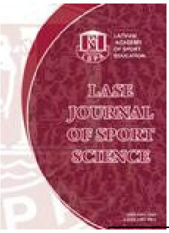

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REVIEW PAPER

A SYSTEMATIC REVIEW: A COMPARISON OF TRADITIONAL WITH MOTOR LEARNING CORE STABILITY TRAINING APPROACHES REGARDING THE EFFECT ON LOWER AND UPPER EXTREMITIES USE, BALANCE AND FUNCTIONAL PERFORMANCE IN OLDER ADULTS

A comparison of traditional with motor learning core stability training approaches in seniors: A Systematic Review

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Abstract

Key points. *Exercise-based core stability training interventions demonstrate considerable emphasis on traditional types of strength training components and only few exercise programs consider motor learning components to enhance function in older adults. It remains unclear whether additional motor learning components are more beneficial for effecting core stability training related outcomes in comparison to traditional exercise programming. Exercise practitioners and therapists should be aware that structured exercise programs for core stability training can be flexible in design, however, come with the probability of impacting differently on core* *stability training related outcomes in older adults.* ***Background.*** *To influence core stability related functioning in elderly, several types of resistance training interventions may be performed. Different types of core stability training will differently effect on training related outcomes. The objective of this systematic review is to investigate the effect of motor learning training strategies in comparison to traditional strength training for core stability.* ***Methods.*** *Selected articles were identified from MEDLINE, EMBASE, CINAHL, PsycINFO and Cochrane. Studies were included if published in English and aimed to train core stability. The studies should target subjects aged 60 years and older.* ***Results.*** *The search strategy yielded 13 studies that met the inclusion criteria; 11 describing traditional trunk strength exercising programmes and 2 using motor learning training strategies. The results do not allow favoring one training approach against the other due to insufficient studies comparing the two training approaches.* ***Conclusion.*** *Currently available literature does not present a wealth of information about the best strategy for core stability training in seniors. The limited availability of high-quality prospective studies that used a comparison between traditional and training approaches that use elements of motor learning warrants targeted future research investigating and comparing the effects of these approaches.*

Keywords: *Motor control exercise, core training, cognitive-trunk training, trunk control, resistance training, balance, videogames, exergames*

Introduction

About a third of community-dwelling people over 65 years of age fall each year (1, 2) and the rate of fall-related injuries increases with age (3). The aging process results in a number of functional changes that contribute to the increased fall incidence (4). Falling is a common geriatric syndrome affecting the general elderly population, but also older populations with cognitive impairment (5). Sarcopenia, or reduced muscle mass and function, is believed to be the first symptom of the cycle towards frailty (6) that may consequentially lead to impairments in ambulation; e.g. slowing of gait (7) and increased gait variability (8).

Gait has long been perceived primarily an automated process (9), and until recently gait related falls were mainly viewed as a failure of these motor mechanisms. Recent research based on dual-task paradigms converge on the notion that cognition, gait and the potential for falls are linked with each other in old age (10, 11). Training interventions aimed at improving gait show different effects on gait related outcomes based on the training type. Recent evidence supports the notion that timing and coordination deficits related to mobility difficulties in older adults rather improve through task-oriented motor learning exercises, whereas standard exercise programs have no such effect (12). This might also explain some of the seemingly contradictory guidelines when it comes to improve gait and prevent falls in elderly. Where it seems important to include progressive resistance training when the training goal is to improve gait speed (13) the inclusion of this training component is deemed less crucial when the aim is to prevent falls (14).

A multi-component exercise intervention aiming to improve fall rates and gait ability in physically frail older adults should contain elements of both strength, endurance and balance exercise (15). While addressing muscle strength properties and training postural control are important components of training programs, there may be more potential to improve function of gait in older adults by targeting neurologic factors and integrating neuro-cognition in training programs (16, 17). Although evidence supports neuromuscular training for effective gait enhancement and fall prevention, many approaches primarily target biomechanical factors and do not explicitly consider cognitive or neurological components (18).

Core stability exercises are considered key components of training programs (19).Core stability is based on three subsystems: the passive spinal column, active spinal muscles and a neural control unit. Core stability is related to the body's ability to control the trunk in response to internal and external disturbances (20). There is evidence of a clear relationship between trunk muscle activity and lower extremity movement (21). Association between trunk muscle strength and functional performance also have been described (22), (23) To gain optimal core stability it is important being able to appropriately recruit muscles together with good timing of the muscle contractions (24) . Training invoked variations in the efficiency with which motor actions can be generated influence the stability of coordination (25) and different types of core muscle training effect differently on physical functioning (26, 27); e.g. on gait function in elderly individuals (28). The importance of voluntary control over the trunk muscles has more recently been emphasised (29) and trunk posture adaptation precedes decline in gait speed (30). To be able to produce appropriate muscle responses while moving, three levels of motor control should be combined: first, the spinal reflex level, second, the brain stem level pathway that coordinates vestibular and visual input and third, the level of cognitive programming that is based on stored central commands leading to voluntary adjustments (31).

So far no consensus has been reached among exercise and conditioning specialists regarding what core exercises are most effective influencing the control of spine equilibrium and mechanical stability for improved walking. Whether the recently reviewed core strength training programs (4) for example included motor learning principles (where in addition to trunk region activity supraspinal centers are also constantly in increased activity(28)) and are, because of this, differing in their effectiveness when compared to more traditional core stability training (where superficial trunk muscles or deep trunk muscles, such as transversus abdominis and multifidus, or both are activated (57)) is unclear. There is evidence of core muscle training, that favoured exercises implementing motor learning principles against general exercise because of superior pain and disability outcomes characterising functional activities in low back patients (59), however substantiated consensus of it cannot be reached We hypothesized that programs applying motor learning theory to core stability training programs improve lower and upper extremities use, balance and functional performance in older adults more compared to traditional types of core strength training. Thus, the purpose of this study was to systematically review the literature with the aims (a) to report on motor skill training in core stability exercise programs and (b) to contrast the effects of more traditional training programs with motor skill training programs on lower and upper extremities use, balance and functional performance in older adults. The following PICO (P: patient, problem or population; I: intervention; C: comparison, control or comparator; O: outcome) research question (32) guided through this systematic review: "What is the effect of motor learning training strategies compared to traditional strength training for Core Stability on lower and upper extremities use, balance and functional performance in older adults?"

Material and methods

Data sources and searches.

Core stability, defined as "activation of deep trunk muscles that stabilise lumbar spine and pelvis (33, 34)" is associated with more efficient use of the lower and upper extremities and improved balance/functional performance outcomes in older adults (4). Based on this definition and these outcomes a search strategy was developed in collaboration with a librarian from the Medical Library of the University of Zurich. The search period covered all years from the inception to August 2017, and included EMBASE, MEDLINE, Cochrane (PubMed), CINAHL, and PsycINFO. Searches were undertaken using MeSH headings and text words adapted to the different databases. Example of the specific search strategy is seen in Table 1. The bibliographies of all eligible articles and related reviews, as well as recent conference proceedings, were checked through hand searching. To ensure the clarity and transparency of reporting, the PRISMA guidelines (35) were followed.

