Archives of Physical Medicine and Rehabilitation
journal homepage: www.archives-pmr.org
Archives of Physical Medicine and Rehabilitation 2022;103: 1651−62

REVIEW ARTICLE

Systematic Review of the Importance of Hip Muscle Strength, Activation, and Structure in Balance and Mobility Tasks

Marcel B. Lanza, PhD,[a] Breanna Arbuco, MS,[a] Alice S. Ryan, PhD,[b,c]
Andrea G. Shipper, PhD,[d] Vicki L. Gray, PhD,[a] Odessa Addison, PhD[a,c]

From the [a]Department of Physical Therapy and Rehabilitation Science, University of Maryland School of Medicine, Baltimore, MD; [b]Department of Medicine, Division of Gerontology and Palliative Medicine, University of Maryland School of Medicine, Baltimore, MD; [c]Baltimore Geriatric Research, Education, and Clinical Center, VAHMC, Baltimore, MD; and [d]Health Sciences and Human Services Library, University of Maryland, Baltimore, MD.

Abstract

Objective: The aim of this systematic review was to identify the associations of the hip abductor muscle strength, structure, and neuromuscular activation on balance and mobility in younger, middle-aged, and older adults.

Data Sources: We followed PRISMA guidelines and performed searches in PubMed, Embase, CINAHL, and Physiotherapy Evidence Database.

Study Selection: Study selection included: (1) studies with patients aged 18 years or older and (2) studies that measured hip abduction torque, surface electromyography, and/or muscle structure and compared these measures with balance or mobility outcomes.

Data Extraction: The extracted data included the study population, setting, sample size, sex, and measurement evaluated.

Data Synthesis: The present systematic review is composed of 59 research articles including a total of 2144 young, middle-aged, and older adults (1337 women). We found that hip abductor strength is critical for balance and mobility function, independent of age. Hip abductor neuromuscular activation is also important for balance and mobility, although it may differ across ages depending on the task. Finally, the amount of fat inside the muscle appears to be one of the important factors of muscle structure influencing balance.

Conclusions: In conclusion, a change in all investigated variables (hip abduction torque, neuromuscular activation, and intramuscular fat) appears to have an effect during balance or mobility tasks across age ranges and may elicit better performance. Future studies are necessary to confirm the effect of these variables across age ranges and the effects of interventions.

Archives of Physical Medicine and Rehabilitation 2022;103:1651−62

Falls are a global health concern,[1,2] the incidence of which significantly increases with age.[3,4] Understanding the factors that influence falls is critical for fall prevention. Muscle function (eg, the ability to produce torque) is essential for balance recovery and fall avoidance.[5-7] Hip abductor muscle function contributes to lateral balance control[8,9] and influences balance with aging in tasks such as stepping in multiple directions,[10,11] obstacle walking,[12] and standing balance.[13] Although previous studies have investigated the role of the hip abductor muscles in a variety of balance tasks, the importance of the hip abductor muscles for balance in younger, middle-aged, and older adults and the contribution of muscle function to balance remains ambiguous.

The capacity of the hip abductor muscles to produce torque is important for balance recovery and fall avoidance.[14-17] The amount of hip abduction force generated depends on the ability to recruit and activate the motor units (neuromuscular activation)[18,19] and overall muscle structure (eg, muscle size and fat infiltration).[7,20-22] Given the large number of studies investigating the hip abductor muscles, the variety of methods used to assess muscle torque, neuromuscular activation, and muscle structure, as well as different balance or mobility tests used to assess the risk of falls, these studies may reach varying conclusions. Currently, the influence of the hip abductor torque production, neuromuscular activation and muscle structure on balance or mobility and avoiding falls is inconclusive. Considering the importance of the hip abductor muscles in controlling lateral balance and the lack of a

Disclosures: none.

0003-9993/$36 - see front matter © 2022 by the American Congress of Rehabilitation Medicine.
https://doi.org/10.1016/j.apmr.2021.12.008

broad consensus on their role in mobility and balance, a systematic review will provide researchers and clinicians with critical information for developing training interventions and rehabilitation exercises among adults across the age span.

Therefore, the primary aim of this systematic review was to determine the associations of hip abductor muscle strength with balance and mobility outcomes in young, middle-aged, and older adults. The secondary aim was to determine the associations of hip abductor neuromuscular activation and muscle structure with balance and mobility outcomes in young, middle-aged, and older adults.

Methods

Study selection and inclusion criteria

The present study followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines to conduct a systematic review. A medical librarian (A.G.S.) performed searches in PubMed, Embase (embase.com), CINAHL (EBSCO), and Physiotherapy Evidence Database (pedro.org.au) on November 13, 2019; updated searches were conducted on October 23, 2020. There was no year limit for the search. The first article to fit the search was published in 1990 and the most recent was published in 2020. Search results were required to contain terms from each of 2 categories: (1) hip abductor and (2) balance terms such as mobility, falls, and stability. No search filters or limits were applied. Searches included both keywords and controlled vocabulary and were modified for each database (see detailed search strategy in supplemental appendix S1, available online only at http://www.archives-pmr.org/). The study selection process for the articles can be seen in the PRISMA flow chart (fig 1). The authors also performed a second search before final submission to ensure that studies published during the process of writing the manuscript could also be included.

The following inclusion criteria were used to identify the studies that answer the proposed research question: (1) included patients aged 18 years and older; (2) measured hip abduction torque and related the measure with balance or mobility; (3) recorded surface electromyography (EMG) from the hip abductor muscle (tensor fasciae latae [TFL], gluteus medius [GM]) and associated the EMG measure with a measure of balance or mobility; (4) assessed muscle structure (muscle cross-sectional area, muscle size, intramuscular fat, high density lean tissue) from the hip abductor muscle (TFL or GM) and associated this with balance or mobility; (5) cross-sectional study design; and (6) separated groups of patients into young (18-39y), middle-aged (40-64y), or older adults (≥65y). Studies were excluded if the participants presented with a medical condition that limited performance (eg, pain), neurologic disease (eg, Parkinson disease) that would alter performance or if the measure of torque, EMG, or muscle structure was not associated with at least 1 balance or mobility outcome.

List of abbreviations:

BBS	Berg Balance Scale
BSE	balance self-efficacy
EMG	electromyography
GM	gluteus medius muscle
HDL	high density lean muscle
IMAT:	intramuscular fat
JBI	Joanna Briggs Institute
OLST	one-legged stance test
RFD	rate of force development
RTD	rate of torque development
SEBT	Star Excursion Balance Test
STST	sit-to-stand test
TFL	tensor fascia latae muscle
TUG	timed Up and Go
YBT	Y balance test

Data extraction and risk of bias assessment

Two authors (M.B.L. and B.A.) extracted the following information from the selected studies: year of publication; study authors; study design; analysis method (ie, hazard ratio, risk ratio, or odds ratio); country; participant demographics; number of participants; exclusion and inclusion criteria; and outcomes measures related to muscle strength, muscle function, neuromuscular activation, and balance or mobility. Conflicts between the 2 reviewers were resolved through a third reviewer (V.G. or O.A.).

