; Ialongo, 2016). The *p*-value of each significant result was also reported. If the study did not provide the p-value, the level of statistical significance set by the authors was reported. If the study adopted the Bayesian framework, no p-value was reported. The findings related to the study aims and the implication for future research were then discussed.

3. Results

3.1. Search results

The initial search led to 8963 studies. After removing duplicates, study titles and abstracts were screened by two reviewers to assess the eligibility of 4849 studies. A total of 280 studies were qualified for the full-text reading stage. This last stage resulted in the identification of 17 studies as eligible in this review. The flowchart of the selection process is charted in Fig. 1.

3.2. Risk of bias

The median score of the modified Quality Index for the included studies was 72% (range from 44 to 89%) indicating a high quality (Table 1). The majority of studies were of high (Alizadehsaravi et al., 2022; Baggen et al., 2020; Clark et al., 2010; da Silva Costa et al., 2020; Santuz et al., 2022; Sawers et al., 2017; Sawers and Bhatt, 2018) or moderate quality (Allen et al., 2019; Allen and Franz, 2018; Collimore et al., 2021; Guo et al., 2022; Hanawa et al., 2017; Kubota et al., 2021; Toda et al., 2016; Yang et al., 2019), and, two were of low methodological quality (An et al., 2013; Yang et al., 2017). The score for reporting elements was high, while external validity elements were rated lower in the studies. Four studies out of seventeen (Alizadehsaravi et al., 2022; da Silva Costa et al., 2020; Sawers et al., 2017; Sawers and Bhatt, 2018) detailed the source of EP and YA populations.

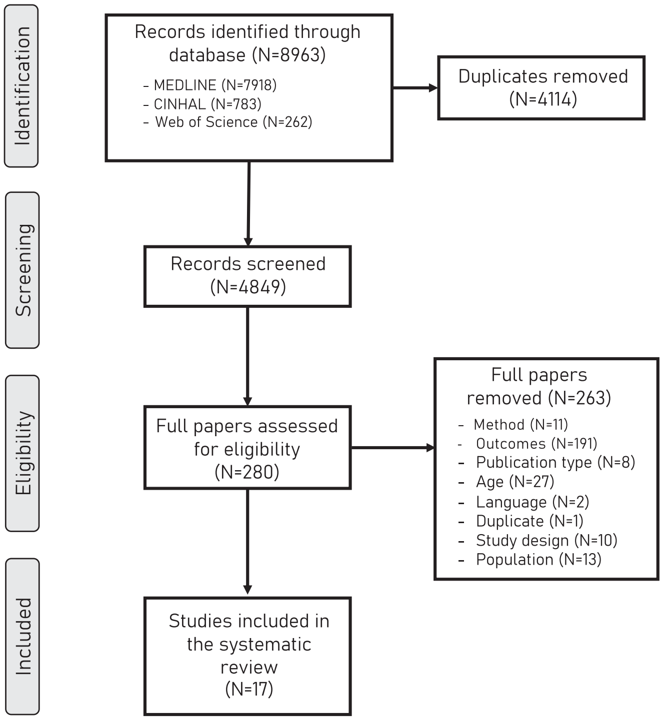

Fig. 1. The scoping review flow diagram.

3.3. Studies characteristics

Table 2 shows the population and methodology characteristics of the 17 studies included in this review. All studies were published between 2009 and 2022. Eleven of them (65%) used an observational cross-sectional study design (Allen and Franz, 2018; An et al., 2013; Baggen et al., 2020; Collimore et al., 2021; Da Silva Costa et al., 2020; Guo et al., 2022; Hanawa et al., 2017; Kubota et al., 2021; Santuz et al., 2022; Toda et al., 2016; Yang et al., 2017), and six studies (35%) focused on EP only (Alizadehsaravi et al., 2022; Allen et al., 2019; Clark et al., 2010; Sawers et al., 2017; Sawers and Bhatt, 2018; Yang et al., 2019). A total of 295 EP and 182 YA were included. The sample size ranged from 3 to 140 participants (group mean ± SD = EP: 17.2 ± 15.6; YA: 16.6 ± 18.6), and group age mean was 70.4 and 25.4 years old for the EP and YA adults, respectively). Eleven studies (65%) focused on muscle synergies during walking (Alizadehsaravi et al., 2022; Allen et al., 2019; Allen and Franz, 2018; Clark et al., 2010; Collimore et al., 2021; Guo et al., 2022; Kubota et al., 2021; Santuz et al., 2022; Sawers et al., 2017; Sawers and Bhatt, 2018; Toda et al., 2016), four studies (23%) on sit-to-stand task (An et al., 2013; Hanawa et al., 2017; Yang et al., 2019, 2017), one (6%) on walking with an additional balance challenge (Da Silva Costa et al., 2020) and one (6%) on stair ascent (Baggen et al., 2020). All studies were recording muscles using surface EMG. Overall, 5 to 16 muscles were included per leg, or leg and trunk. Seven studies (An et al., 2013; Baggen et al., 2020; Da Silva Costa et al., 2020; Guo et al., 2022; Kubota et al., 2021; Yang et al., 2019, 2017) on seventeen (41%) focused on both leg and trunk muscles. The reported muscles for the leg muscle activities were: adductor magnus (ADD), biceps femoris (BF), biceps femoris long head (BFL), biceps femoris short head (BFS), gastrocnemius (GAS), gastrocnemius lateralis (GL), gastrocnemius medialis (GM), gluteus maximus (GMax), gluteus medius (GMed), gluteus minimus (GMin), hamstrings (H), iliopsoas (IL), medial hamstrings (MH), peroneus longus (PL), rectus abdominis (RA), rectus femoris (RF), semitendinosus (ST), soleus (SOL), tensor fasciae latae (TFL), tibialis anterior (TA), vastus muscles (VAS), vastus lateralis (VL), and vastus medialis (VM). Among the seventeen included studies, the most common muscles recorded for the anterior part of the leg were: TA ($n = 17$; 100%), RF ($n = 14$; 82%), and VL ($n = 15$; 88%) (Fig. 2). The most common muscles recorded for the posterior part of the leg were: SOL (n = 15; 88%), GM ($n = 12$; 71%), GMax ($n = 11$; 65%), and GMed (n = 11; 65%). The reported muscles for the trunk muscle activities were: erector spinae (ES), external obliques (EOB), latissimus dorsi (LD), paravertebral muscle (PVM), and rectus abdominis (RA). The raw EMG data was most processed using the following steps: high-pass filtered, rectified, low-pass filtered, amplitude scaled, and time-normalized (see Table 2 for more details). The majority of studies (n = 11; 65%) normalized the EMG envelopes by the maximum value during the task (Alizadehsaravi et al., 2022; Allen et al., 2019; Allen and Franz, 2018; Baggen et al., 2020; Clark et al., 2010; da Silva Costa et al., 2020; Kubota et al., 2021; Santuz et al., 2022; Sawers et al., 2017; Sawers and Bhatt, 2018; Yang et al., 2019). However, few studies ($n = 4$; 23%) did not report any data normalization to extract muscles synergies (An et al., 2013; Guo et al., 2022; Toda et al., 2016; Yang et al., 2017).

3.4. Walking tasks

A range of 4 to 8 synergies that account for >80% of the variance have been reported by eleven studies that have focused on normal walking task (see Table 3). Although the majority of studies (64%) (Alizadehsaravi et al., 2022; Allen et al., 2019; Allen and Franz, 2018; Clark et al., 2010; Kubota et al., 2021; Santuz et al., 2022; Toda et al., 2016) reported 4 to 5 synergies during overground or treadmill walking at different speed (speed range [max, min]: [0.30 m/s, 1.57 m/s]), one study (Collimore et al., 2021) reported only 3 synergies during treadmill walking at monitored speed (speed: 1.1 m/s), two studies (Sawers et al., 2017; Sawers and Bhatt, 2018) mentioned the presence of 6 synergies

Table 1

Methodological quality assessment scores of included studies using the modified version of Downs and Black checklist.