Table 1

The specific search strategy done in the EBSCOhost database

#	Query	Limiters/Expanders	Last Run Via	Results
1	**2**	**3**	**4**	**5**
S4	S1 AND S2 AND S3	Search modes - Find all my search terms	Interface – EBSCOhost Research Databases Search Screen – Advanced Search Database – CINAHL with Full Text	190
S3	((MH "Exercise") OR (MH "Therapeutic Exercise") OR (MH "Balance Training, Physical") OR ((MH "Balance, Postural") AND (therap* or training* OR exercise*))) OR (TX (exercise OR physical N3 therapy OR physiotherapy OR pilates OR (((muscle N3 strength) OR resistance OR balance) N3 (training OR therapy))))	Search modes - Find all my search terms	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - CINAHL with Full Text	307,481
S2	TI (((motor N3 control) OR (neuromuscular N3 control) OR (motor N3 skill) OR (cognit* N3 motor) OR (cognitive N3 trunk) OR feedback OR (swiss N3 ball)) N6 (training OR exercise* OR therapy OR rehabilitation OR mov*)) OR TI ((cognit* OR propriocept* OR coordinative OR voluntary OR deliberat* OR intentional* OR willful OR wilful OR purpose* OR designed OR planned OR intended) N6 (training OR exercise* OR therapy OR rehabilitation OR mov*)) OR TI (sensorimotor OR sensorymotor OR (sensory N3 motor) OR videogames OR exergames OR "dual task" OR proprioreception OR (coordinat* N3 muscle*)) OR AB (((motor N3 control) OR (neuromuscular N3 control) OR (motor N3 skill) OR (cognit* N3 motor) OR (cognitive N3 trunk) OR feedback OR (swiss N3 ball)) N6 (training OR exercise* OR therapy OR rehabilitation OR mov*)) OR AB ((cognit* OR propriocept* OR coordinative OR voluntary OR deliberat* OR intentional* OR willful OR wilful OR purpose* OR designed OR planned OR intended) N6 (training OR exercise* OR therapy OR rehabilitation OR mov*)) OR AB (sensorimotor OR sensorymotor OR (sensory N3 motor) OR videogames OR exergames OR "dual task" OR proprioreception OR (coordinat* N3 muscle*))	Search modes - Find all my search terms	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - CINAHL with Full Text	19,891

Table 1 (Continued)

1	2	3	4	5
S1	(((MH "Torso") OR (MH "Thorax+") OR (MH "Pelvis") OR (MH "Back") OR (MH "Abdomen+") OR TX (torso OR trunk OR back OR abdomen OR pelvis OR thorax)) AND TX (muscle N3 strength OR ((muscle N3 composition) AND (balance OR ‘‘functional performance’’ OR (falls AND (association OR relationship OR correlation))))) OR TX (trunk OR core OR postural) N3 (strenght* OR stabili*)) AND ((MH "Aged+") OR TX ((aged OR elder*) N3 (person* OR patient* OR man OR men OR woman OR women OR people)))	Search modes - Find all my search terms	Interface - EBSCOhost Research Databases Search Screen - Advanced Search Database - CINAHL with Full Text	3,007

Selection criteria.

The search strategy included: 1) all types of physical exercise training for the core stability, including studies that focused on cognitive motor programming, 2) randomized control trials (RCT), controlled clinical trials (CCT) or one-group pre-post intervention studies, 3) individuals with a mean age of 60 years or older. Study outcomes were determined on efficiency of using the lower and upper extremities and improved balance/functional performance outcomes in older adults, which included measures of muscle strength, balance, functional performance and/or fall-related outcomes. Studies were excluded if published as an abstract without full text publication, designed as a single case study or written in languages other than English.

Selection process.

The first step was the removal of duplicate citations. Thereafter two reviewers (RK, AL) determined which studies were to be included by independently screening of title, abstract and keywords. The a priori set inclusion and exclusion criteria were applied to the articles (An article was eligible, if the investigator examined traditional (TRAD) or motor learning (ML) training targeting trunk/core stability in humans. Only studies were included that carried out an intervention (irrespective of the intervention duration). Subsequently, the results from the screening were discussed to reach consensus regarding the inclusion decisions. In case of disagreement, EDB served as referee. Full text reading of the remaining literature yielded the final list of papers.

Data extraction and data synthesis.

A purpose adjusted individualized data extraction form (36) was used to collect data from single studies. The extraction of the data included (1) reference information: author and date; (2) characteristics of study population: number of participants, sex, age; (3) characteristics of physical exercise intervention: type of exercise, frequency, intensity and duration; (4) characteristics of outcomes: outcome measures and results. The data are presented in the results section as a descriptive summary of the studies and their results. Furthermore, a qualitative synthesis of the studies was executed. A meta-analysis was not performed due to the heterogeneity of intervention types and outcome variables among the limited amount of two studies identified using a ML approach for training. No substantial missing data was detected; therefore, there was no need to contact authors of the selected studies. Effect sizes from studies not reporting these were calculated using the following equations: Cohen's d = (M2 – M1) ⁄ SD pooled; where M is the mean of group 1 or 2 and SD is standard deviation, and Cohen’s f = sqrt (eta2/(1-eta2)); where sqrt means square root and eta2 is η^2 (37). Cohen’s d effect sizes of 0.20, 0.50, and 0.8 are termed *small*, *medium*, and *large*, respectively, whereas Cohen’s f effect sizes of 0.02, 0.15, and 0.35 are termed *small*, *medium*, and *large*, respectively (37).

Quality appraisal.

Quality evaluation of the studies was done by reporting potential sources of bias (38). For critical quality appraisal, the purpose-adjusted Downs & Black checklist for randomized and non-randomized studies of health care interventions was used (39). The quality checklist consisted of 27 items having a theoretical maximum score of 28 points. The checklist scored 5 different domains: the quality of reporting (10 items, maximum 11 points), the external validity (3 items, maximum 3 points), internal validity – bias (7 items, maximum 7 points), internal validity – confounding (selection bias) (6 items, maximum 6 points) and power (1 item with maximum 1 point). The scoring of the last item (‘‘study power’’) was modified from a 0 – 5 scale to a 0 – 1 scale, where 1 was scored if the authors reported whether and how they determined their sample size a priori. For intervention studies with a one-group design several items had to be scored 0 (items 5, 14, 15, and 21 – 25), which implied a possible range score from 0 to 19 for those study designs. A summary of the set criteria for quality assessments that were used is displayed in Table 3. The quality evaluation procedure was done independently by two reviewers (AL, RK), as previously described (38). The level of agreement was assessed with Cohen’s kappa analysis on all items of the checklist. Landis and Koch’s benchmark for assessing agreement ranges from almost perfect (0.81 – 1.0), substantial (0.61 – 0.8), moderate (0.41 – 0.6), fair (0.21 – 0.4), slight (0.0-0.2), and poor (<0) (40). Disagreements were resolved by consensus or by consulting a third reviewer (EDdB).