The risk of bias assessment was completed using the Checklist for Analytical Cross Sectional Studies by the Joanna Briggs Institute (JBI).[23] The independent reviewers (M.B.L. and B.A.) completed the JBI Critical Appraisal Checklist for Analytical Cross Sectional Studies questionnaire (https://reviewersmanual.joannabriggs.org/); discrepancies were resolved by a third reviewer (V.G. or O.A.). The JBI questionnaire has 8 questions that assess the methodological quality of a study and concomitantly examine the extent to which a study has addressed the possibility of bias in its design, conduct, and analysis (https://reviewersmanual.joannabriggs.org/). The results of the risk of bias assessment are found in supplemental appendix S2 (available online only at http://www.archives-pmr.org/).

Data syntheses

The association of hip abductor strength, neuromuscular activation, and muscle structure with balance or mobility was the primary outcome. Therefore, the findings from the selected studies were narratively synthesized to demonstrate the relationship of hip abductor muscle strength, neuromuscular activation, and muscle structure on balance and mobility in young, middle-aged, and older adults.

Results

Initially 2763 studies were identified. After removing duplicates, 1675 remained. After screening 1473 abstracts and titles, full-text screen of 202 texts was conducted. The present systematic review comprises 59 research articles with a total of 2144 patients (1337 women) comprising young, middle-aged, and older adults (see fig 1). The following balance or mobility tests were used across studies: one-legged stance test (OLST), timed Up and Go (TUG), sit-to-stand test (STST), balance self-efficacy (BSE), Berg Balance Scale (BBS), Star Excursion Balance Test (SEBT), Y Balance Test (YBT), platform translation, perturbation induced step and voluntary step test, walking, walking over obstacles, and stair climbing. Hip abduction strength measures included maximal torque (or force) and rate of torque development (RTD) or rate of force development (RFD). Also, studies reporting peak torque (or force) are defined as maximal torque (or force). Maximal torque

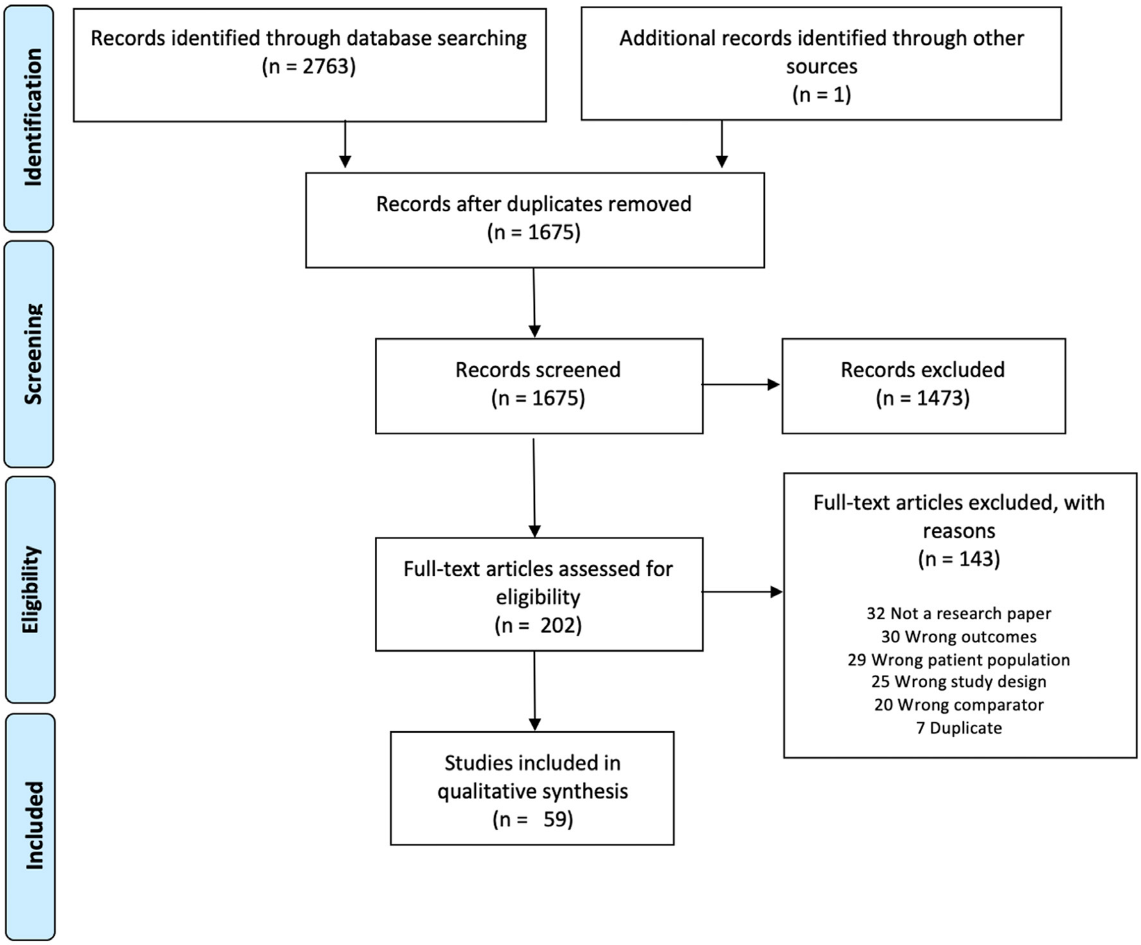

Fig. 1 PRISMA flow chart of the selection process of eligible studies.

(or force) was measured during a maximal task (ie, isokinetic dynamometer) or in-task (ie, stepping task). Measures of neuromuscular activation from GM or TFL included EMG amplitude, frequency, or latency. Finally, measures of muscle structure by computed tomography or magnetic resonance imaging included muscle cross-sectional area, high-density lean tissue (HDL) muscle area, intramuscular fat (IMAT) muscle area, and muscle attenuation. Importantly, many of the studies reported data from other joints or muscles; however, we focused on data relevant to our research question. Moreover considering the vast number of different methodological approaches between studies, we tried to provide as much detail as possible.

Relationship of hip abductor strength and balance and mobility

Young and middle-aged adults

Eight studies were included in this section,[10,11,24-29] with patients presenting with an average age of 25 years among 192 young adults (94 women) and 53 years among 39 middle-aged adults (39 women) (table 1). Among the studies selected in this section, maximal torque (or force) was assessed most often isometrically [10,11,25-27,29] and less frequently by inverse dynamics.[24,28]

Balance perturbations. Two studies examined the effect of disrupting balance with external induced lateral perturbations on hip abductor strength in young adults with contrasting results. The hip abduction torque (measured by inverse dynamics) produced during stepping did not vary based on the stepping strategy (lateral vs crossover step) when lateral waist-pulls perturbed standing balance occurred.[24] In contrast, for the same type of lateral perturbation, Inacio et al found that those with greater hip abductor torque during an isometric contraction had a higher incidence of lateral steps.[27]

Dynamic and static tests. There were mixed results in the relationship between dynamic and static balance tests and hip abductor strength. Two studies demonstrated that young individuals with greater hip abductor torque while performing concentric (30 degrees) or isometric contractions reached greater distances in all directions on the YBT.[10,11] In contrast, 1 study in middle-aged adults found only a relationship in the posteromedial distance of the YBT with hip abductor strength of the reaching leg.[25] Another study found no significant relationship between hip abductor strength of the moving leg and YBT or the BBS in middle-aged adults.[26] In addition, younger adults producing greater torque (measured by inverse dynamics) during walking and directing the leg toward a target with a lateral and crossover step did not reflect greater stability measured by the margin of stability.[28] When assessing standing balance in a variety of situations (rigid vs foam, eyes open vs closed) the inability to produce a steady torque