Studies	Reporting								External validity		Internal validity (bias)				Internal validity (confounding)			Power	Power	Quality
	1	2	3	4	5^a	6	7	10	11	12	15	16	18	20	21	22	25	27	(%)	
Alizadehsaravi et al. (2022)	1	1	1	1	1	1	1	1	1	1	0	1	1	1	1	UD	1	1	89	High
Allen and Franz (2018)	1	1	1	1	2	1	1	0	0	0	0	1	1	1	UD	UD	1	0	67	Moderate
Allen et al. (2019)	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	UD	1	0	72	Moderate
An et al. (2013)	1	1	0	1	0	1	1	0	0	0	0	1	1	1	UD	UD	0	0	44	Low
Baggen et al. (2020)	1	1	1	1	2	1	1	1	0	0	0	1	1	1	1	UD	1	0	78	High
Clark et al. (2010)	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	UD	1	1	78	High
Collimore et al. (2021)	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	UD	1	UD	72	Moderate
Da Silva Costa et al. (2020)	1	1	1	1	2	1	1	1	1	0	0	1	1	1	1	UD	1	1	89	High
Guo et al. (2022)	1	1	0	1	2	1	1	0	0	0	0	1	1	1	1	UD	1	0	67	Moderate
Hanawa et al. (2017)	0	1	1	1	1	1	1	0	0	0	0	1	1	1	1	UD	1	0	61	Moderate
Kubota et al. (2021)	1	1	1	1	1	1	1	0	0	0	0	1	1	1	1	UD	1	0	67	Moderate
Santuz et al. (2022)	1	1	1	1	2	1	1	1	1	0	0	1	1	1	1	UD	1	1	89	High
Sawers et al. (2017)	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	UD	1	UD	78	High
Sawers and Bhatt (2018)	1	1	1	1	1	1	1	1	1	0	0	1	1	1	1	UD	1	UD	78	High
Toda et al. (2016)	1	1	1	1	1	1	1	0	0	0	0	1	1	1	1	UD	1	1	72	Moderate
Yang et al. (2017)	0	1	1	1	0	1	1	0	0	0	0	1	1	1	UD	UD	1	0	50	Low
Yang et al. (2019)	1	1	1	1	1	1	1	1	0	0	0	1	1	1	1	UD	1	UD	72	Moderate

1 = Yes; 2 = No; UD = Unable to Determine; [a] The score for item 5 is 0: No, 1: partially, and 2: Yes, similar to Down & Black checklist.

during overground walking (speed range [max, min]: [0.55 m/s, 1.26 m/s]), and one study (Guo et al., 2022) extracted 8 synergies during overground walking at different self-selected speeds (i.e., slow, normal, fast). Four of the eleven studies carried out their experiment on a treadmill, either imposing a walking speed (Alizadehsaravi et al., 2022; Collimore et al., 2021; Kubota et al., 2021), or at a self-selected speed and imposed speed (Clark et al., 2010), while seven of them conducted their experiment overground, at a self-selected (Allen et al., 2019; Allen and Franz, 2018; Guo et al., 2022; Santuz et al., 2022; Sawers et al., 2017; Sawers and Bhatt, 2018; Toda et al., 2016). All studies assessed at least the activity of 1 muscle from each sagittal lower limb muscle groups (i.e., hip flexor/extensor, knee flexor/extensor, and ankle plantar flexor/dorsiflexor), and one study (Guo et al., 2022) supplemented this with the assessment of trunk flexor/extensor, and another (Kubota et al., 2021) with the measurement of paravertebral muscles activity.

When comparing EP vs YA using a Dynamic Motor Control (DMC) index to identify individuals with neuromuscular complexity impairment during walking, Collimore et al. (2021) observed group difference in the number of impaired individuals. Indeed, The authors reported that 11.1% of YA (18–35 years old), 38.5% of young EP (65–74 years old) and 80% of older EP (75+ years old) presented impaired neuromuscular control (Collimore et al., 2021). Allen and Franz (2018) found that fall history, but not age, was associated with reduced number of synergies (difference: 0.90 synergy, $d = 1.630$, $p < 0.001$), and greater VAF-1 (difference: +19.58%, $d = 2.097$, $p < 0.01$) (see Table 4). In opposition, Kubota et al. (2021) reported a reduced number of synergies for the EP group (difference: −0.87 synergy, $d = 1.774$, $p < 0.05$). However, Allen and Franz (2018) highlighted that age was related to a greater synergy timing variability independent of falling history (EP-fallers difference: +1.21, $d = 1.046$, $p < 0.05$, and EP-non fallers difference: +1.32, $d = 1.396$, $p < 0.05$), which is in line with the results of Guo et al. (2022), who reported greater inter and intra-subject timing activation variability for most synergies at normal and slow speed. Overall, EP and YA synergies appear to differ temporally, as shown by the greater duration of activation reported by Santuz et al. (2022) for all four extracted synergies ($\beta = 7.510$ to 12.390), and the earlier shift in the activity timing of 3 of the 4 extracted synergies ($\beta = -7.240$ to 17.140). Also, our findings indicate a tendency towards a greater muscular weighting in EP for specific synergy when walking at normal speed. Indeed, Kubota et al. (2021) reported greater weighting of the ST (difference: +0.19, $d = 0.732$, $p < 0.05$) and BF (difference: +0.30, $d = 0.978$, $p < 0.05$) in the synergy 1 (i.e., synergy involved in loading response), Guo et al. (2022) observed a greater weighting of the ADD in the synergy 4 (i.e., synergy involved in early stance and late swing), and Toda et al. (2016) reported a greater weighting of the TA (difference: N/A, male: $d = 0.526$, $p < 0.05$; female: $d = 0.696$, $p < 0.05$) in the synergy 1 (i.e., synergy involved in early stance), the GMax (difference: N/A, male: $d = 0.936$, $p < 0.05$; female: $d = 0.564$, $p < 0.05$) and RF (difference: N/A, male: $d = 0.021$, $p < 0.05$; female: $d = 1.102$, $p < 0.05$) in the synergy 2 (i.e., synergy involved in late stance), the TA (difference: N/A, male: $d = 0.261$, $p < 0.05$; female: $d = 0.294$, $p < 0.05$) in the synergy 4 (i.e., synergy involved in late swing), and the GAS (difference: N/A, male: $d = 0.936$, $p < 0.05$; female: $d = 0.958$, $p < 0.05$) in the synergy 5 (i.e., synergy involved in early stance). Guo et al. (2022), who also compared differences between walking speeds, reported greater weighting of the TA and lower weighting of the TFL in the synergy 3 (i.e., synergy that contributes to loading response and leg stabilization before the foot contact) only at fast speed, and greater weighting of the EOB in the synergy 9 only at slow speed.

As for walking task with an additional balance challenge, Da Silva Costa et al. (2020) investigated two complex tasks: tape and beam walking. Six and seven synergies, that accounted for >90% of the variance, have been extracted for the tape and beam walking conditions, respectively. Compared to YA, the authors reported higher muscle coactivation (i.e., number of significantly active muscles) within each muscle synergy (difference: +1.20 muscles, $d = 0.630$, $p = 0.026$), greater muscle weighting (i.e., sum of the weightings of significantly active muscle) within a muscle synergy (difference: +0.50, $d = 0.660$, $p = 0.016$), and greater VAF-1 (difference: +5.3%, $d = 0.840$, $p = 0.04$) in EP, regardless the condition (Da Silva Costa et al., 2020).

3.5. Stair ascent

The only study that focused on stair ascent reported 4 synergies (Baggen et al., 2020), that accounted for 90.5%, 89.8% and 91.8% of variance in young women, and 88.5%, 87.3% and 87.4% in older women for step heights of 10, 20 and 30 cm, respectively (see Table 5). The number of synergies was similar between step heights, and the muscle composition of Synergy 1 (i.e., synergy involved in the pull-up part of the movement), appeared to be the most variable across step heights.

The results showed that the VAF obtained when extracting 4 synergies was lower (i.e., indicating higher synergy complexity) when step height was increased, and that EP had lower VAF than YA, across all step heights (difference (10 cm): +1.92%, $d = 0.092$, $p = 0.005$; difference (20 cm): +2.53%, $d = 0.101$, $p = 0.041$; difference (30 cm): +2.88%, d

Table 2
Summary of the included studies.