Results

The database search returned 398 results. Eight additional potentially eligible articles were retrieved from hand searching. The total amount reduced to 310 after duplicates were removed. 287 articles were excluded after reviewing the titles and abstracts for eligibility. Full versions were retrieved for 23 articles, of which 13 were eligible for inclusion. The article screening process is detailed in Figure 1.

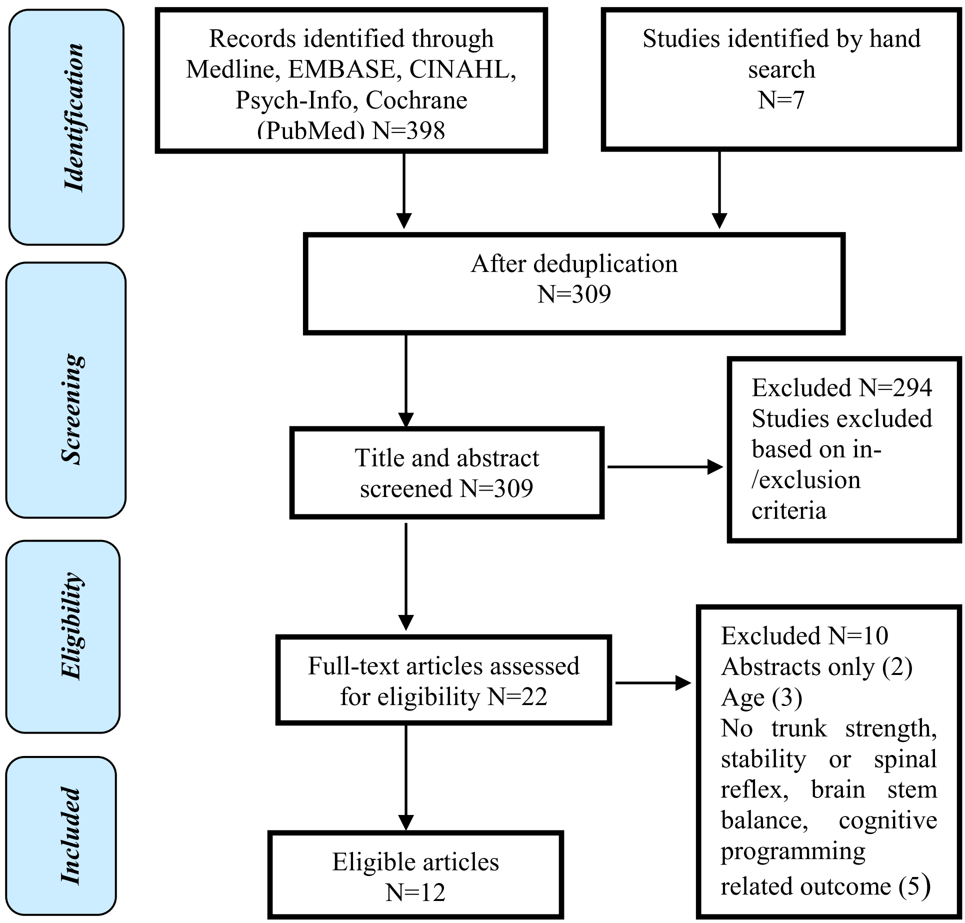

Figure 1. Study selection flow diagram

Description of included studies

Study details and intervention summaries are displayed in Table 2. Four studies were conducted in the United States, three in Germany, two in Australia, two in South Korea, and one each in Croatia and Italy. Four studies were one group pre-posttest intervention (41 – 44) studies, and 9 studies were RCT's (23, 28, 45 – 51). Eligible outcome data was available from a total of 292 participants across the 13 studies; 215 were assigned and completed TRAD training intervention, 77 ML training conditions. Interventions lasted an average of 10 weeks (range = 4 – 24 weeks), with an average of 2.7 sessions per week. In 9 studies participants were not receiving any training when in the comparison group and were expected to maintain regular levels of physical activity during the time of the trial (23, 41, 44-49, 51). In 2 studies participants were hospitalized or living in a nursing home (42, 43), one study was performed in a senior citizen center (28). One study described the intervention both in hospitalized patients and in outpatients (50). The traditional core stability training equipment/methods used were: Pneumatic resistance machines (23, 45, 50), resistance machines (43, 44), semi recumbent stepper (23), semi recumbent cycle ergometer (23), Pilates exercise intervention (41, 49), and exercises incorporating core muscles (46, 48). Furthermore, trunk stabilization exercises carried out on a Professional Exercise Ball (28, 42) using elastic bands for dynamic exercises (28), and training with in-gym available equipment and machines (e.g. bilateral leg press, chest press, lat pulldown, seated row machines, dumbbells, dumbbell Romanian deadlifts, bilateral knee extension/flexion seated machine) (47, 51). The ML elements used were dance training with cognitive tasks (47) and a core resistance training device incorporating force modulation exercises that placed an additional cognitive load to the motor task (49) (Table 2). Twelve studies delivered the intervention program in one center-based location (23, 41 – 47, 49 – 51). One study administered a home-based intervention (48). In one study participants could continue their training program after completion of the research in their home environment (41).

From the included thirteen studies, two included a training program that stimulated cognitive function (47, 49) and were categorised as ML. The rationale for this classification was that Hamacher and colleagues (47) used dancing for training, an activity for which learning is the only fast enough mechanism to master such a new task (52). Markovic et al. included feedback-based core resistance training which is known to effect on motor learning (53).