Table 1 Summary of the studies included in the association of hip abductors strength on balance or mobility for young and middle-aged adults

Study	Women/Men	Patient Group, Age, Mean ± SD (in Years)	Strength Assessment	Balance Assessment	Conclusion
Mille et al[24]	6/3	Young adults, 24±1	Estimated hip torque by inverse dynamics	Lateral Waist pulls	Hip torque capacity did not influence step strategy (loaded vs unloaded step)
Lee et al[25]	19/0	Middle-aged adults, 52±4	Maximal hip abduction strength	YBT	There was a positive relationship between hip abduction strength and posteromedial step distance during the YBT
Hurt and Grabiner[28]	10/9	Young adults, 23±3	Maximal hip abduction moment	Step during walking	The greater maximal moment across different step types did not reflect a larger dynamic stability
Lee et al[26]	20/0	Middle-aged adults, 54±5	Maximal hip abduction strength	YBT, BBS	There was no correlation between hip abduction strength and YBT or BBS
Francis et al[10]	18/27	Young adults, 27±8	Maximal hip abduction torque	YBT	There was a positive relationship between hip abduction torque and all step distances during the YBT
Wilson et al[11]	33/40	Young adults, 25±5	Maximal hip abduction torque	YBT	There was a positive relationship between hip abduction torque and all step distances during the YBT
Inacio et al[27]	8/7	Young adults, 29±1	Maximal hip abduction torque / RTD	Lateral waist pulls	There was a positive relationship between hip abduction torque and RTD and incidence of lateral steps
Davis et al[29]	19/12	Young adults, 25±4	Maximal hip abduction torque	Sway rate during standing balance	Hip abductors strength when supporting a light load explained the variance of sway-area rate in most of the balance conditions

in the hip abductors during an isometric contraction explained part of the variance in sway for most of the testing conditions.[29]

Older adults

Eighteen studies[9,14,17,22,24,27-39] with 967 older adults (667 women) with an average age of 71 years were included (table 2). Among the studies in older adults, maximal torque (or force) was assessed isometrically,[9,26,27,29,31,33-37,39] dynamically (isokinetic dynamometer),[14,17,22,30,38] or during a task by inverse dynamics.[24,28,36]

Balance perturbations. In older adults, hip abduction torque measured during an isokinetic contraction was found to be a predictor of falls in the lateral direction.[17] Another study found that the hip abduction torque (measured by inverse dynamics) could not distinguish individuals who took a lateral step from those who used a crossover step.[24] Similar to young adults, those with a greater hip abductor torque during an isometric contraction had a higher incidence of lateral steps.[27] Furthermore, those who took a crossover step had greater hip abduction torque during an isometric contraction than medial steppers.[22]

Dynamic and static tests. Older individuals who performed better on balance tests (static [ie, OLST, single-leg stance] and dynamic [ie, TUG, platform translation, tandem gait]) also produced greater hip abduction torque,[9,33] torque (measured by inverse dynamics),[36] or force[37] and had a greater RFD.[31] In contrast, others did not find a correlation between the rate of torque development[39] or hip abduction torque during an isometric contraction with static and dynamic balance test (ie, voluntary stepping[39] and YBT[26]) in older adults. During dynamic stability tests (ie, STST, BBS, TUG), studies that separated older adults into groups of fallers and nonfallers found that fallers had a reduced hip abduction force[34] or torque during an isometric contraction[38] and also scored lower on static (OLST)[34] and dynamic balance tests (STST, TUG, BBS).[34,35] In addition, nonfallers showed a more significant hip abductor torque production on the isokinetic dynamometer (60 degrees/s, 0-30-degree range of motion) than fallers.[30] In contrast, 1 study found no differences in isometric hip abduction strength between fallers and nonfallers.[35] In older adults, greater isokinetic hip abduction torque (120 degrees/s) was associated (r=0.49) with better hip stability (measured as walking speed).[14] Moreover, individuals with greater hip abductor moment during a voluntary step (measured in-task by inverse dynamics) had a greater margin of stability regardless of the type of voluntary step

Table 2 Summary of the studies included in the association of hip abductors strength on balance or mobility for older adults

Study	Women/Men	Age, Mean ± SD (in Years)	Strength Assessment	Balance Assessment	Conclusion
Iverson et al[33]	0/54	71±6	Maximal hip abduction torque	Sharpened Romberg test/OLST	Hip abduction torque presented a positive relationship with both balance tests
MacRae et al[34]	65/29	73±1	Maximal hip abduction force	OLST/STST	Greater values in the OLST, STST, and hip abduction force can differentiate fallers and nonfallers
Gunter et al[35]	113/29	79±5	Maximal hip abduction strength	BBS/TUG	Nonfallers presented better TUG and BSE results than fallers, although there was no difference in hip abduction strength
Chang et al[31]	17/16	75±6	Hip abductor RFD	OLST	RFD was positively correlated with OLST and tandem gait variables
Mille et al[24]	10/0	73±6	Estimated hip torque by inverse dynamics	Lateral waist pulls	Hip torque capacity did not influence step strategy (loaded vs unloaded step)
Hilliard et al[17]	38/13	73±6	Maximal hip abduction torque	Lateral waist pulls/ fall incidence	Hip adduction torque was considered a predictor of fall after lateral perturbance
Marques et al[14]	37/0	68±7	Maximal hip abduction torque	BBS	Higher hip abduction torque was suggested to provide more hip stability
Inacio et al[30]	32/26	74±1	Maximal hip abduction torque	Fall incidence	Fallers presented lower hip abduction torque than nonfallers
Morcelli et al[38]	44/0	67±6	Maximal hip abduction torque	Fall incidence/BBS	Fallers presented lower hip abduction torque than nonfallers (12%)
Hurt and Grabiner[28]	9/9	73±5	Maximal hip abduction moment	Step during walking	The higher maximal moment across different step types did not reflect a larger margin of stability at the step types
Lee et al[26]	20/0	77±3	Maximal hip abduction strength	YBT, BBS	There was no correlation between hip abduction strength and YBT or BBS
Arvin et al[36]	12/04	68±5	Maximal hip abduction moment	Platform translation	Higher hip abduction moment was necessary during harder balance tasks, although maximal hip torque capacity was not associated with better performance on the balance tests
Addison et al[22]	15/25	75±2	Maximal hip abduction torque	Lateral waist pulls	Higher hip abduction torque (26%) was found for cross-steppers compared with medial steppers
Sadowska et al[37]	72/41	74±7	Maximal hip abduction force	TUG	Older adults with higher hip abduction force presented better results on TUG
Inacio et al[27]	6/9	71±1	Maximal hip abduction torque/ RTD	Lateral waist pulls	Positive relationship between hip abduction torque and RTD and the incidence of lateral steps
Porto et al[9]	62/19	67±5	Maximal hip abduction torque/ RTD	Tandem gait/single-leg stance	Higher hip abduction torque, and not RTD, was associated with better dynamic and static balance
Davis et al[29]	5/19	71±5	Maximal hip abduction torque	Sway rate during standing balance	Hip abductors strength when supporting a light load explained the variance of sway-area rate in most of the balance conditions
Lanza et al[39]	7/7	71± 4	Maximal hip abduction torque/ RTD	Choice reaction step test	There was no significant correlation between the hip abductor RTD or maximum torque with the weight transfer phase of the stance (or stepping) leg during the choice reaction step test

taken (crossover vs lateral).[28] Nonetheless the inability to produce a steady torque in the hip abductors during an isometric contraction explained the part of the variance of sway-area rate during standing balance.[29]

Relationship of hip abductor neuromuscular activation on balance or mobility

Young and middle-aged adults

This section is composed of 28 studies[12,13,15,27,40-63] with 384 adults (203 women), 369 of whom were young adults (192 women) with an average age of 21 years and 15 of whom were middle-aged adults (11 women) with an average age of 53 years. Eighteen participants were excluded from our demographics, given that 1 study did not separate participants by sex.[40] The studies investigating the relationship of neuromuscular activation of hip abductors on balance in young adults assessed GM or TFL activation across different balance or mobility measures (table 3). The studies measured activation in-task during the balance and mobility task.