Studies	Population characteristics			Studies methods				
	N	Age	Sex	Task	Condition(s)	Number of cycles/trials	Muscles recorded	EMG pre-processing method
Alizadehsaravi et al. (2022)	EP: 22	EP: 72.6 ± 4.2	EP: 11 M/11F	Walking	**1.** Fixed (0.97 m/s) Treadmill	Minimum 50	**D side:** TA, VL, GL, SOL, PL, RF, BF, GMed **ND side:** RF, BF, GMed	High-pass filtered (50 Hz), notch filtered (50 Hz and signal harmonics), Hilbert transformed, rectified, low-pass filtered (20 Hz). EMG normalized by maximum value during task.
Allen and Franz (2018)	EP: 11 YA: 12	EP: 75.1 ± 5.8 YA: 24.8 ± 4.6	EP: 5 M/6F YA: 6 M/6F	Walking	**1.** Self-selected speed (EP: 0.60–1.57 m/s; YA: 1.29 m/s) Overground	Minimum 42	TA, GM, SOL, PL, VL, MH, GMed	High-pass filtered (35 Hz), demeaned, rectified, low-pass filtered (10 Hz). EMG normalized to the maximum observed in each muscle during task.
Allen et al. (2019)	EP: 6	EP: 62.0 ± 6.6	EP: 3 M/5F	Walking	**1.** Self-selected speed (1.36 m/s) Overground	3 × 7.6-m trial	GMax, GMed, TFL, ADD, BFL, RF, VL, GM, GL, SOL, PL, TA	High-pass filtered (35 Hz), demeaned, rectified, low-pass filtered (40 Hz). EMG normalized to the maximum activation observed during walking at self-selected speed
Clark et al. (2010)	EP: 20	EP: 65.5 ± 9.8	EP: 4 M/16F	Walking	**1.** Comfortable speed **2.** Fastest speed **3.** Six speeds (0.3–1.8 m/s) Treadmill	**1.** 3 × 30-s trial **2.** 2 × 30-s trial **3.** 6 × 30-s trial	TA, SOL, GM, VM, RF, MH, BF, GMed	High pass filtered (40 Hz), demeaned, rectified, smoothed (4 Hz). EMG normalized to maximum value from self-selected walking and resampled at each 1% of the gait cycle.
Collimore et al. (2021)	EP: 18 YA: 18	EP: 72.0 ± 5.0 YA: 27.0 ± 3.0	EP: 5 M/13F YA: 7 M/11F	Walking	**1.** Fixed (EP: 1.1 m/s; YA: 1.2 m/s) Treadmill	30	VM, RF, VL, TFL, SOL, GM, PL, TA, BF, MH, GMax, GMed	High-pass filtered (40 Hz), demeaned, rectified, low-pass filtered (4 Hz), resampled (1000 Hz). No EMG normalization.
Guo et al. (2022)	EP: 11 YA: 11	EP: 67.2 ± 4.3 YA: 23.4 ± 2.5	EP: 4 M/7F YA: 4 M/7F	Walking	**1.** Slow speed **2.** Normal speed **3.** Fast speed Overground	EP: 19 ± 3 YA: 11 ± 3	TA, GM, GL, SOL, VL, VM, RF, H, ADD, TFL, GMax, ES, EOB, LD	Noise removed from powerline interference, high-pass filtered (40 Hz), rectification, low-pass filtered (40 Hz), integrated (20-ms intervals). Normalization not described.
Santuz et al. (2022)	EP: 70 YA: 70	EP-M: 73.3 ± 4.5; EP-F: 71.4 ± 4.9 YA-M: 28.3 ± 4.3; YA-F: 25.5 ± 3.5	EP: 35 M/35F YA: 35 M/35F	Walking	**1.** Self-selected speed (EP: 1.0–1.4 m/s; YA: 1.1–1.5 m/s) Overground	30	GMed, GMax, TFL, RF, VM, VL, ST, BFL, TA, PL, GM, GL, SOL	High-pass filtered (50 Hz), full-wave rectified, low-pass filtered (20 Hz). EMG normalized to the maximum of each trial.
Kubota et al. (2021)	EP: 10 YA: 11	EP: 70.0 ± 5.0 YA: 20.5 ± 1.8	EP: 8 M/2F YA: 11 M/0F	Walking	**1.** Fixed (0.83 m/s) Treadmill	10	PVM, OPVM, GMax, GMed, TFL, ADD, RF, VM, VL, ST, BF, PL, TA, GM, GL, SOL	Band-pass filtered (20–450 Hz), demeaned, rectified, smoothed (4 Hz). Normalized by the peak value (over all maximum)
Toda et al. (2016)	EP: 20 YA: 20	EP-M: 68.4 ± 3.0 EP-F: 69.1 ± 4.3 YA-M: 21.7 ± 2.1 YA-F: 24.1 ± 2.9	EP: 10 M/10F YA: 10 M/10F	Walking	**1.** Self-selected speed (EP: 0.89–1.42 m/s; YA: 1.00–1.56 m/s) Overground	Not mentioned	GMax, GMed, GMin, IL, RF, VAS, H, GAS, SOL, TA	Not mentioned
Sawers et al. (2017)	EP-Fall: 15 EP-Recovery: 13	EP-Fall: 71.0 ± 2.0 EP-Recovery: 72 ± 5.0	EP-Fall: 2 M/13F EP-Recovery: 8 M/5F	Walking	**1.** Self-selected speed (EP-Fall: 0.55–1.23 m/s; EP-Recovery: 0.74–1.26 m/s) Overground	18–24	TA, GM, VL, BFL	Band-pass filtered (10–200 Hz), rectified, low pass filtered (50 Hz). EMG normalized to the maximum activation during nonslip walking trials.
Sawers and Bhatt (2018)	EP-Fall: 12 EP-Recovery: 13	EP-Fall: 73.0 ± 4.9 EP-Recovery: 74.0 ± 4.1	EP-Fall: 2 M/10F EP-Recovery: 7 M/6F	Walking	**1.** Self-selected speed (EP-Fall: 0.80–1.46 m/s; EP-Recovery: 0.69–1.35 m/s) Overground	18–24	TA, GM, VL, BFL	Band-pass filtered (10–200 Hz), rectified, low pass filtered (50 Hz). EMG normalized to the maximum activation during nonslip walking trials.
Da Silva Costa et al. (2020)	EP: 14 YA: 17	EP: 69.0 ± 4.0 YA: 24.0 ± 3.0	EP: 3 M/11F YA: 11 M/6F	Balance challenge walking	**1.** Along a 2-cm wide tape **2.** On a 6-cm wide aluminium beam	20 × 4-m trial	TA, PL, GM, SOL, VM, VL, BFL, ST, GMed, RF, ADD, EOB, ES	High-pass filtered (35 Hz), demeaned, rectified, low-pass filtered (40 Hz). EMG normalized

(*continued on next page*)

Table 2 (*continued*)

Studies	Population characteristics			Studies methods				
	N	Age	Sex	Task	Condition(s)	Number of cycles/trials	Muscles recorded	EMG pre-processing method
								to maximum activation observed during the line walking trials.
Baggen et al. (2020)	EP: 11 YA: 10	EP: 67.0 ± 2.5 YA: 22.5 ± 1.6	EP: 0 M/ 11F YA: 0 M/ 10F	Step ascent	**1.** Forward step (10, 20, 30 cm)	9	TA, GL, SOL, VL, RF, BF, ST, GMax, GMed, ES	High-pass filtered (20 Hz), rectified, smoothed (0.1 s moving window). EMG normalized to the respective maximum obtained over all trials.
An et al. (2013)	EP: 7 YA: 3	EP: 67.1 ± 7.3 YA: 24.0 ± 3.5	Not mentioned	Sit-to-stand	**1.** Stand up in a way they found comfortable	12 to 20	RF, TA, VL, SOL, GAS, BF, GMax, LD	High-pass filtered (10 Hz), notch filtered (50–60 Hz), centered, rectified, smoothed. Normalization not described.
Hanawa et al. (2017)	EP: 3 YA: 4	EP: 72.0 ± 2.0 YA: 22.5 ± 1.2	EP: 3 M YA: 4 M	Sit-to-stand	**1.** Natural speed **2.** As fast as possible	10	TA, SOL, GM, VL, RF, ST, GMax	Band-pass filtered (20–500 Hz), demeaned, rectified, smoothed (10 Hz). EMG normalized to maximum EMG activity for a given muscle across all trials.
Yang et al. (2017)	EP: 5 YA: 6	EP: 66.8 ± 8.5 YA: 25.0 ± 3.0	Not mentioned	Sit-to-stand	**1.** Chair height adjusted to the lower leg height	15	TA, GAS, SOL, RF, VL, BFL, BFS, GMax, RA, ES	Not mentioned
Yang et al. (2019)	EP: 12	EP: 64.2 ± 3.2	EP: 10 M/ 2F	Sit-to-stand	**1.** Chair height adjusted to the lower leg height	10	TA, GL, GM, PL, SOL, RF, VL, VM, BF, SM, Gmax, Gmed, RA, EOB, ES	Band-pass filtered (40–400 Hz), rectified, low-pass filtered (4 Hz). EMG normalized to maximum value during the task.