Table 2

Summary description of the included articles

Source	Design	Sample	Exercise intervention	Outcome variable	Results
TRAD training strategies					
Baker et al., 2007 (23)	RCT with one (Exercise) Intervention group and one Control group.	Elderly subjects from a retirement village; 76±6 years old. Allocated to Exercise (n=20), Control (n=18); Completed Exercise (n=14), Control (n=16). Australia.	Supervised Exercise training: F1: 10 wks, 3x/wk; I1: HI 80% of 1RM PRT; Time: 2 sets of 8 reps. Knee flex, ext & hip flex, ext, abd, chest press, seated row, latissimus pull down; Type: Strength Training; F2: 10 wks, 2x/ wk; I2: moderate-intensity (RPE 11 to 14/20); Time2: 20 min; Type2: AET; F3: 10 wks, 1x/wk; I3: n/a; Time: n/a; Type3: PBT. Control group received no intervention.	Chest press, latissimus pull down, seated row, upper body strength, dynamic balance.	Exercise group showed significant increase in chest press strength (Cohen's d=0.65; p=0.04) compared to control group.
Bergamin et al., 2015 (41)	A one intervention (Pilates group pilot study.	Post-menopausal women from a senior citizens center 63±2 years old. Allocated Pilates (n=25); completed training (n=23). Italy.	Supervised Pilates training: F: 12 wks, 2x/wk; I: warm-up with VLI exercises/ only floor. Pilates exercises such as leg circle single leg kick, double leg kick, side kick, one leg stretch, single leg heel, single leg toes, side lying hip abduction, side lying, hip adduction, roll up, rolling back, leg rises on all, fours, pelvic curl and the hundred (2 sets/10 reps for each exercise)/ cool down consisting of stretching exercises; Time: 10min/40min/10min; Type: Pilates training.	Static balance with additional cognitive task, static balance (without cognitive task), abdominal strength, dynamic balance (8 ft up and go test).	Significant improvements on medio-lateral oscillations with eyes-open (ES d=0.7; p<0.01) and dual-task condition (ES d=0.37; p=0.02), 8 ft up and go test (ES d=0.46; p=0.02), abdominal strength (ES d=0.69; p<0.01).
Granacher et al., 2013 (46)	RCT with one intervention (CIT) and one Control group.	Community-dwelling older adults 63 to 80 years old. Intervention group (n=16), Control (n=16); Completers Intervention group (n=16), Control (n=16). Germany.	Supervised Core Instability Strength Training: F: 9 wks, 2x/wk; I: warm-up at moderate intensity/ Exercises in supine, prone, quadruped and side- lying positions. Training intensity progressively and individually increased by modulating lever lengths, range of motion, movement velocity (isometric, dynamic) and level of stability/ instability (3-4 sets per exercise 15–20sec contr time (isometric condition), or 15–20 reps (dynamic condition)/cool down consisting of stretching exercises; Time: 10min /45min /5min; Type: Core Instability Strength Training. Control group received no treatment or intervention. They maintained their normal PA.	Maximal isometric strength of the trunk flexors, maximal isometric strength of the trunk extensors, maximal isometric strength of the trunk lateral flexors (right, left), maximal isometric strength of the trunk rotators (left, right), dynamic balance (Functional Reach test).	Significant increase in the trunk muscle strength in all directions except right rotators (ES f=0.23-1.02; p≤0.05), in dynamic balance (ES f=0.41-0.59; p<0.05) was established in CIT group when compared to control group.

Table 2 (Continued)

Source	Design	Sample	Exercise intervention	Outcome variable	Results
Kim et al., 2014 (42)	One training group intervention with one intervention (Trunk stabilization exercise) group.	Hospitalized elderly people in a geriatric hospital (n=15) 76±10 years old. Completed (n=n/a). Republic of Korea.	Supervised trunk stabilization exercises with Swiss ball: F: 8 wks, 5x/wk; I: Trunk stabilization exercises carried out using Professional Exercise Ball; Time: 20 min; Type: trunk stabilization exercise.	Muscle activation of the rectus abdominis, muscle activation of the erector spinae, muscle activation of the quadratus lumborum, muscle activation of the external oblique.	The muscle activations of the rectus abdominis (ES d=1.95; p<0.05), erector spinae (ES d=1.69; p<0.05), low lateral back (ES d=3,4; p<0.05).
Kim et al., 2015 (28)	RCT with two training groups; random allocation to an isometric (n=10) and a dynamic trunk exercise group (n=10).	Senior citizen center; 20 elderly people in an isometric trunk exercise group (n=10; mean age 73) and a dynamic trunk exercise group (n=10; mean age 73.5).	Supervised exercises performed for 30 minutes 3x/wk for 12 weeks: The isometric trunk exercise program and dynamic trunk exercise program consisted of: five minutes of warm-up exercises, 20 minutes of main exercises, and five minutes of cooldown exercises.	Cadence, cycle time, gait velocity, step time, double support time, stance time, stride length, and functional ambulation performance score were measured.	Isometric strength training: significant differences in gait velocity, left step length, right step length, left stride length, and right stride length (p<0.05). Dynamic strength training: significant differences in gait velocity, cadence, left step time, right step time, left step length, right step length, left stride length, and right stride length (p<0.05). Gait velocity, Cadence, Step length left, and Stride length left change of the isometric trunk exercise group were significantly greater (ES d ranging between 0.33-0.54; p<0.05)
Petrofsky et al., 2005 (44)	One training group intervention with one intervention (The 6 sec Abs machine) group.	Seniors between 61-82 years old (n=13); completed (n=n/a) USA.	Supervised 6 sec Abs maschine training: F: 1 month, 3x/wk; I: passive stretching/4 different trunk strength exercises with workload progrssively increased (weight set such that with repetitive contr of the muscles over 6sec cycles of contr, muscle fatigued in 5min; Time: 10min/20 min; Type: 6sec Abs maschine training.	Strength (kg) of abdominal flexors, strength (kg) of abdominal extensors, balance (Functional reach (cm).	Strength of trunk flex and ext significantly increased (ES d=1.02 and 1.11; p<0.01), the maximal reach in all directions (right, forward, left) significantly increased (ES d=0.65, 1.34, 1.39; p<0.01).

Table 2 (Continued)