Balance perturbations. Six studies used perturbations to standing balance delivered by a mechanical system (pulley, torque at pelvis, or platform translations) to create balance instability that produced postural responses or a protective step. During a lateral pull to the pelvis, the GM[46] was more active (higher amplitude) than during a forward pull. Similarly, TFL showed maximal activation during a lateral translation compared to other directions (eg, forward, backward, diagonal).[47] During unexpected multidirectional platform translations that produced stepping, the TFL of the stance leg was recruited earlier during lateral translations than during forward or posterior translations,[47] whereas the GM of the stance leg was activated earlier in younger adults than in middle-aged or older adults.[41] During lateral waist pull perturbations, increased neuromuscular activation of the TFL and GM was associated with a greater incidence of lateral steps during preloaded conditions of the stepping leg.[27] Furthermore, when only postural adjustments were used (ie, feet in place), the GM EMG amplitude was greater for unpredictable perturbations than for predictable perturbations[58] and for the first trial compared with subsequent trials.[61]

Dynamic and static tests. Two studies that investigated the SEBT reported greater GM activation during forward and lateral reaching compared with posterior reaching.[55] In addition, when the leg was directed medially, there was greater GM activation than other directions.[42] Another study showed that during a voluntary step with an obstacle, GM activation was greater during a lateral step than during a forward step.[49] Five other studies investigated weight-bearing tasks and the relationship of GM activation and showed a higher activation during: (1) static single-limb support than double limb support,[44] (2) single-limb stance with hip abduction and internal rotation of the unloaded leg,[51] (3) larger loads regardless of the surface being stable or unstable,[52] and (4) tandem standing with eyes closed compared with tandem standing with eyes open.[13] However, no differences in GM activation was found when lunges were performed traditionally (ie, legs separately at shoulder distance) or with both legs narrowly aligned (1 leg in front of the other).[55] Nonetheless, during a forward voluntary step, GM neuromuscular activation of the swing leg was greater in young adults but not in middle-aged adults.[43] Additionally, 1 study investigated the relationship of arm movement (cyclic upper limb movements) on postural stabilization while standing and found a decreased GM EMG amplitude during in-phase arm movements than during anti-phase or single arm movements.[62] Lastly, 1 study showed that standing on the platform with vibration required higher GM EMG amplitude but a lower mean frequency than without vibration.[63]

Walking, step ups, or stair climbing. Eleven studies investigated the ability to step and restore balance during walking, step ups, or stair climbing.[12,15,40,46,48,50,53,56,57,59,60] Greater neuromuscular activation was required with a greater height of the step, when an obstacle was present during a step,[50,59] or during stair climbing/incline walking.[46,53,56] In addition, greater neuromuscular activation was seen during obstructed gait[12] than during gait with no obstacles, and walking or stair descent (or step down) in the TFL muscle[46,59] and GM muscles.[12,50,53,56,59] Earlier EMG activity was noted for the GM, during a step up than during a forward step on level ground.[59] Additionally, individuals with greater GM activation during the stance phase of the gait cycle performed better on the BBS.[15]

Walking with perturbation. Four studies investigated the relationship of walking with perturbation (waist pull[48] and platform translation[40,57,60]) on EMG amplitude and latency. A larger mediolateral displacement of the swing leg during perturbed walking balance was associated with greater GM EMG amplitude of the perturbed leg[48,57,60] and unperturbed walking,[57] whereas GM activation from both the swing and stance leg was greater during perturbed than unperturbed walking.[40]

Older adults

This section comprises 9 studies[12,14-16,27,39,41,49,64] with 191 older patients presenting with an average age of 73 years (99 women) (table 4). In this section, only 1 study did not measure neuromuscular activation during the task.[39]

Similar to young and middle-aged adults, the studies investigating the relationship of hip abductor neuromuscular activation on balance or mobility in older adults used various balance or mobility tasks.

Balance perturbations. During unpredictable mediolateral perturbations, GM showed either no difference in EMG latency among sedentary and nonsedentary (engaged in Tai Chi and jogging) older adults,[64] but GM was activated early in young adults compared with middle-aged and older adults.[41] In addition, a greater GM activation was associated with a higher incidence of lateral steps.[27]

Dynamic and static tests. Greater GM activation was found during voluntarily initiated lateral steps compared with forward steps.[16,49] Additionally, the weight transfer toward the stance leg preceding a choice reaction step was primarily explained by the earlier activation of the TFL, not the GM[39] measured during a maximal isometric hip abduction.

Walking, step ups, or stair climbing. GM activation was greater in older adults than in young adults during the stance phase of steady walking.[15] Similarly, older adults classified as fallers generated greater GM neuromuscular activation during walking compared with nonfallers.[14]

Table 3 Summary of the studies included in the association of hip abductors EMG amplitude on balance or mobility for young and middle-aged adults

Study	Women/Men	Patient Group, Age, Mean ± SD or Range (in Years)	EMG Measurement/ Muscle(s)	Balance Assessment	Conclusion
Henry et al[47]	4/3	Young adults, 21-41	EMG amplitude and latency/TFL	Multidirectional displacement	TFL presented maximal activation and was recruited early when the platform translates to the lateral
Gilles et al[45]	2/3	Young and middle-aged adults, 29-48	EMG amplitude and latency/TFL	Forward and lateral displacement	Lateral push increased ipsilateral GM activity compared with forward push, whereas EMG latency was not different
Sims et al[59]	5/4	Young adults, 28±6	EMG amplitude and latency/TFL and GM	Forward step and step up	GM and TFL of the stance limb presented larger EMG amplitude, and early EMG activity for GM, during step up than in the step forward task
Allum et al[41]	6/6	Young adults, 20-34	EMG amplitude/GM	Forward displacement	GM was activated earlier in young adults than middle-aged adults
Torvinen et al[63]	8/8	Young adults, 18-35	EMG amplitude and frequency/GM	Postural sway with vibration	Exercise with vibration required an increase of GM activation, although lower GM mean frequency was detected
Earl et al[44]	10/10	Young adults, 23±5	EMG amplitude/GM	Single leg stance	GM presented higher activation during single stance when hip abduction with internal rotation was performed
Hahn et al[12]	7/8	Young adults, 24±4	EMG amplitude/GM	Walking over an obstacle	Higher obstacles led to increased GM EMG amplitude
Chu et al[43]	12/6	Young adults, 22±3 Middle-aged adults, 52±8	EMG latency/GM	Forward step reaction test	GM neuromuscular activation of the swing leg during a forward step was found to be essential in younger adults
Kim and Brunt[50]	6/3	Young adults, 30±5	EMG amplitude and latency/GM	Step with obstacle	GM activation from swing and stance leg were primarily activated for a diagonal or a long step, compared with a normal step
Krause et al[51]	14/6	Young adults, 25±2	EMG amplitude/GM	Weight-bearing exercises	Single-limb stance exercises require more activation from GM than double stance exercises
Santos et al[58]	4/4	Young adults, 25±2	EMG amplitude and latency/GM	Balance perturbation at shoulder level	GM was more active when compensatory postural adjustments were performed during unpredictable perturbations than predictable
Norris et al[55]	11/11	Young adults, 22-38	EMG amplitude/GM	SEBT	GM presented higher activation during anterior and medial stepping than posterior
Gottschall et al[46]	10/10	Young adults, 22±2	EMG amplitude/TFL	Walking with obstacle	TFL muscle activity was higher during both up-ramp walking or up-stairs walking than level walking
Tang et al[61]	35/35	Young adults, 18-30	EMG amplitude/GM	Involuntary multidirectional displacement	Higher GM activation during first trial than subsequent trials
Hof et al[48]	6/3	Young adults, 19-23	EMG amplitude and latency/GM	Walking with perturbation	GM voluntary activation is important for the swing leg to perform the step after the perturbation during the walking
Kim et al[49]	5/4	Young adults, 27±4	EMG amplitude/GM	Forward and diagonal voluntary stepping	Lateral steps required higher GM activation using stepping and stance leg
Li et al[52]	0/13	Young adults, 19±1	EMG amplitude/GM	Reebok core board	GM muscle activity increased with load, although there was no