Abbreviations**:** adductor magnus (ADD), biceps femoris (BF), biceps femoris long head (BFL), biceps femoris short head (BFS), dominant (D), elderly people (EP); erector spinae (ES), external obliques (EOB), female (F), gastrocnemius (GAS), gastrocnemius lateralis (GL), gastrocnemius medialis (GM), gluteus maximus (GMax), gluteus medius (GMed), gluteus minimus (GMin), hamstrings (H), iliopsoas (IL), latissimus dorsi (LD), male (M), medial hamstrings (MH), non-dominant (ND), non-negative matrix factorization (NNMF), opposite (opp), opposite paravertebral muscle (OPVM), paravertebral muscle (PVM), peroneus longus (PL), rectus abdominis (RA), rectus femoris (RF), semitendinosus (ST), soleus (SOL), tensor fasciae latae (TFL), tibialis anterior (TA), vastii muscles (VAS), vastus lateralis (VL), vastus medialis (VM), young adults (YA).

= 0.163, p = 0.019). For all step heights, muscle weighting analysis showed that the RF weighting in EP is greater in the synergy 4, which is involved in the second half of foot clearance and pull-up phases (difference (10 cm): +0.21, d = 1.360; difference (20 cm): +0.13, d = 1.644, $p < 0.05$; difference (30 cm): +0.20, d = 1.387, $p < 0.05$), and lower in the synergy 2, that is contributing during the beginning of foot clearance and the end of pull-up phases (difference (10 cm): +0.26, d = 1.435, $p < 0.05$; difference (20 cm): +0.23, d = 1.322, $p < 0.05$; difference (30 cm): +0.36, d = 2.400, $p < 0.05$), compared to YA. Overall, the muscle weighting differences between EP and YA appears highly variable across step heights (see Table 5). Regarding temporal activation patterns, higher between-subjects variability of temporal activation was shown for all step heights in the synergy 2 (difference (10 cm): +5.58, d = 1.636, $p < 0.01$; difference (20 cm): +9.97, d = 1.556, $p < 0.05$; difference (30 cm): +8.04, d = 2.125, $p < 0.01$), and the synergy 4, (difference (10 cm): +6.50, d = 1.908, $p < 0.01$; difference (20 cm): +5.36, d = 1.460, $p < 0.01$; difference (30 cm): +9.37, d = 1.625, $p < 0.01$) in EP, compared to YA. The same tendency was noticed, solely for 20 and 30 cm step heights, in the synergy 3, that is contributing during the end of foot clearance and the pull-up phase (difference (20 cm): +9.76, d = 1.381, $p < 0.05$; difference (30 cm): +10.64, d = 1.295, $p < 0.01$).

3.6. Sit-to-stand task

Three studies (An et al., 2013; Hanawa et al., 2017; Yang et al., 2017), among the four that focused on sit-to-stand task (An et al., 2013; Hanawa et al., 2017; Yang et al., 2019, 2017), describe the temporal occurrence of muscle synergies according to the phasic description of Schenkman et al. (1990)**: Phase 1** (i.e., flexion momentum phase) begins with the first shoulder movement in the horizontal direction; **Phase 2** (i.e., momentum transfer phase) begins at contact loss with the stool; **Phase 3** (i.e., vertical extension phase) begins when the shank segment tilted forward to the maximum; **Phase 4** (i.e., stabilization phase) begins when the vertical shoulder position achieved its maximum height. A range of 3 to 4 muscle synergies that account for 88% of the variance have been reported by the four studies that have focused on sit-to-stand task (see Table 6).

Overall, the results suggest similar muscle synergies underlying the sit-to-stand task between EP and YA groups. Still, An et al. (2013) observed that 5 of 7 EP had no synergy for flexing their ankle and bending their trunk (i.e., during phase 1 and 2). Also, Yang et al. (2019) reported difference in the temporal (i.e., delayed peak time), and spatial (i.e., decreased gradient steepness after peak value) structure of one synergy in EP, compared to YA. Furthermore, Hanawa et al. (2017) investigated muscle synergies during sit-to-stand task at different speeds. Three synergies, with similar spatial structure, were observed in both EP and YA groups, regardless the speed. Conversely, the change in movement speed affected the temporal structure of synergies (i.e., prolonged activation for one synergy), but no effect of age was observed.

4. Discussion

The goal of this scoping review was to summarize the existing literature investigating muscle synergies in EP during daily living tasks which are critical to maintaining their autonomy. We highlighted how muscle synergies in EP differ from those exhibited by YA. The main findings were: 1) EP retain in general similar number of muscle synergies compared to YA although increased VAF could be observed in EP compared to YA during walking tasks as well as sit-to-stand task; 2) Generally, higher muscles weighting was reported in EP during normal walking and walking with an additional balance challenge tasks; and 3) in terms of synergies temporal structure, EP had an increased inter-subject variability during stair ascent, and an increased intra and inter-subject variability during normal walking, compared to YA.