Source	Design	Sample	Exercise intervention	Outcome variable	Results
Villanueva et al., 2015 (51)	RCT with one group utilizing short rest interval lengths and one group utilizing extended rest interval lengths	Healthy, recreationally active male seniors 68±4 years old (n=22). In each group (n=11). Completed (n=n/a). USA.	Supervised RT utilising short rest interval lengths in between sets: F: 12 wks, 3x/wk; I: wk 1-4 sets 2 to 4, reps 15 to 8, bouts 4 to 6 exercises, wk 5-12 sets 2 to 3, reps 6 to 4 (performed as fast as possible), bouts 4 to 6 exercises (rest between sets: 60 sec in wk 5-12); Time: n/a; Type: PRT (short rest). Supervised RT utilising extended rest interval lengths in between sets: F: 12 wks, 3x/wk; I: wk 1-4 sets 2 to 4, reps 15 to 8, bouts 4 to 6 exercises, wk 5-12 sets 2 to 3, reps 6 to 4 (performed as fast as possible), bouts 4 to 6 exercises (rest between sets: 4 min in wk 5-12); Time: n/a; Type: PRT (long rest).	Chest press, narrow/neutral latissimus pull down, postural control (dynamic balance).	From wk 8 to 12 strength in short rest group had significantly greater increase in chest press 1-RM (ES d=0.65; p<0.01), narrow /neutral lat pulldown (ES d=0.59; p<0.01) compared to long rest group.
de Vos et al., 2005 (45)	RCT with 3 training groups differing in intensity (HI RT, MI RT, LI RT) and one control group.	Healthy older adults (n=112) 69±6 years old. In each group (n=28). Completed HI RT (n=24), MI RT (n=25), LI RT(n=25), Control group (n=26). Australia.	Supervised RT on Keiser pneumatic maschines: F: 10±2 wks, 2x/wk; I: 4 slow reps at ½RT weight to warm-up before each of 5 exercises (bilateral horizontal leg press, seated chest press, bilateral, leg ext, seated row, seated bilateral leg curl)/each wk 1. RT 3 sets of 8 reps, each wk 2. RT 1RM, 2 sets of 8 reps at I of 20%, 50% or 80% depending on group - HI, MI or LI. Rest between reps 10-15 sec. First 2 RT HI group performed at 50% and 70% 1RM; Time: n/a; Type: PRT. Control group did not undergo PRT, but kept their current level of PA.	Chest press: muscle power, muscle strength, muscle endurance. Seated row: muscle power, muscle strength, muscle endurance.	Chest press muscle power in HI, MI, LI and group (ES d=0.95, 0.94, 1.06 and 0.21; p<0.01), strength (ES d=1.77, 1.06, 1.29 and 0.6; p < 0.01), endurance (ES d=2.00, 1.00, 1.00 and 1.00; p<0.01) significantly increased. Seated row muscle power in HI MI, LI and control group (ES d=0.72, 0.821.40 and 0.22; p<0.01), strength (ES d=1.43, 1.87, 1.19 and 0.35; p<0.01), endurance (ES d=1.60, 1.20, 1.00 and 0.66; p<0.01) significantly increased.
Kahle and Tevald, 2014 (48)	RCT with one exercise and one control group	Healthy community-dwelling seniors (n=26) 65 to 85 years old. Completed exercise (n=12); control(n=12). USA.	Core strengthening home exercise program: F: 6 wks, 3x/wk; I: 8 exercises (Bridging, Reclining curl, Curl-up, Seated oblique crunch, Abdominal contr, Lower trunk rotation, Straight leg raise, Seated marching) each 10 reps (hold of 1 rep 5-25sec). Rest 1–2min between sets. Every 2 wks 5 reps or 5sec hold added; Time: 20min (some did less than 35min); Type: Progressive core stength and endurance training. Control group did not core program, but kept their current level of PA.	Dynamic balance (Functional reach test, Star Excursion Balance Test), core strength (Curl - up test).	Exercise group performed significant improvements in Curl-up (ES d=3.26; p<0.05), Functional reach test (ES d=0.88; p<0.05) and Star Excursion Balance tests in all directions (ES d=0.84-1.35; p<0.05). No significant changes in control group.

Table 2 (Continued)

Source	Design	Sample	Exercise intervention	Outcome variable	Results
Krist et al., 2013 (43)	A one-group pilot study with PRT.	Nursing-home residents (n=15) between 77–97 years old. Completed (n=10). Germany.	Supervised PRT: F: 8 wks, 2x/wk; I: 6 gym maschines (chest press, rowing machine, and butterfly reverse for the upper limb, leg press and leg ext for the lower limb, and a crunch trainer for the abdominals). 3 sets of 8 reps, at least 1 min rest between sets. If lifted more than 8 times in a row all 3 sets, then increased weight 5-10kg; Time: 45min; Type: PRT.	Muscle strength: chest press, rowing machine, butterfly reverse.	Significant improvements were detected in chest press (ES d=1.3; p<0.01), rowing machine (ES d=1.68; p<0.01), butterfly reverse (ES d = 1.5; p<0.01).
Sullivan et al., 2007 (50)	Double-blind RCT with one (LRE + 800mg per day of MA) group, one (HI PRT + 800mg/day of MA), one (LRE + placebo) and one (HI PRT + placebo) group.	Inpatient and outpatient seniors 65 to 93 years old with recent functional decline. (I): LRE + MA (n=7); (II): HI PRT + MA (n=8); (III): LRE + placebo (n=7); (IV): HI PRT + placebo (n=7). Completed (I) + (IV) (n=14), (II) (n=6), (III) (n=4). USA.	Supervised LRE training: F: 12 wks, n/a x/wk; I: warm-up 10% of 1RM/3 sets of 8 reps at 20% of 1RM; Time: n/a; Type: Low resistance exercises. Supervised HI PRT training: F: 12 wks, n/a x/wk; I1: wk 1 20% of 1RM, wk 2 warm-up 8 reps of 30%-40% of 1RM/3 sets of 8 reps 50% of 1RM, wk 3 as high as could for 3 sets with original aim 80% of 1RM, wk 4 at least 80% of 1RM; Time: n/a; Type: High intensity progressive resistance training.	Chest press, cognitive function.	Chest press significantly increased in LRE+ placebo (ES d=0.02; p=0.01), LRE + MA (ES d=-0.05; p=0.01), HI PRT + placebo (ES d=1.28; p=0.01) and in HI PRT + MA (ES d=0.74; p=0.01).
ML training strategies					
Hamacher et al., 2016 (47)	RCT with one health-related exercise intervention group and one (dancing) group.	Older healthy participants' health-related exercise group (n=16, age: 68±3 years old) or a dancing group (n=16, age: 66±3 years old). Completed (n=n/a) Germany.	Supervised Health-related exercise training: F: 6 months, 2x/wk; I: AET (bicycle ergometers), strength-endurance (barbells, rubber band, ball, gymnastic stick, etc.) at predefined heart rates (70% of net max oxy uptake), and flexibility training; Time: 90 min; Type: Health-related exercise training. Supervised dancing training: F: 6 months, 2x/wk; I: Predefined heart rates, set at 70% of net max oxy uptake. Learn 5 genres: Line Dance, Jazz Dance, Rock 'n' Roll, Latin- American Dance and Square Dance. Last 2wks participants recalled learned choreographies; Time: 90min; Type: Dancing training.	Trunk kinematics; Local dynamic stability.	For Local dynamic stability of trunk movements an interaction effect in favour of the dancing group was observed (ES f=0.41; p = 0.02).

Table 2 (Continued)

Source	Design	Sample	Exercise intervention	Outcome variable	Results
Markovic et al., 2015 (49)	RCT with one Huber intervention group and one Pilates training control group.	Elderly women between 66-79 years old, who responded to local newspaper advertisement. Huber (n=17), Pilates (n=17). Completed Huber (n=16), Pilates (n=14). Croatia.	Supervised Huber training: F: 8 wks, 3x/wk; I1: MVC wk 1+2: 50%, wk 3-5: 65%, wk 6-8: 75%; I2: Isometric contr: 5-7sec, 30-60 contr/session without (wk 1-2)/with (3-8 wk) balance perturbations; Time: 25-30 min; Type: Force modulation on Huber machine handles as added cognitive loading. Supervised Pilates training: F: 8 wks , 3x/wk; I: 2-4 sets, 15-20sec contr time (isometric exercise) or 15-20 reps (dynamic exercise) supine, side lying, sitting & quadruped exercises; Time: 60 min; Type: Pilates.	Static balance, static balance with additional cognitive task, trunk muscle strength, upper body muscle strength (Chest press, kg).	Huber training with ML was more efficacious in improving single- and dual-task balance ability (ES d=0.48-0.52; p<0.05) and trunk muscle strength in all directions (ES d=0.90-1.11; p<0.01) when compared to Pilates. Both groups (Huber; ES d=0.36; p<0.05; Pilates, ES d=0.25; p<0.05) significantly improved upper-body strength.