(*continued on next page*)

Table 3 (*Continued*)

Study	Women/Men	Patient Group, Age, Mean ± SD or Range (in Years)	EMG Measurement/ Muscle(s)	Balance Assessment	Conclusion
					difference between induced vs unstable surface
Tettamanti et al[62]	7/8	Young adults, 22±2	EMG amplitude/GM	Upper limbs movements	Lower GM activity was presented during in-phase movements than anti-phase or single arm movements
Tse et al[13]	8/9	Young adults, 27±3	EMG amplitude/GM	Standing balance task	Muscle activity of GM was higher during tandem standing tasks and with eyes closed
Rankin et al[57]	8/2	Young adults, 23±1	EMG amplitude/GM	Walking with perturbation	Larger mediolateral displacement was associated with higher GM activity during perturbed and unperturbed conditions
Lin et al[53]	11/4	Middle-aged adults, 54±8	EMG amplitude/GM	Stair ambulation	GM activation appears to be larger during stair ascent than level walking and stair descent.
Lee et al[15]	15/16	Young adults, 24±2/ middle-aged adults, 54±2	EMG amplitude/GM	BBS	GM activation was higher during the stance phase of the gait cycle and was associated with better performance on the BBS
Stokes et al[60]	7/5	Young adults, 25±5	EMG amplitude/GM	Walking with perturbation	Mediolateral displacement with larger steps were follow by higher GM activity in the swing leg during perturbed conditions
Afschrift et al[40]	18	Young adults, 21±2	EMG amplitude/GM	Walking with perturbation	GM of stance and swing leg is more active after mediolateral translation during perturbed walking than normal walking
Marchetti et al[54]	0/15	Young adults, 25±5	EMG amplitude/GM	Lunge exercises	There was no difference in GM activation between traditional and inline lunge exercises
Bhanot et al[42]	11/11	Young adults, 23±4	EMG amplitude/GM	SEBT	GM of the stance leg was more active during the medial direction of the SEBT
Inacio et al[27]	8/7	Young adults, 29±1	EMG amplitude/GM	Lateral Waist Pulls	GM activation presented moderate correlation with the incidence of lateral steps
Park et al[56]	19/0	Young adults, 21±1	EMG amplitude/GM	Step-up and step-down	GM presented higher activation during step-up than step-down task

Relationship of hip abductor muscle structure on balance and mobility

This section was limited to 5 studies,[22,30,39,65,66] with 356 older adults presenting with an average age of 75 years (235 women); hence, this section focuses only on older adults. Among the selected studies, we are report muscle structure of the GM[22,30,39,65,66] and TFL[39,65] assessed by magnetic resonance imaging or computed tomography. It is important to note that 3 studies reported GM combined with gluteus minimus (Table 5).[22,30,39]

Older adults

Three studies compared GM muscle structure by assessing IMAT between fallers and nonfallers and found that fallers had greater IMAT than nonfallers,[30,65,66] which was not observed for TFL IMAT.[65] It is important to highlight that 2 studies measured IMAT qualitatively by Goutalier's stage (Chi et al,[65] Kiyoshige and Watanabe[66]), whereas 1 study measured quantitatively (Inacio et al[30]). One study found no difference in muscle attenuation in fallers compared with nonfallers.[30] A second study assessed muscle structure by measuring IMAT and HDL[22] and found that medial steppers had greater gluteal muscle (GM + gluteus minimus) IMAT than crossover-steppers, but no difference was found in HDL between fallers and no-fallers.[30] Finally, neither the GM or TFL muscle structure (cross-sectional area, IMAT, or HDL) correlated with the duration of the weight transfer that preceded the choice reaction step.[39]

Discussion

This systematic review investigated and synthesized the association of the hip abductor strength, neuromuscular activation, and structure on balance or mobility in young, middle-aged, and older

Table 4 Summary of the studies included in the association of hip abductors EMG amplitude on balance or mobility for older adults

Study	Women/Men	Age, Mean ± SD or Range (in Years)	EMG Measurement/ Muscle(s)	Balance Assessment	Conclusion
Allum et al[41]	6/6	60-75	EMG amplitude/GM	Anteroposterior displacement	GM was activated earlier in young than older adults
Hahn et al[12]	7/8	73±5	EMG amplitude/GM	Walking over an obstacle	Higher obstacles led to increased GM EMG amplitudes
Mercer et al[16]	20/7	79±8	EMG amplitude/GM	Forward and lateral step-up exercises	Higher GM EMG amplitude is required for lateral than forward step-up exercises
Kim et al[49]	5/4	75±7	EMG amplitude/GM	Forward and diagonal voluntary stepping	Lateral steps required higher GM activation from stepping and stance leg
Marques et al[14]	37/0	68±7	EMG amplitude/GM	Fall incidence/BBS	GM activation was higher the final moments of the stance
Lee et al[15]	11/9	76±4	EMG amplitude/GM	BBS	Higher GM activation at the stance phase of the gait cycle resulted in higher BBS
Wang et al[64]	0/42	71±4	EMG latency	Lateral displacement	No difference in GM EMG latency between groups during task
Inacio et al[27]	6/9	71±1	EMG amplitude/GM	Lateral waist pulls	GM activation presented moderate correlation with the incidence of lateral steps
Lanza et al[68]	7/7	71± 4	EMG amplitude/GM and TFL	Choice reaction step test	The weight transfer phase of the stance leg during the choice reaction step test was largely explained by the earlier activation of the TFL during a maximal hip abduction task

adults. We identified 59 articles that met the inclusion criteria of our systematic review consisting of cross-sectional studies involving a wide range of study methodologies; sample sizes; balance or mobility tests; and muscle strength, neuromuscular activation, and muscle structure measures. Thus, with these variables in mind, we provide preliminary conclusions on the associations of the hip abductor strength, neuromuscular activation, and structure on balance or mobility.