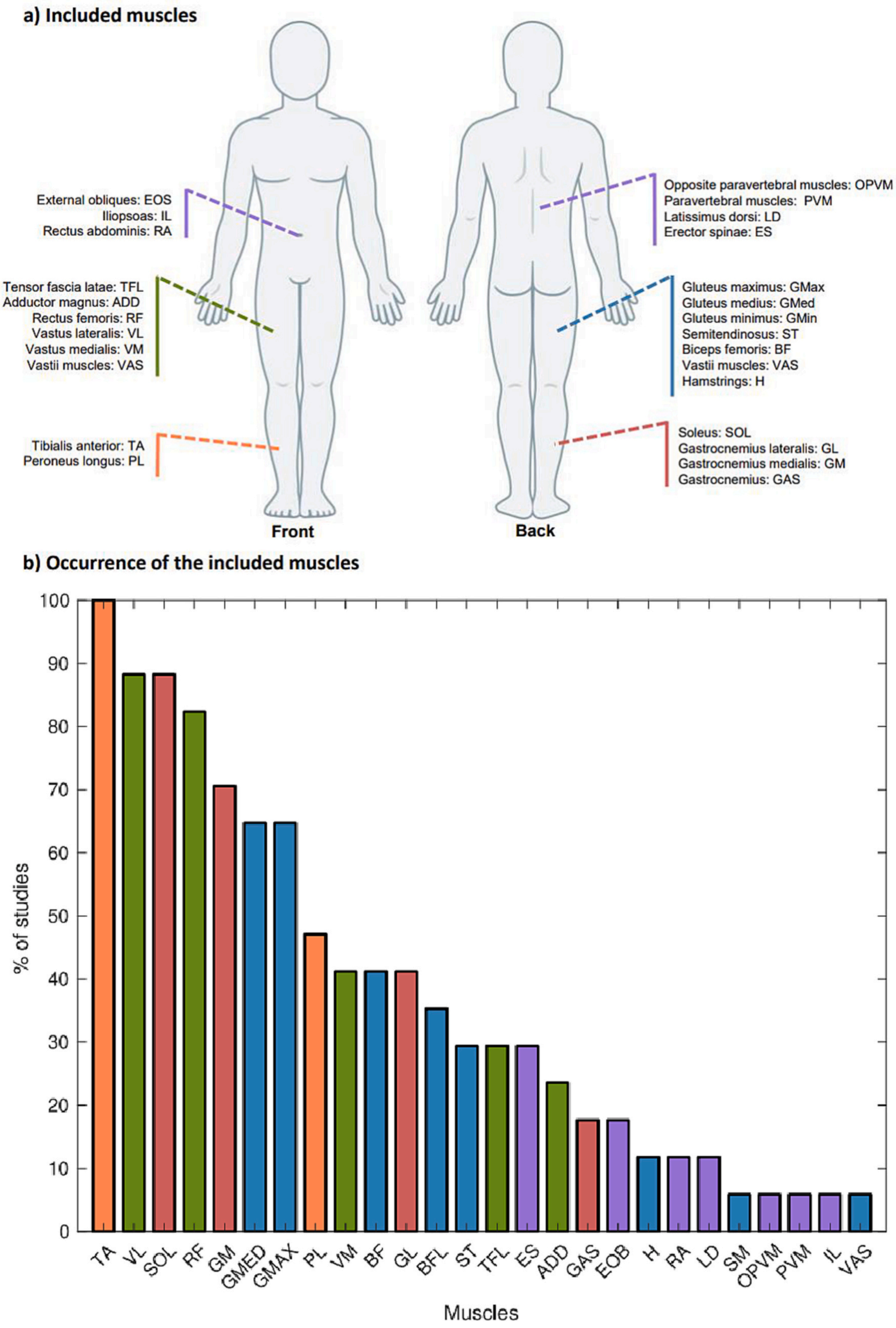

Fig. 2. Names of the included muscles and related occurrence (% of the included studies).

Table 3
Muscle synergies during normal walking and balance challenge walking in elderly people.

Normal walking				
Studies	VAF (%)	Number of synergies	Major involved muscles	Predominant temporal occurrence
Alizadehsaravi et al. (2022)	87 ± 2	1	Dominant leg: SOL, GL	Stance phase
		2	Dominant leg: VL, RF	Weight acceptance
		3	Non Dominant leg: GMed, RF	Stance phase
		4	Dominant leg: BF	Prior heel strike
		5	Non Dominant leg: BF	Prior heel strike
Allen and Franz (2018)	>90	1	GM, SOL, PL	Late stance
		2	MH	Early stance
		3	TA, VL	Swing phase
		4	Med, VL	Early stance
Allen et al. (2019)	>90	1	BF, RF, VL, PL, TA	Not mentioned
		2	GM, GL, SOL, PL	
		3	ADD	
		4	GMed	
Clark et al. (2010)	85–98	1	GMed, VM, RF	Weight acceptance
		2	SOL, GM	Late stance
		3	TA, RF	Early stance & early swing
		4	MH, BF	Late swing & early stance
Collimore et al. (2021)	>90	1 2 3	Not mentioned	Not mentioned
Guo et al. (2022)	>80	1	TA	Early stance & swing phase
		2	GM, GL, SOL	Late stance
		3	VL, VM, RF	Early stance & late swing
		4	H, ADD	Early stance & late swing
		5	TFL	Whole gait cycle
		6	GMax	Early stance & late swing
		7	EOB	Whole gait cycle
		8	ES, LD	Late stance
		An additional synergy involving RF is identified at fast speed compared to normal and slow speed		
Kubota et al. (2021)	≥90%	1	GMax, GMed, TFL, RF, VM, VL, OPVM	Early stance
		2	GMed, TFL, OPVM, GM, GL, SOL, PL	Late stance
		3	ADD, PVM, TA, ST, BF	Early swing
		4	PVM, TA, ST, BF	Late swing
Santuz et al. (2022)	>80	1	GMed, GMax, TFL, RF, VM, VL	Weight acceptance
		2	PL, GM, GL, SOL	Propulsion
		3	TA	Early swing
		4	SR, BF	Late swing
Sawers et al. (2017)	>90	1	TA, BFL, VL	Stance phase & late swing
		2	TA	Stance phase
		3	GM, oppBFL	Stance phase
		4	TA, GM VL, BFL	Swing phase
		5	GM, oppBFL	Whole gait cycle
		6	BFL	Whole gait cycle
Sawers and Bhatt (2018)	>90	1	TA, VL	Early stance & swing
		2	oppTA, oppVL	Late stance & early swing
		3	GM, BFL	Late stance
		4	oppGM, oppBFL	Early stance & late swing
		5	VL, BFL	Early stance
		6	oppVL, oppBFL	Late stance & early swing
Toda et al. (2016)	>90	1	GMed, GMin, VAS	Early stance
		2	GAS, SOL	Late stance
		3	IL, RF	Stance phase
		4	GMax, H	Late swing
		5	TA	Early stance
Balance challenge walking				
Da Silva Costa et al. (2020) **(Tape)**	>90	1	VL, RF, GM	Stance phase
		2	PL, GM	Stance phase
		3	PL, EOB	Whole gait cycle
		4	BFL, ST	Late swing & early stance
		5	ES	Early stance & late stance
		6	TA, VM, SOL, ADD	Mid-swing
Da Silva Costa et al. (2020) **(Beam)**	>90	1	VL, RF	Stance phase
		2	PL	Stance phase
		3	RF, GM, SOL, GMed, EOB	Constant on all gait cycle
		4	BFL, ST, ADD	Late swing & early stance
		5	ES, EOB	Early stance & late stance
		6	SOL	Mid-swing
		7	TA, VM	Mid-stance & mid-swing

The number of synergies in elderly people (EP) and highest weighting muscles within the synergy are reported. The variability accounted for (VAF) is presented for all synergies or segregate by unique synergy, if available. Temporal component is represented by the predominant temporal occurrence (i.e., when the synergy activation is predominant compared to the rest of the movement). **Abbreviations:** adductor magnus (ADD), biceps femoris (BF), biceps femoris long head (BFL), biceps femoris short head (BFS), erector spinae (ES), external obliques (EOB), gastrocnemius (GAS), gastrocnemius lateralis (GL), gastrocnemius medialis (GM), gluteus maximus (GMax), gluteus medius (GMed), gluteus minimus (GMin), hamstrings (H), iliopsoas (IL), latissimus dorsi (LD), medial hamstrings (MH), opposite (opp), opposite paravertebral muscle (OPVM), paravertebral muscle (PVM), peroneus longus (PL), rectus femoris (RF), semitendinosus (ST), soleus (SOL), tensor fasciae latae (TFL), tibialis anterior (TA), vastii muscles (VAS), vastus lateralis (VL), vastus medialis (VM). * An additional synergy involving RF is identified at fast speed compared to normal and slow speed.

4.1. Walking tasks

Despite no independent effect of age on motor module complexity in terms of number of synergies, some studies reported an age-related decrease in neuromuscular complexity (i.e., higher VAF-1) and efficiency (i.e., higher muscle coactivity) during normal walking (Allen et al., 2019; Da Silva Costa et al., 2020) and walking with an additional balance challenge (Da Silva Costa et al., 2020). The choice of the number of synergies reflects the degree of complexity considered in the model. Evaluating the VAF through a given number of synergies enables to quantify the complexity of an individual's muscle activation pattern (Steele et al., 2015). A high VAF for a small number of synergies suggests that the muscle activation patterns are relatively simple and can be

Table 4
Significant differences in synergy characteristic between elderly people and young adults during normal walking and balance challenge walking.