Abd abduction, AET aerobic endurance training, CIT core instability strength training, Control contraction, CST chair-sit-to-stand test, ES d effect size Cohen’s d, ES f effect size Cohen's f, Ext extension, Flex flexion, F frequency, F2 or F3sec or third type of frequency for the same intervention, HI high intensity, Huber training feedback-based balance and core resistance training, I intensity, I2 or I3sec or third type of intensity for the same intervention, LI low intensity, LRE low resistance exercise, MA megestrol acetate, Max maximum, MI medium intensity, Min minutes, MVC maximal voluntary contraction, N/a not available, Oxy oxygen, PA physical activity, PBT progressive balance training, PRT progressive resistance training, RCT randomized clinical trial, Reps repetitions, RPE rating of perceived exertion, RT resistance training, Sec seconds, Time duration of the exercise intervention, Time 2 or 3sec or third type of time for the same intervention, Type of theexercise intervention, Type 2 or 3sec or third type of type for the same intervention, VLI very low intensity, Wk week, 1RM 1 repetition maximum

Methodological quality of included studies

The agreement on study quality criteria between the two reviewers was ‘good’ with an estimated Kappa value of 0.74 (95% confidence interval between 0.66 and 0.81). The percentage of agreement between the two raters was 86.9%. Table 3 summarizes the results of the methodological quality assessment for the included studies. The quality scores of studies ranged from 9 to 24 out of a maximum of 28 points. The mean quality score was 15.8 ± 4.9 points.

Table 3

Assessment of methodological quality of included studies using the Downs and Black scale

Source	Risk assessment items																											
	1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**	**19**	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**T/P**
TRAD resistance training strategies																												
Baker 2007 (23)	1	1	1	1	2	1	1	1	1	1	0	1	0	0	1	1	0	1	1	1	1	1	1	1	1	1	1	27/ 28
Bergamin 2015 (41)	1	1	1	1	0	1	1	0	1	1	0	0	1	0	0	1	1	1	1	1	0	0	0	0	0	1	0	15/ 19
Granacher 2013 (46)	1	1	1	1	1	1	1	0	0	1	0	0	0	0	0	1	1	1	0	1	1	0	1	0	0	0	0	14/ 28
Kahle 2014 (48)	1	1	1	1	1	1	1	1	1	1	0	0	1	0	0	1	0	1	1	1	1	0	1	1	1	1	0	20/ 28
Kim 2014 (42)	1	1	1	0	0	1	1	0	0	0	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	9/ 19
Kim 2015 (28)	1	1	1	1	0	0	0	0	1	1	0	0	1	0	0	1	0	1	0	1	1	0	0	0	0	1	0	12/ 28
Krist 2013 (43)	1	1	1	1	0	1	1	0	1	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	1	0	14/ 19
Petrofsky 2005 (44)	1	1	0	0	0	1	1	0	1	1	0	0	0	0	0	1	1	0	1	0	0	0	0	0	0	0	0	9/ 19
Sullivan 2007 (50)	1	1	1	1	2	1	1	0	1	1	0	0	1	0	1	1	1	1	1	1	1	1	0	0	0	1	0	20/ 28
Villanueva 2015 (51)	1	1	1	1	1	1	1	1	1	1	0	0	0	0	0	1	1	1	1	1	0	0	0	0	0	1	0	16/ 28
de Vos 2005 (45)	1	1	1	1	2	1	1	1	1	1	0	1	0	0	0	1	1	1	1	1	1	0	0	0	1	1	0	20/ 28
ML resistance training strategies																												
Hamacher 2015 (47)	1	1	0	0	0	1	1	0	0	1	0	0	0	0	0	1	1	1	0	1	0	0	0	0	0	0	0	9/ 28
Markovic 2015 (49)	1	1	1	1	0	1	1	0	1	1	0	0	0	0	1	1	1	1	1	1	1	0	1	0	0	1	1	18/ 28

P, possible achievable points; T, total points. Risk assessment items, 1 – 10 Reporting, 1. hypothesis/aim/objectives described? 2. Main outcomes described? 3. Participant characteristics described? 4. Intervention/s described? 5. Distributions of principal confounders in each group described? 6. Main findings described? 7. Provision of estimates of random variability in the data for the main outcomes? 8. Reporting of adverse events? 9. Characteristics of participants lost to follow-up described? 10. Actual probability values reported? 11 – 13 External validity, 11. Participants asked to participate representative for population from which they were recruited? 12. Participants prepared to participate representative for population from which they were recruited? 13. Staff, places, and facilities where the participants were treated representative of the treatment the majority of participants receive? 14 – 20 internal validity (bias), 14. Blinding of study participants? 15. Blinding of outcome assessors? 16. If any of the results of the study were based on "data dredging", was this made clear? 17. In trials and cohort studies, do the analyses adjust for different lengths of follow-up of participants, or in case–control studies, is the time period between the intervention and outcome the same for cases and controls? 18. Statistical tests appropriate? 19. Was compliance with intervention/s reliable? 20. Were the main outcome measures used accurate (valid and reliable)? 21 – 26 internal validity (confounding), 21. Were the participants in different intervention groups (trials and cohort studies) or were the cases and controls (case–control studies) recruited from the same population? 22. Were study subjects in different intervention groups (trials and cohort studies) or were the cases and controls (case–control studies) recruited over the same period of time? 23. Randomization, and if yes procedure described? 24. Allocation concealment? 25. Was there adequate adjustment for confounding in the analyses from which the main findings were drawn? 26. Losses of participants to follow-up taken into account? 27 power, 27. Power analysis done a priori? Ratings no = 0, unable to determine = 0, yes = 1; rating item 5: no = 0, partially = 1, yes = 2.

Effect of TRAD and ML training.

TRAD training

The majority of the studies used traditional resistance training strategies to train muscles for core stability (23, 28, 43 – 46, 48, 50, 51) and reported significant pre to post strength gains of chest press in the intervention groups (23, 43, 50, 51) when compared to passive and active control groups, abdominal flexors (43, 44, 46, 48) compared to passive control groups, back extensors (44, 46), latissimus pull-down (51), seated row (43, 45) and butterfly reverse (43). One study reported on gait performance and showed that gait velocity changed more in the isometric trunk exercise group than in the dynamic trunk exercise group (28). The effect sizes ranged between small and large for measures of muscle strength (Table 2). No significant improvements were reported compared with controls in latissimus pull down and seated row exercises in one study (23). Functional measures; e.g. medio-lateral sway, functional reach, balance, etc., showed in general positive changes, however, with large heterogeneity of effect sizes ranging from small to large.