Relationship of hip abductor strength on balance and mobility

Although well documented, the ability to produce torque is important for physical function (higher torque indicates higher function during activities of daily living). More importantly, hip abductors are essential for avoiding a fall.[10,11] The effect of the hip abductor torque capacity on the ability to recover balance across the age spectrum in adults is still relatively unknown. The present systematic review demonstrated that, overall, young and older adults with higher hip abduction torque perform better during balance (eg, YBT, BBS, TUG) and mobility tasks (eg, walking and stair climbing), whereas hip abduction torque appears to play less of a role on balance and mobility in middle-aged adults. It is important to note that, overall, the low number of studies conducted in middle-aged adults compared with older and younger adults makes it difficult to make conclusions about the results in middle-aged adults. Even the sample sizes of the studies with young and middle-aged adults are relatively small, with only 1 study including more than 50 participants. Furthermore, most studies were conducted in older adults, suggesting that more studies are needed in young and middle-aged adults to make strong conclusions. These results suggest that, independent of age, greater hip abduction torque results in better performance during balance or mobility tasks. Although this systematic review did not present the effects of any types of training interventions on hip abductor torque, considering the importance of balance recovery to avoiding a fall,[14-16] exercises targeting increases in hip abductor torque may be considered as part of clinical practice and training intervention across all ages.

Relationship of hip abductor neuromuscular activation on balance and mobility

To avoid a fall, it is necessary to react as fast as possible to produce enough force to recover balance.[27,39] Neuromuscular activation is a determinant of muscle strength during explosive conditions.[67,68] In the present systematic review, we identified that, overall, during predictable or unpredictable induced balance perturbations, a lateral step requires greater hip abductor neuromuscular activation compared with other step types across the age groups. However, middle-aged and older adults activate the hip abductors later than young adults. During voluntary tasks, whereas younger adults had greater hip abductors neuromuscular activation during the forward and medial reaching task, for older adults, the lateral step resulted in greater activation of the hip abductor muscle than forward steps. Nevertheless, during a forward voluntary step, the activation of the hip abductors of the swing leg was increased for young adults but not in middle-aged adults. Thus, neuromuscular activation depends on the task (voluntary vs induced) and step type to differentiate across different age groups.

Other static balance tasks (ie, single- and double-limb stance with higher loads and tasks with eyes closed) that challenge balance stability resulted in increased neuromuscular activation in young adults. Given that we did not find similar studies in middle-aged or older adults with similar types of balance tasks and neuromuscular activation, further studies are needed in these populations to gain insight. Mobility tasks (eg, walking and stair climbing) that require avoiding obstacles have greater hip abductor neuromuscular activation compared with overground walking or stair descent in young and middle-aged adults. Whereas older

Table 5 Summary of the studies included in the association of hip abductors muscle structure on balance or mobility for older adults

Study	Women/Men	Age, Mean ± SD (in Years)	Groups	Muscle(s) of Interest	Muscle Assessment	Variables	Conclusion
Inacio et al[30]	33/26	73±1	Fallers vs nonfallers	Sum of GM + gluteus minimus	CT scans	IMAT and muscle attenuation	Gluteus muscles IMAT was greater and muscle attenuation was lower in fallers than in nonfallers
Kiyoshige et al[66]	64/19	79±2	Fallers vs nonfallers	GM	MRI	IMAT	GM IMAT was greater in fallers than in nonfallers
Chi et al[65]	116/44	79±31	Fallers vs nonfallers	GM, TFL	CT scans	IMAT	GM IMAT was greater in fallers than in nonfallers
Addison et al[22]	15/25	75±2	Medial steppers vs cross-steppers	Sum of GM + gluteus minimus	CT scans	IMAT, HDL	Gluteus muscles IMAT was greater in medial steppers than cross-steppers
Lanza et al[68]	7/7	71±4	No groups	Sum of GM + gluteus minimus	CT scans	IMAT, HDL, CSA	Gluteus muscles showed no correlation with the weight transfer phase of the choice reaction step test

Abbreviations: CSA, cross-sectional area; CT, computed tomography; MRI, magnetic resonance imaging.

adults had an overall higher neuromuscular activation during the stance phase of walking. Finally, the ability to activate the muscles earlier was associated with a better performance during a voluntary step in older adults. However, no studies have been published comparing young and middle-aged adults. Therefore, the ability to activate the hip abductor muscles (GM and TFL) is important to balance or mobility tasks and probably should be taken into consideration when preparing interventions aiming to improve balance or mobility.

Relationship of hip abductor muscle structure on balance and mobility

Muscle structure (eg, cross-sectional area, IMAT) is known to be one of the determinants of muscle function[21,22,69,70]; hence, it may directly affect an individual's ability to recover balance and ultimately avoid a fall. Older fallers have higher intramuscular fat in the GM than nonfallers, whereas TFL fat content appears not to differ between age groups. Older adults who perform medial steps to recover balance presented with greater IMAT, but similar HDL, in the GM than cross-steppers, which may be a factor that influences falls. Thus, these results reinforce that the amount of fat inside the GM might be an important factor related to balance recovery. However, GM and TFL muscle structure (total cross-sectional area, IMAT, or HDL) may not influence the ability to transfer weight from one leg to the other (quick task performed before a protective step occurs) during a step choice reaction step.[39] Therefore, although IMAT was found to be related to balance recovery after a perturbation, it may not be critical for short-time tasks (>200ms). This is an important finding, as it is reported that reacting as fast as possible to recover balance might be important to avoid falls[27,39] and thus other factors such as neuromuscular activation maybe more important during the first moments of the task (≈200ms).[39] Considering that only 5 studies were found in the literature that examined the hip abductors muscle structure and balance or mobility and all were in older adults, these conclusions should be considered with caution. Therefore, more research is needed to understand the effect of muscle structure of the hip abductors muscles on balance or mobility.

Study limitations

It is important to highlight the limitations and strengths of this systematic review. Among all the selected studies, the balance or mobility tests largely varied between studies (static, dynamic, or induced). The current literature does not provide a consistent assessment of balance or mobility tests across studies when evaluating the hip abductor muscles (strength, neuromuscular activation, and muscle structure). This is the first systematic review to combine the studies to produce a summary of their findings. Synthesizing the findings from a large variety of studies with variable methodology is challenging and has limitations in attempting to draw conclusions. GM neuromuscular activation was assessed in almost all the selected studies, whereas TFL was evaluated in only 1 study. Similarly, strength assessments differ between studies with a variety of methodologies (isometric vs dynamic) used. The methods used to assess and analyze muscle strength and EMG signals differed among studies, which limits the comparisons and conclusions that can be drawn.[71] Additionally, there were limited studies examining muscle structure. Only 5 studies in older adults examined muscle structure, which suggests that further investigations are required to provide a more robust understanding of the role of hip abductor muscle structure for balance or mobility. Additionally, it is important to mention that investigating the relationships between measures of muscle strength, neuromuscular activation, and muscle structure and balance and mobility outcomes do not suggest causation. Among the selected studies, the most measured neuromuscular activation in a task (balance or mobility task) except one.[39] In contrast, only a few studies [24,28,36] have assessed hip abductor strength during balance or mobility tasks. Therefore, our conclusions should be interpreted with caution. This review also highlights the importance of consistency in the type of assessment among studies and a need for future studies to provide a better understanding of the relationship between these variables. Further studies are needed with the eventual goal of providing advice and stimulating new treatment interventions for clinicians and trainers.