		VAF		Muscle weighting		Number of synergies		Timing activation		Other indexes	
		Difference in older	ES	Difference in older	ES	Difference in older	ES	Difference in older	ES	Difference in older	ES
Normal walking	Allen and Franz (2018)	↑ VAF-1 only in EP-fallers	2.097			↓ only in EP-fallers	1.630	↑ TAV - EP-fallers ↑ TAV - EP-non fallers	1.046 1.396		
	Collimore et al. (2021)									↓ DMC index	0.919^{Δ}
	Guo et al. (2022)			↑ TA - S3 at fast speed ↓ TFL - S3 at fast speed ↓ TA - S4 at fast speed ↑ EOB - S4 at fast speed ↑ ADD - S4 at normal speed ↑ EOB - S9 at slow speed ↓ S6 amplitude in early swing at all speed ↑ S1 amplitude in late stance at fast speed	● ● ● ● ● ● ● ●			↑ inter-subject TAV - S1, S2, S3, S4, S5, S8 at normal & slow speed ↑ intra-subject TAV - S6 at fast speed ↑ intra-subject TAV - S2, S4 at normal speed ↑ intra-subject TAV - S1 at slow speed ↓ intra-subject TAV - S7, S8 at normal & slow speed	● ● ● ● ●		
	Kubota et al. (2021)	↑ VAF - S1 ↑ VAF - S2 ↑ VAF - S3 ↑ VAF - S4	1.851 1.922 2.273 2.473	↑ ST - S1 ↑ BF – S1	0.732 0.978	↓	1.774				
	Santuz et al. (2022)							↑ time of activation - S1 ↑ time of activation - S2 ↑ time of activation - S3 ↑ time of activation - S4 Earlier shifting - S2 Earlier shifting - S3 Earlier shifting - S4	7.510^{δ} 6.530^{δ} 12.750^{δ} 12.390^{δ} -7.240^{δ} -15.480^{δ} -17.140^{δ}	↑ reduction of local complexity - F vs. M ↑ reduction of global complexity - F vs. M	0.040^{δ} 0.040^{δ}
	Toda et al. (2016)			↓ SOL in F - S1 ↑ TA - S1 ↑ TA - S2 ↑ GMax - S2 ↑ RF - S2 ↓ IL - S3 ↑ GAS in F - S3 ↑ TA - S4 ↑ GAS - S5	1.405 M: 0.526; F: 0.696 M: 1.039; F: 0.878 M: 0.936; F: 0.564 M: 0.021; F: 1.102 M: 0.714; F: 0.436 1.064 M: 0.261; F: 0.294 M: 0.936; F: 0.958						
Balance challenge walking	Costa et al. (2020)	↑ VAF-1	0.840							↑ Wmus ↑ Wsum	0.630 0.660

Lower-limb muscle synergies difference in elderly people (EP) compared to young adults (YA) are presented. Synergy (S) numbers are based on Table 3. If available (● if not), effect size (ES) are reported as Cohen's d, or Glass's delta (Δ) or Hedges (δ). **Abbreviations**: increased/higher (↑), decreased/lower (↓), adductor magnus (ADD), bicep femoris (BF), dynamic motor control index (DMC), external obliques (EOB), females (F), gastrocnemius (GAS), gluteus maximus (GMax), iliopsoas (IL), males (M), soleus (SOL), temporal activation variability (TAV), tibialis anterior (TA), variance accounted for (VAF), VAF the first muscle synergy (VAF-1), number of significantly active muscles/muscle synergy (Wmus), sum of the contribution of active muscles within a muscle synergy (Wsum).

Table 5
Muscle synergies in elderly people during stair ascent and differences with young adults.

Baggen et al. (2020)											
10 cm				20 cm				30 cm			
Synergy	VAF (%)	Major involved muscles	Predominant temporal occurrence	Synergy	VAF (%)	Major involved muscles	Predominant temporal occurrence	Synergy	VAF (%)	Major involved muscles	Predominant temporal occurrence
1	88.5	GL, RF, GMed	Pull-up	1	87.3	GL, SOL	Pull-up	1	87.4	GL, RF, GMax, GMed	Pull-up
2		RF, BF, ST,	First half of FC & pull-up	2		VL, RF, BF, ST,	First half of FC & end of pull-up	2		VL, BF, ST	First half of FC & end of pull-up
3		TA, SOL, ES	End of FC & beginning of pull-up	3		TA, ES	Foot clearance & Pull-up	3		TA, SOL, ES	End of FC & pull-up
4		TA, SOL, RF	Middle of FC & pull- up	4		TA, SOL	Second half of FC & pull- up	4		TA, ST	Second half of FC & pull- up

	Difference in older	ES	Difference in older	ES	Difference in older	ES
VAF	↓ VAF	0.092	↓ VAF	0.101	↓ VAF	0.163
Muscle weighting	↓ VL - S1	1.140	↑ GL - S1	2.740	↑ RF - S1	2.785
	↑ RF - S1	1.537	↓ VL - S2	1.029	↑ BF - S1	1.467
	↓ Gmed - S1	1.154	↓ RF - S2	1.322	↓ RF - S2	2.400
	↓ RF - S2	1.435	↑ ST - S2	1.631	↑ SOL - S3	1.397
	↑ ES - S2	1.580	↓ GL - S3	3.667	↓ ES - S3	1.231
	↑ SOL - S4	1.037	↓ SOL - S3	1.506	↑ RF - S4	1.387
	↑ RF - S4	1.360	↑ RF - S4	1.644	↑ ST - S4	1.159
			↓ GMed - S4	1.302	↓ Gmed - S4	1.031
Timing activation	↑ BSV of temporal activations - S2	1.636	↑ BSV of temporal activations - S2	1.556	↑ BSV of temporal activations - S2	2.125
	↑ BSV of temporal activations - S4	1.908	↑ BSV of temporal activations - S3	1.381	↑ BSV of temporal activations - S3	1.295
			↑ BSV of temporal activations - S4	1.460	↑ BSV of temporal activations – S4	1.625

Upper part: The number of synergies in elderly people (EP) and highest weighting muscles within the synergy are reported. The variability accounted for (VAF) is presented for all synergies. Temporal component is represented by the predominant temporal occurrence. Lower part: Lower-limb muscle synergies difference in EP compared to young adults (YA) are presented. Synergy (S) numbers are based on the upper part. Effect size (ES) are reported Cohen's d. **Abbreviations**: increased/higher (↑), decreased/lower (↓), biceps femoris (BF), between-subject variability (BSV) erector spinae (ES), gastrocnemius lateralis (GL), gluteus maximus (GMax), gluteus medius (GMed), rectus femoris (RF), semitendinosus (ST), soleus (SOL), tibialis anterior (TA), vastus lateralis (VL), foot clearance (FC).

adequately represented by a small set of coordinated muscle groups. Conversely, a lower VAF for the same number of synergies implies a more complex or less predictable coordination of muscles (Steele et al., 2015). The VAF-1 appears to be a more sensitive measure of changes in the complexity of neuromuscular control that accompanies cortical modifications related to aging (Douaud et al., 2014). Moreover, the results suggests that age increases the variability of module recruitment timing during walking (Allen et al., 2019; Guo et al., 2022), which can be associated with an altered neuromuscular control at the highest levels of control (e.g., cortical). To assess changes, that we suppose occur with age, it is likely that other synergies metrics (i.e., temporal and spatio-temporal synergy models) might provide additional information, and perhaps reveals more subtle differences. Moreover, the DMC index has been shown to be a relevant predictor related to aging, in contrast to the number of synergies (Collimore et al., 2021). Indeed, within EP group differences (young-EP vs older-EP) has been reported, suggesting that the use of two age groups (EP vs YA) as a differentiating factor can be overly crude.

Da Silva Costa et al. (2020) have shown that EP have increased muscle coactivation and weighting within synergies, which supports the increased biomechanical control demand required in EP, compared to YA. Greater antagonistic activation is a well-known adaptation when the task requires a more precise control such as walking on slippery surfaces (Chambers and Cham, 2007) or descending slopes (Lay et al., 2007), and it increases dramatically with age (Ortega and Farley, 2015). This control strategy appears intuitive, as neural delays are thought to be too long to allow feedback mechanisms to sufficiently respond to instabilities during tasks, but the effect of antagonist co-activation on control remains to be fully elucidated (Latash, 2018). Indeed, Da Silva Costa et al. (2020) have shown that task complexity, such as greater balance challenges during gait (i.e., beam vs tape walking), results in an increased muscle coactivation (i.e., within a synergy), and an increased number of muscle synergies, which reflect the greater complexity of neuromuscular activation patterns when the task is more complex. Thus, increasing the difficulty of functional task may potentially distinguished neuromuscular control deficit that are not present when the task difficulty is low (Da Silva Costa et al., 2020). Allen and Franz (2018), who assessed the effect of balanced perturbations during walking in EP with and without history of fall, suggested that fall history was an important contributor of motor module complexity. Indeed, their results indicate that fall history has a larger effect on motor module recruitment than age itself, which suggest fall experience has perceptual and biomechanical/physiological consequences on control of posture, and this likely explains the abnormal responses to balance perturbations and the associated greater risk of fall in EP with fall history observed elsewhere (Tinetti et al., 1988).