ML training

Two studies that used ML approaches while progressing through the intervention (47, 49) used rather traditional type exercises in their comparison groups. Results from these two studies indicate more improvements in measures of balance and local dynamic stability in the ML groups compared to the traditional types of exercises used. Markovic and colleagues (2015) reported, furthermore, larger improvements for upper body strength measures (49) in the ML training group as compared to the group training more traditional. The quality of these two studies was low (47) and moderate (49) respectively.

A summary of the findings is given in Table 2. Performance of a meta-analysis was not feasible due to the limited amount of two studies identified using ML approaches for training and due to the heterogeneity in study outcome measures used in these two studies. A descriptive summary of the results was carried out in lieu.

Discussion

The purpose of this systematic review was to find an answer to the question "What is the effect of motor learning training strategies compared to traditional strength training for Core Stability on lower and upper extremities use, balance and functional performance in older adults?" The results of our search strategy does not allow giving a conclusive answer to this question in the sense that one approach is superior compared to the other. The majority of identified studies used traditional strength training for core stability training and no substantial amount of studies assessing the effects of ML training approaches in comparison to TRAD approaches was identified. In addition, 8 of 13 studies interventions were not explicitly focused on the trunk muscle composition's improvements, but rather on lower, upper extremities and trunk parameters (23, 41, 43, 45, 47, 49 – 51). The search strategy led to the identification of many articles from which, however, the majority were targeting core muscles using TRAD trunk strength exercising programmes. The two studies that used elements of a ML approach had a poor (47) and moderate (49) quality and were rather heterogenic considering their outcomes, which, in turn, led to difficulties comparing the results and hindered performing a meta-analysis. The limited availability of high-quality prospective studies that used a comparison between ML and TRAD training approaches warrants targeted future research investigating and comparing the effects of these approaches on lower and upper extremities use and on balance/functional performance outcomes in older adults. Based on our findings we will discuss and suggest directions for future research related to interventions where these two training approaches are contrasted. Through this systematic review, it became apparent that interventions using either TRAD or ML training were both able to effect on lower and upper extremities use and also effected on balance and/or functional performance outcomes in older adults. However, interventions contrasting these approaches were not having a clear enough effect to conclude superiority of either approach against the other.

The number of studies that use TRAD principles to effect on core stability related outcomes form the majority when elderly subjects train core stability. In contrast, the number of studies that use ML based training is negligible. Existing literature on Core Stability exercise using ML principles has been varied in approach, intention and outcome. We continue this discussion by considering the effects of studies applying either TRAD or ML with the aim to effect on lower and upper extremities use and on balance/functional performance outcomes in older adults. Practices of TRAD & ML interventions are discussed together with the underlying mechanisms that theoretically would explain the effects of the used intervention components.

Those studies, that targeted core stability directly with TRAD training showed significant improvements both in trunk muscles strength and dynamic balance. Scanty evidence of ML integration in core training programs might be explained by findings that indicate discrepancies in outcome measurements when investigating the effect of cognitive involvement in exercise programs. For instance, Schoene and colleagues revealed that interactive cognitive-motor interventions (which require participants to interact with a computer interface via gross motor movements) appear to be of equivalent efficacy in ameliorating fall risk as compared with traditional training programs (17). Such interventions are, furthermore, able to improve cognitive functioning in both clinical and non-clinical populations (54). However, core stability was not under the scope of neither of these reviews. Spinal locomotor ('central pattern generator') as well as non-locomotor activity are both under supra-spinal control (29). Motor skill training has the potential to allow the brain relearning and reintegrating of the timing and sequencing of movements together with the postures and phases of gait (18). It is in this context that efficient patterns of brain and neuromuscular activation might be able restoring the energy efficiency of movements. Restoration of energy efficiency would make walking easier because of adaptive changes in the brain attributable to motor skill training (55 – 57).

Our review found two RCT studies using a ML training approach (47, 49). Such an approach would make sense considering that muscle actions must be precisely coordinated to occur at the right time, for the correct duration and with the adequate combination of forces (58). Coordinated muscles activation improve stabilization of the trunk (59) that is crucial for maintaining static or dynamic balance (60). Considering ML approach to elderly patients, it might beneficial if "movement memory" element is applied to the program. One of the ML training approach study's intervention was based on learning and remembering specific dancing skills, making sure that the participants learned something new in each session (47). The second was Markovic's study where a special Huber device with an interactive interface and balance platform was used (49). These ML training approaches (47, 49) did not disturb the external focus of attention by diminishing visual input. Such an approach would make sense considering that older persons frequently fall or trip on objects below eye level (61) and there is evidence, that orientation input from the ankle appears to have greater importance for preventing falls compared with a visual reference (62). Furthermore, in the absence of visual feedback (or partly of level 2 by Radebold (31)), poor balance performance correlates significantly with longer trunk muscle onset times in response to sudden force release in those with chronic back pain (31). This underlines the importance of sensorimotor coordination without visual feedback between trunk muscles and supra-spinal centres (e.g. level 3 that ensures so-called anticipatory postural adjustments to maintain the balance).

Specific motor control training as part of core stability training protocols for older adults can, furthermore, be justified by the observation from a recent systematic review evaluating the effectiveness of motor control exercise targeting core muscles in low back pain patients that favored motor control exercises against general exercise because of superior pain and disability outcomes (63). Normal motor control in the lumbar spine is important because of the observed maladaptive differences seen between people with and without core muscles related disabilities in relation to feed forward mechanisms (64, 65), reduced core muscles cross sections (66, 67) and altered cortical representations of motor patterns (68). Furthermore, both neurogenic and myogenic factors occur in aging leading to muscle weakness and impaired functions (69, 70). From this it can be hypothesized that the training of motor control is an important component of core stability training in older adults. However, as the results from our systematic review indicate so far there is no clear and extensive mechanistic and randomised controlled trial based data supporting the rationale for ML for core stability training in older adults?

Therefore, studies investigating ML in combination with core stability exercises are warranted.

It is striking that our review revealed one study only that focused on gait function as outcome for training in elderly individuals (28). This notwithstanding that there is a clear assumed relationship between trunk muscle activity and lower extremity movement (21). Training invoked variations in the efficiency with which motor actions can be generated influence the stability of coordination (25) and the assumption that different types of core muscle training will effect differently on physical functioning seems justified. From a theoretical perspective, it can be hypothesized that more traditional forms of resistance training improve gait speed (13) as also shown in some of the manuscripts (28, 41). However, such traditional training will not influence variability measures of gait. Variability of gait in older adults is associated with areas important for sensorimotor integration and coordination (71) implying that motor skill training components that target these areas as part of an intervention should be included in training programs (18).