Conclusions

In conclusion, greater hip abduction torque capacity appears to be critical during balance or mobility tasks across age groups and may elicit better functional performance. Although hip abductor neuromuscular activation was also important, its significance may differ across age ranges depending on the task. There is evidence, although limited, that the amount of fat inside the muscle appears to be one of the main factors of muscle structure influencing balance across age ranges. Finally, considering the limitations of the present study, the effect of torque production, neuromuscular activation, and muscle structure on balance and mobility is still uncertain, and more research is required to elucidate their relationship.

Keywords

Aging; Hip; Muscle strength; Postural balance; Rehabilitation

Corresponding author

Marcel B. Lanza, PhD, Department of Physical Therapy and Rehabilitation, University of Maryland, 100 Penn Street, Baltimore, MD, 20201. *E-mail address:* mlanza@som.umaryland.edu.

References

1. Hausdorff JM, Rios DA, Edelberg HK. Gait variability and fall risk in community-living older adults: a 1-year prospective study. Arch Phys Med Rehabil 2001;82:1050–6.
2. Phelan EA, Mahoney JE, Voit JC, Stevens JA. Assessment and management of fall risk in primary care settings. Med Clin North Am 2015;99:281–93.
3. Kannus P, Parkkari J, Niemi S, Sievänen H. Continuously declining incidence of fall injuries in older adults: nationwide statistics from Finland between 1970 and 2016. Eur Geriatr Med 2018;9:371–5.
4. Lord SR, Ward JA, Williams P, Anstey KJ. An epidemiological study of falls in older community-dwelling women: the Randwick falls and fractures study. Aust J Public Health 1993;17:240–5.
5. Janssen I, Heymsfield SB, Ross R. Low relative skeletal muscle mass (sarcopenia) in older persons is associated with functional impairment and physical disability. J Am Geriatr Soc 2002;50:889–96.
6. Tieland M, Trouwborst I, Clark BC. Skeletal muscle performance and ageing. J Cachexia Sarcopenia Muscle 2018;9:3–19.
7. Minetti AE. On the mechanical power of joint extensions as affected by the change in muscle force (or cross-sectional area), ceteris paribus. Eur J Appl Physiol 2002;86:363–9.
8. Hwang W, Jang JH, Huh M, et al. The effect of hip abductor fatigue on static balance and gait parameters. Phys Ther Rehabil Sci 2016;5:34–9.
9. Porto JM, Freire Júnior RC, Bocarde L, et al. Contribution of hip abductor−adductor muscles on static and dynamic balance of community-dwelling older adults. Aging Clin Exp Res 2019;31:621–7.
10. Francis P, Gray K, Perrem N. The relationship between concentric hip abductor strength and performance of the Y-balance test (YBT). International Journal of Athletic Therapy and Training 2018;23:42–7.
11. Wilson BR, Robertson KE, Burnham JM, Yonz MC, Ireland ML, Noehren B. The Relationship Between Hip Strength and the Y Balance Test. J Sport Rehabil 2018;27:445–50.
12. Hahn ME, Lee HJ, Chou LS. Increased muscular challenge in older adults during obstructed gait. Gait Posture 2005;22:356–61.
13. Tse YYF, Petrofsky J, Berk L, et al. Postural sway and EMG analysis of hip and ankle muscles during balance tasks. Int J Ther Rehabil 2013;20:280–8.
14. Marques NR, Hallal CZ, Crozara LF, et al. Lower limb strength is associated with gait biomechanical abnormalities in older female fallers and non-fallers. Isokinet Exerc Sci 2013;21:151–9.
15. Lee HJ, Chang WH, Hwang SH, Choi BO, Ryu GH, Kim YH. Age-related locomotion characteristics in association with balance function in young, middle-aged, and older adults. J Aging Phys Act 2017;25:247–53.
16. Mercer VS, Gross MT, Sharma S, Weeks E. Comparison of gluteus medius muscle electromyographic activity during forward and lateral step-up exercises in older adults. Phys Ther 2009;89:1205–14.
17. Hilliard MJ, Martinez KM, Janssen I, et al. Lateral balance factors predict future falls in community-living older adults. Arch Phys Med Rehabil 2008;89:1708–13.
18. Farina D, Holobar A, Merletti R, Enoka RM. Decoding the neural drive to muscles from the surface electromyogram. Clin Neurophysiol 2010;121:1616–23.
19. Semmler JG. Motor unit synchronization and neuromuscular performance. Exerc Sport Sci Rev 2002;30:8–14.
20. Suchomel TJ, Stone M. The relationships between hip and knee extensor cross-sectional area, strength, power, and potentiation characteristics. Sports 2017;5:66.
21. Visser M, Goodpaster BH, Kritchevsky SB, et al. Muscle mass, muscle strength, and muscle fat infiltration as predictors of incident mobility limitations in well-functioning older persons. J Gerontol A Biol Sci Med Sci 2005;60:324–33.
22. Addison O, Inacio M, Bair W-N, Beamer BA, Ryan AS, Rogers MW. Role of hip abductor muscle composition and torque in protective stepping for lateral balance recovery in older adults. Arch Phys Med Rehabil 2017;98:1223–8.
23. Vardell E, Malloy M. Joanna Briggs Institute: an evidence-based practice database. Med Ref Serv Q 2013;32:434–42.
24. Mille M-L, Johnson ME, Martinez KM, Rogers MW. Age-dependent differences in lateral balance recovery through protective stepping. Clin Biomech 2005;20:607–16.
25. Lee DK, Kim GM, Ha SM, Oh JS. Correlation of the Y-balance test with lower-limb strength of adult women. J Phys Ther Sci 2014;26:641–3.
26. Lee DK, Kang MH, Lee TS, Oh JS. Relationships among the Y balance test, Berg Balance Scale, and lower limb strength in middle-aged and older females. Braz J Phys Ther 2015;19:227–34.
27. Inacio M, Creath R, Rogers MW. Effects of aging on hip abductor-adductor neuromuscular and mechanical performance during the weight transfer phase of lateral protective stepping. J Biomech 2019;82:244–50.
28. Hurt CP, Grabiner MD. Age-related differences in the maintenance of frontal plane dynamic stability while stepping to targets. J Biomech 2015;48:592–7.
29. Davis LA, Allen SP, Hamilton LD, Grabowski AM, Enoka RM. Differences in postural sway among healthy adults are associated with the ability to perform steady contractions with leg muscles. Exp Brain Res 2020;238:487–97.