The methodological choices (i.e., environmental setting) may explain differences in EP and YA that are not supported by all studies

Table 6
Muscle synergies in elderly people during sit-to-stand task and differences with young adults.

Studies	VAF (%)	Number of synergies	Major involved muscles	Predominant temporal occurrence	Difference in older	ES
An et al. (2013)	Not mentioned	1	GAS, RF, GMax	Phase 1 & 2	5/7 participants have no synergy at all for flexing their ankle and bending trunk - S1	•
		2	TA, VL, BF	Phase 3		
		3	SOL, GAS, BF, GMax	Phase 3 & 4		
Hanawa et al. (2017)	>90	1	TA, RF, VL	Phase 2	*No information*	
		2	VL, RF, ST, GM	Phase 3		
		3	SOL, GM	Phase 4		
Yang et al. (2017)	88 ± 3	1	RA	Phase 1	*No information*	
		2	TA, VL, RF	End phase 1 & phase 2		
		3	ES, VL, BFL, BFS	Phase 2 & phase 3		
		4	GAS, SOL, GMax	Phase 3 & phase 4		
Yang et al. (2019)	88.7	1	RA, EOB	Phase 1	Peak time comes after - S2	•
		2	TA, RF, VM, VL	Phase 2		
		3	ES, BF, ST, GMax, GMed	Phase 3 & 4	↓ gradient steepness after the peak value of S2	•
		4	GL, GM, PL, SOL	Phase 3 and 4		

On the left side: The number of synergies in elderly people (EP) and highest weighting muscles within the synergy are reported. The variability accounted for (VAF) is presented for all synergies. Temporal component is represented by the predominant temporal occurrence. Phase 1 begins with the first shoulder movement in the horizontal direction; Phase 2 begins at contact loss with the stool; Phase 3 begins when the shank segment tilted forward to the maximum; Phase 4 begins when the vertical shoulder position achieved its maximum height (Schenkman et al., 1990). On the right side: Lower-limb muscle synergies difference in EP compared to young adults (YA) are presented. Synergy (S) numbers are based on the left side. Effect size (ES) were not available (•). **Abbreviations:** increased/higher (↑), decreased/lower (↓), biceps femoris (BF), biceps femoris long head (BFL), biceps femoris short head (BFS), external obliques (EOB), erector spinae (ES), gastrocnemii (GAS), gluteus maximus (GMax), gluteus medius (GMed), gastrocnemius medialis (GM), gastrocnemius lateralis (GL), latissimus dorsi (LD), peroneus longus (PL), rectus femoris (RF), semitendinosus (ST), soleus (SOL), tibialis anterior (TA), vastus lateralis (VL).

that focussed on gait. For instance, the reduced number of synergies in EP vs. YA reported by Kubota et al. (2021) is not supported by Allen and Franz (2018) and the discrepancy could be the results of the walking environment (treadmill vs. overground), walking speed (fixed vs. self-selected), or fall history. Indeed, walking on a treadmill at a fixed speed imposes a cadenced pattern of joint motion, which may standardize the condition for the assessment of the true differences between EP and YA, despite the effect of fast speed variation that can occur during overground walking. Indeed, it could be argued that the walking environment may affects the number of synergies; Guo et al. (2022) identified an additional synergy at fast speed, compared to normal and slow speed during overground walking, while Clark et al. (2010) did not support this result with their experimentation on a treadmill. Overall, results suggest that differences in synergy outcomes are mainly observed when the conditions are the most challenging, and less observed in basic standardized conditions. Also, between studies comparison in terms of spatiotemporal structures within synergies must be approached with caution in view of methodological heterogeneity, either due to a different number of extracted synergies (probably due to different VAF levels), or due to differences in sorting algorithms.

4.2. *Stair ascent*

During stair ascent task, Baggen et al. (2020) reported a decreased VAF-1 was observed in older women, and when step height was increased, suggesting a higher synergy complexity. According to the current literature, population with impaired mobility, such as cerebral palsy (Steele et al., 2015) and Parkinson's disease (Rodriguez et al., 2013), have a reduced neuromuscular complexity, which limits their ability to perform complex locomotor task such as walking up-stairs. Thus, a greater synergy complexity in EP, compared to YA during stair ascent is not expected. However, the author proposes that the increased complexity of synergies arises from the greater challenge of stepping up stairs in EP, which requires the adoption of different control strategies to compensate for their reduced functional capacity (Baggen et al., 2020).

The spatiotemporal organization of the muscle synergies showed differences between EP and YA. Indeed, decreased contribution of RF was observed in synergy 2 (i.e., which was active during the initial foot clearance phase) in EP regardless of the step height, while its contribution was increased in synergy 4 (i.e., active during the second half of the foot clearance). As reported by Reeves et al. (2009), this result suggests that the decreased physical capacity of EP leads to alternative movement strategy to operate within their maximum capabilities (i.e., modulation the spatiotemporal organization of the synergies) (Reeves et al., 2009). Moreover, tasks such as beam walking and stair ascent are generally challenging for old people and are associated with greater antagonist muscles coactivation (DeVita and Hortobagyi, 2000; Llewellyn et al., 1990). These tasks also lead to variations in the structure of the muscle synergies depending on the difficulty of the task or the population tested (Baggen et al., 2020; Sawers et al., 2015). The coactivation might not be specific to older people and, therefore, the presence of coactivation might reflect the challenging nature of the task and not only spinal alterations (i.e., diminished reciprocal inhibition). However, the greater heterogeneity of synergy organization that was observed within the EP group (i.e., increased between-subject variability of temporal activation patterns) may suggest that motor skill level or age impacts the choice of specific spatiotemporal organization of muscle synergies.

4.3. *Sit-to-stand task*

The ability to rise from seated position is critical for EP to maintain their independence and functional fitness (Van Lummel et al., 2015; Yee et al., 2021). In the absence of any fall history, Hanawa et al. (2017) reported common muscle synergies during sit-to-stand task in both YA ($n = 4$) and EP ($n = 3$). In the other hand, compared to YA, An et al. (2013) observed less activated synergies, and no synergy involved in ankle flexion and trunk bending (i.e., to raise the hip from the seat) in 5/7 EP. These results may be related to the low muscle strength of EP individuals, knowing that this latter is one of the most important factors to succeed in getting up from a chair (Alexander et al., 1997; Van Lummel et al., 2015). In a similar context, Van Lummel et al. (2015), showed that EP with low grip strength used a different strategy to rise from a seated position than EP with higher grip strength, which is characterized by greater trunk flexion and more dynamic trunk use during the extension phase. Indeed, peripherical muscle weakness of EP may be compensated by using their trunk, exhibiting increased sway due to the high inertia of the trunk, which is challenging to halt without control and may contribute to fall risk. However, the small sample size of studies investigating muscle synergies underlying the sit-to-stand task in EP (i.e., 3 to 12 participants) limits the results' generalizability.

4.4. Clinical implications

To the best of our knowledge, this is the first review investigating the neuromuscular control as assessed by muscle synergies in EP during three common tasks: walking, sit-to-stand and stair ascent. These tasks require precise and dynamic coordination of several muscles of the lower limb and trunk. Muscle synergy analysis can provide a more generalizable assessment of motor function by identifying whether common neuromuscular control mechanisms are altered when performing multiple motor tasks. This scoping review highlighted the presence of common muscles synergies between different daily living tasks, particularly during the early stance phase of walking and the second phase of sit-to-stand task. Indeed, the concomitant activation of the TA with one or many quadriceps' muscles (i.e., RF, VL, VM), and/or with one or many muscles of the posterior thigh (i.e., ST, BF) has been reported during early stance phase (i.e., heel strike, loading response/weight acceptance) by most of studies that focused on gait (Allen et al., 2019; Allen and Franz, 2018; Clark et al., 2010; Guo et al., 2022; Sawers et al., 2017; Sawers and Bhatt, 2018; Toda et al., 2016). Similar synergies have been observed in all studies that focused on sit-to-stand task during the second phase of the movement (Hanawa et al., 2017; Yang et al., 2019, 2017), or during the third phase (An et al., 2013). The presence of similar synergies represents a significant advantage for therapeutic managements in EP. Indeed, these results suggest the possibility to improve the neuromuscular control of problematic gait phases (e.g., during the stance phase when dynamic stability is challenged) through the practice of functional tasks that represent a lower risk of falls (e.g., chair rising with handhold).

4.5. Recommendations for future studies

In order that future studies may contribute to establishing a better theoretical framework concerning muscle synergies during daily living tasks in EP, authors should consider the following elements. First, the names of the muscles should be specifically defined. Some studies included in this scoping review (An et al., 2013; Guo et al., 2022; Toda et al., 2016; Yang et al., 2017) mentioned muscles group (e.g., GAS or H) without specifying which muscles were included in these groups, thereby limiting the results' comparison with other studies. Indeed, although muscles within the same muscles group (e.g., H) work synergistically during the movement (e.g., walking), the weighting of each muscle (e.g., BF, ST, SM) may vary depending on the specific demands of the gait phase.

Second, the number and the choice of the muscles included in the analysis should be chosen carefully. Indeed, Steele et al. (Steele et al., 2015) have shown that the structure of synergies is dependent of the number and the muscles choice in the analysis. They have reported that the VAF is over-estimated when fewer muscles are included in the analysis (Steele et al., 2015). In line with this latter and the results of this scoping, we recommend 1) to record the muscle activity of as many muscles as possible that are involved in the task (i.e., muscles recognized as reliable through surface EMG recording), 2) to select the largest muscles (i.e., determined by maximum isometric force (Maughan et al., 1983)) if the number of muscles that can be recorded is limited (Steele et al., 2015), and 3) to either perform some of the analysis with respect to previously chosen muscle sets or to publish the data online. The heterogeneity of the muscles set in all the mentioned studied limits our ability to perform accurate meta-analysis. One remedy one can suggest would be to create databases that future authors could access.

Third, attention should be given to minimizing noise when recording EMG signals. Indeed, Steele et al. (2015) have shown that noise affects synergy analysis outcomes when a small number of muscles are recorded. However, when the analysis includes >15 muscles, they reported that a signal that is at least 10 times stronger than the noise has minimal effect on muscle combinations (Steele et al., 2015). Noise can be limited, for instance, by a good skin preparation (i.e., shaving, sandpapering and cleaning of the skin), by choosing the best location and orientation of the sensor on the muscle (i.e., region away from the innervation zone and the end zone of the muscle), and by good fixation of the sensor (i.e., with elastic band or tape) (Hermens et al., 2000).

Fourth, there is no one-size-fits-all method for signal processing, but authors should be aware of the effect of the signal preprocessing on synergies estimation. For instance, Guo et al. (2022), who used an unconventional signal processing technique (i.e., a quasi-raw pattern/lightly filtered, and cluster synergies), found a total of 8 synergies, which is largely above the number of synergies conventionally reported (i.e., $n = 4$ to 5) by previous studies focusing on walking task (Alizadehsaravi et al., 2022; Allen et al., 2019; Allen and Franz, 2018; Clark et al., 2010; Kubota et al., 2021; Santuz et al., 2022; Toda et al., 2016).

Fifth, the VAF-1, the number of synergies or the DMC are interesting, but too gross and indiscriminating. An analysis of the synergy's spatial and temporal structure is warranted to detect neuromuscular control deficits. A conventional EMG analysis can provide an overview of the spinal cord's output, and the synergy analysis allows identifying its structuring. The following three approaches, that are not well reported in the current literature, would be interesting to consider: 1) assessing neuromuscular robustness over time throughout a task, by calculating the variability using the cross-VAF (Ghislieri et al., 2023; Gizzi et al., 2015). This would make it possible to describe how an epoch containing N gait cycles can be reconstructed by a muscle synergy model calculated from a different epoch of N gait cycles. 2) Using the intra-subject approach, and 3) an inter-subject/repertory approach, which both allow a better synthetization of results across subjects or condition (Cheung et al., 2020; Funato et al., 2022; Guo et al., 2022). The intra-subject approach is promising, but the inter-subject comparison is questionable in the absence of adequate EMG signals normalization, since synergies may differ because of the normalization technique used or the different muscle activation level.

Finally, the heterogeneity of the number of cycles/trials may influence muscle synergies, particularly when considering a limited number of cycles (Steele et al., 2015). Indeed, Oliveira et al. (2014) highlighted that using at least 20 concatenated steps optimally reflect the modular structure of human locomotion and its variability over time (Oliveira et al., 2014). Thus, for future research, we suggest the authors to state systematically the number of cycles (not only the number of trials) used for the synergy calculations to allow the consideration of this effect when comparing results across studies. In the included studies, 4/17 studies used >25 cycles/condition, 8/17 studies considered 10 to 25 cycles, one study considered <10 cycles, 3/17 studies only mentioned the number of trials, and one study did not mention the number of cycles or trials.

4.6. Limitations

Regarding the review itself, a few limitations must be acknowledged. A limitation concerns the restrictions on the language, and the type of publication. Indeed, we have chosen to include only English and French publications to ensure that we fully comprehend the content of the articles and accurately extract relevant information. Regarding the qualities of included studies, several studies included a limited number of participants, without performing prospective sample size calculations. Therefore, some of them may not have the power to detect changes in muscle synergies. Also, two of the four studies that focused on sit-to-stand task have a low methodological quality assessment score, which constrained the quality of our results concerning this latter. However, most of the included studies have a large sample size and a moderate to high methodological quality assessment score. Moreover, the metrics used to describe synergies are numerous (e.g., VAF, VAF-1, DMC, TAV), and these methodological discrepancies limit the information synthetization across studies. Finally, some studies focused on a restricted set of muscles, failing to encompass the entire spectrum of lower limb motion during the functional task. For instance, 25% of the studies included the adductor magnus muscle, and 2 studies selected only 4 muscles for their synergy analysis. Consequently, the relative contribution of each muscle may differ from studies that considered a more comprehensive array of agonistic and antagonistic muscles, which also limits the overall understanding of muscle interactions during functional task.

5. Conclusion

The identification and analysis of muscle synergies provide insights into the coordination and functional implications of muscle activation patterns during common daily activity. This approach was prioritized in this review to understand age-related changes in neuromuscular control when performing daily living tasks such as walking, sit-to-stand and stair ascent. Our findings suggested that although the number of synergies remains similar between YA and EP, other metrics such as DMC, VAF, and spatial and temporal structures of synergies enable the identification of decline in neuromuscular control in EP.

Authors' contributions

YC developed the search strategy and methodology for this review, which have been validated by a science librarian. **YC** and **SH** screened the search hits for eligibility and rated the quality of the included studies. **CDP** and **YC** extracted and synthesized the relevant data. **CDP** and **YC** wrote the first draft of the manuscript. **YC**, **NT**, **KT** and **FM** performed a major revision of the manuscript. All authors have read and agreed to the published version of the manuscript.

CRediT authorship contribution statement

Cloé Dussault-Picard: Writing – original draft, Formal analysis. **Sara Havashinezhadian:** Data curation, Writing – review & editing. **Nicolas A. Turpin:** Validation, Writing – review & editing. **Florent Moissenet:** Validation, Writing – review & editing. **Katia Turcot:** Validation, Writing – review & editing. **Yosra Cherni:** Conceptualization, Data curation, Formal analysis, Investigation, Methodology, Supervision, Validation, Writing – original draft, Writing – review & editing.

Declaration of competing interest

The authors declare that they have no competing interest.

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