30. Inacio M, Ryan AS, Bair W-N, Prettyman M, Beamer BA, Rogers MW. Gluteal muscle composition differentiates fallers from non-fallers in community dwelling older adults. BMC Geriatr 2014;14:37.
31. Chang SHJ, Mercer VS, Giuliani CA, Sloane PD. Relationship between hip abductor rate of force development and mediolateral stability in older adults. Arch Phys Med Rehabil 2005;86:1843–50.
32. Lee D, Li Z, Sohail QZ, Jackson K, Fiume E, Agur A. A three-dimensional approach to pennation angle estimation for human skeletal muscle. Comput Methods Biomech Biomed Engin 2015;18:1474–84.
33. Iverson BD, Gossman MR, Shaddeau SA, Turner ME. Balance performance, force production, and activity levels in noninstitutionalized men 60 to 90 years of age. Phys Ther 1990;70:348–55.
34. MacRae PG, Lacourse M, Moldavon R. Physical performance measures that predict faller status in community-dwelling older adults. J Orthop Sports Phys Ther 1992;16:123–8.
35. Gunter KB, De Costa J, White KN, Hooker K, Hayes WC, Snow CM. Balance self-efficacy predicts risk factors for side falls and frequent falls in community-dwelling elderly. J Aging Phys Act 2003;11:28–39.
36. Arvin M, van Dieën JH, Faber GS, Pijnappels M, Hoozemans MJM, Verschueren SMP. Hip abductor neuromuscular capacity: a limiting factor in mediolateral balance control in older adults? Clin Biomech 2016;37:27–33.
37. Sadowska D, Osiński W, Gumny M. Muscle strength of lower limbs as a predictor of postural stability and fear of falling in physically active and inactive older men and women. Top Geriatr Rehabil 2018;34:124–30.
38. Morcelli MH, Crozara LF, Rossi DM, et al. Hip muscles strength and activation in older fallers and non-fallers. Isokinet Exerc Sci 2014;22:191–6.
39. Lanza MB, Addison O, Ryan AS, Perez WJ, Gray V. Kinetic, muscle structure, and neuromuscular determinants of weight transfer phase prior to a lateral choice reaction step in older adults. J Electromyogr Kinesiol 2020;55:102484.
40. Afschrift M, Pitto L, Aerts W, van Deursen R, Jonkers I, De Groote F. Modulation of gluteus medius activity reflects the potential of the muscle to meet the mechanical demands during perturbed walking. Sci Rep 2018;8:11675.
41. Allum JHJ, Carpenter MG, Honegger F, Adkin AL, Bloem BR. Age-dependent variations in the directional sensitivity of balance corrections and compensatory arm movements in man. J Physiol 2002;542:643–63.
42. Bhanot K, Kaur N, Brody LT, Bridges J, Berry DC, Ode JJ. Hip and trunk muscle activity during the star excursion balance test in healthy adults. J Sport Rehabil 2019;28:682–91.
43. Chu YH, Tang PF, Chen HY, Cheng CH. Altered muscle activation characteristics associated with single volitional forward stepping in middle-aged adults. Clin Biomech 2009;24:735–43.
44. Earl JE. Gluteus medius activity during 3 variations of isometric single-leg stance. J Sport Rehabil 2005;14:1–11.
45. Gilles M, Wing AM, Kirker SGB. Lateral balance organisation in human stance in response to a random or predictable perturbation. Exp Brain Res 1999;124:137–44.
46. Gottschall JS, Okita N, Sheehan RC. Muscle activity patterns of the tensor fascia latae and adductor longus for ramp and stair walking. J Electromyogr Kinesiol 2012;22:67–73.
47. Henry SM, Fung J, Horak FB. Control of stance during lateral and anterior/posterior surface translations. IEEE Trans Rehabil Eng 1998;6:32–42.
48. Hof AL, Duysens J. Responses of human hip abductor muscles to lateral balance perturbations during walking. Exp Brain Res 2013;230:301–10.
49. Kim H-D, Brunt D. Effect of a change in step direction from a forward to a lateral target in response to a sensory perturbation. J Electromyogr Kinesiol 2013;23:851–7.
50. Kim HD, Brunt D. The effect of a sensory perturbation on step direction or length while crossing an obstacle from quiet stance. Gait Posture 2009;30:1–4.
51. Krause DA, Jacobs RS, Pilger KE, Sather BR, Sibunka SP, Hollman JH. Electromyographic analysis of the gluteus medius in five weight-bearing exercises. J Strength Cond Res 2009;23:2689–94.
52. Li Y, Cao C, Chen X. Similar electromyographic activities of lower limbs between squatting on a Reebok core board and ground. J Strength Cond Res 2013;27:1349–53.
53. Lin YC, Fok LA, Schache AG, Pandy MG. Muscle coordination of support, progression and balance during stair ambulation. J Biomech 2015;48:340–7.
54. Marchetti PH, Guiselini MA, da Silva JJ, Tucker R, Behm DG, Brown LE. Balance and lower limb muscle activation between in-line and traditional lunge exercises. J Hum Kinet 2018;62:15–22.
55. Norris B, Trudelle-Jackson E. Hip- and thigh-muscle activation during the star excursion balance test. J Sport Rehabil 2011;20:428–41.
56. Park SH, Lee YS, Cheon SH, Yong MS, Lee D, Lee EJ. Analysis of the ratios of medial-lateral and proximal-distal muscle activities surrounding the hip joint in the step-up and step-down positions. J Back Musculoskelet Rehabil 2019;32:299–303.
57. Rankin BL, Buffo SK, Dean JC. A neuromechanical strategy for mediolateral foot placement in walking humans. J Neurophysiol 2014;112:374–83.
58. Santos MJ, Kanekar N, Aruin AS. The role of anticipatory postural adjustments in compensatory control of posture: 1. Electromyographic analysis. J Electromyogr Kinesiol 2010;20:388–97.
59. Sims KJ, Brauer SG. A rapid upward step challenges medio-lateral postural stability. Gait Posture 2000;12:217–24.
60. Stokes HE, Thompson JD, Franz JR. The neuromuscular origins of kinematic variability during perturbed walking. Sci Rep 2017;7:808.
61. Tang K-S, Honegger F, Allum JHJ. Movement patterns underlying first trial responses in human balance corrections. Neuroscience 2012;225:140–51.
62. Tettamanti A, Giordano M, Gatti R. Effects of coupled upper limbs movements on postural stabilisation. J Electromyogr Kinesiol 2013;23:1222–8.
63. Torvinen S, Sievänen H, Järvinen TA, Pasanen M, Kontulainen S, Kannus P. Effect of 4-min vertical whole body vibration on muscle performance and body balance: a randomized cross-over study. Int J Sports Med 2002;23:374–9.
64. Wang SJ, Xu DQ, Li JX. Effects of regular Tai Chi practice and jogging on neuromuscular reaction during lateral postural control in older people. Res Sports Med 2017;25:111–7.
65. Chi AS, Long SS, Zoga AC, Parker L, Morrison WB. Association of gluteus medius and minimus muscle atrophy and fall-related hip fracture in older individuals using computed tomography. J Comput Assist Tomogr 2016;40:238–42.
66. Kiyoshige Y, Watanabe E. Fatty degeneration of gluteus minimus muscle as a predictor of falls. Arch Gerontol Geriatr 2015;60:59–61.
67. Folland JP, Buckthorpe MW, Hannah R. Human capacity for explosive force production: neural and contractile determinants. Scand J Med Sci Sports 2014;24:894–906.
68. Lanza MB, Balshaw TG, Folland JP. Explosive strength: effect of knee-joint angle on functional, neural, and intrinsic contractile properties. Eur J Appl Physiol 2019;119:1735–46.
69. McGregor RA, Cameron-Smith D, Poppitt SD. It is not just muscle mass: a review of muscle quality, composition and metabolism during ageing as determinants of muscle function and mobility in later life. Longev Healthspan 2014;3:9.
70. Maden-Wilkinson TM, McPhee JS, Jones DA, Degens H. Age-related loss of muscle mass, strength, and power and their association with mobility in recreationally-active older adults in the United Kingdom. J Aging Phys Act 2015;23:352–60.
71. Besomi M, Hodges PW, Clancy EA, et al. Consensus for experimental design in electromyography (CEDE) project: amplitude normalization matrix. J Electromyogr Kinesiol 2020;53:102438.