Limitations of the study

Several limitations of this review can be identified. It is possible that some research studies have been missed, because these were not published in the main databases we searched, because of non-English language publications, or being not referred to by other articles. Studies published in languages other than English were not included. Because randomized and non-randomized study designs were both considered in our review we referred to the Downs and Black list (39) for study quality assessment. This list has a drawback in the sense that the ability of the Downs and Black scale differentiating studies containing potential sources of bias is limited (72).

Furthermore, the scoring of the methodological quality of the included studies is not entirely clear since there is no clear cut-off point known for the purpose-adjusted list for the assessment of the methodological quality of both randomized and non-randomized studies. It is difficult, therefore, to give clinically relevant meaning to the scores of the studies included in this review.

Conclusion

The number of studies that use TRAD training approaches for core stability training with the aim to effect on use of the lower and upper extremities and improved balance/functional performance outcomes in older adults form the majority. In contrast, the number of studies that use ML approaches is small. Existing literature on core stability training has been widely varied in approach, intention and outcome. Currently available literature does not present a wealth of information about the best strategy for core stability training in subjects older than 60 years. Evidence-based clinical applications of TRAD & ML methods are, therefore, in need of (further) development. Our findings indicate that the challenge for the various developed training programs is evaluation of transfer effects in "real life" settings. Before selecting an exercise program clinical practitioners should formulate clear goals of measuring program effects in clinical settings in order to receive credible information about the best suited program.

Conflicts of Interest

Agris Liepa, Ruud Knols, Viesturs Larins, Federico Gennaro and Eling de Bruin declare that they have no conflicts of interest relevant to the content of this review.

Authors' contribution

AL, RHK and EDB developed the research question. The concept and design part was established by AL and RHK while EDB acted as methodological council. AL, EDB and RHK did data acquisition as well as, together with FG, analysis and interpretation of the results which was edited and improved by VL & EDB. AL and RHK produced an early version of the manuscript. FG and EDB substantially revised the manuscript to bring it to its current version. All authors have read and approved the final manuscript.

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Compliance with Ethical Standards

Not applicable.

Abbreviations

ML: motor learning training, TRAD: traditional training.

References

1. Campbell, A. J., Borrie, M. J., Spears, G. F., Jackson, S. L., Brown, J. S. & Fitzgerald, J. L. (1990). Circumstances and consequences of falls experienced by a community population 70 years and over during a prospective study. *Age Ageing,* 19(2), 136-41.
2. Tinetti, M. E., Speechley, M. & Ginter, S. F. (1988). Risk factors for falls among elderly persons living in the community. *N Engl J Med,* 319(26), 1701-7.
3. Peel, N. M. Kassulke, D. J. & McClure, R. J. (2002). Population based study of hospitalised fall related injuries in older people. *Inj Prev,* 8(4), 280-3.
4. Granacher, U., Gollhofer, A., Hortobagyi, T., Kressig, R. W. & Muehlbauer, T. (2013). The importance of trunk muscle strength for balance, functional performance, and fall prevention in seniors: a systematic review. *Sports Med,* 43(7), 627-41.
5. Eriksson, S., Gustafson, Y. & Lundin-Olsson, L. (2008). Risk factors for falls in people with and without a diagnose of dementia living in residential care facilities: a prospective study. *Arch Gerontol Geriatr,* 46(3), 293-306.
6. Fried, L. P., Tangen, C. M., Walston, J., Newman, A. B., Hirsch, C. & Gottdiener, J. (2001). Frailty in older adults: evidence for a phenotype. *J Gerontol A Biol Sci Med Sci,* 56(3), M146-56.
7. Rosano, C., Studenski, S. A., Aizenstein, H. J., Boudreau, R. M., Longstreth, W. T. & Newman, A. B. (2012). Slower gait, slower information processing and smaller prefrontal area in older adults. *Age Ageing,* 41(1), 58-64.

   Aboutorabi, A., Arazpour, M., Bahramizadeh, M., Hutchins, S. W. & Fadayevatan, R. (2016). The effect of aging on gait parameters in able-bodie older subjects: a literature review. *Aging Clin Exp Res,* 28(3), 393-405.
8. Yogev-Seligmann, G., Hausdorff, J. M. & Giladi, N. (2008). The role of executive function and attention in gait. *Mov Disord,* 23(3), 329-42, quiz 472.
9. Alexander, N. B. & Hausdorff, J. M. (2008). Guest editorial: linking thinking, walking, and falling. *The journals of gerontology Series A, Biological sciences and medical sciences,* 63(12), 1325-8.
10. Beurskens, R. & Bock, O. (2012). Age-related deficits of dual-task walking: a review. *Neural Plast,* 2012:131608
11. Brach, J. S., Lowry, K., Perera, S., Hornyak, V., Wert, D. & Studenski, S. A. (2015). Improving motor control in walking: a randomized clinical trial in older adults with subclinical walking difficulty. *Arch Phys Med Rehabil,* 96(3), 388-94.
12. Van Abbema, R., De Greef, M., Craje, C., Krijnen, W., Hobbelen, H. & Van Der Schans, C. (2015). What type, or combination of exercise can improve preferred gait speed in older adults? A meta-analysis. *BMC Geriatr,* 15:72.
13. Sherrington, C., Tiedemann, A., Fairhall, N., Close, J. C. & Lord, S. R. (2011). Exercise to prevent falls in older adults: an updated meta-analysis and best practice recommendations. *N S W Public Health Bull,* 22(3-4), 78-83.

14. Cadore, E. L., Rodriguez-Manas, L., Sinclair, A. & Izquierdo, M. (2013). Effects of different exercise interventions on risk of falls, gait ability, and balance in physically frail older adults: a systematic review. *Rejuvenation Res,* 16(2), 105-14.
15. De Bruin, E. D., Schoene, D., Pichierri, G. & Smith, S. T. (2010). Use of virtual reality technique for the training of motor control in the elderly. Some theoretical considerations. *Z Gerontol Geriatr,* 43(4), 229-34.
16. Schoene, D., Valenzuela, T., Lord, S. R. & De Bruin, E. D. (2014). The effect of interactive cognitive-motor training in reducing fall risk in older people: a systematic review. *BMC Geriatr,* 14-107.
17. Van Swearingen, J. M. & Studenski, S. A. (2014). Aging, motor skill, and the energy cost of walking: implications for the prevention and treatment of mobility decline in older persons. *J Gerontol A Biol Sci Med Sci,* 69(11), 1429-36.
18. Bliss, L. S. & Teeple, P. (2005). Core stability: the centerpiece of any training program. *Curr Sports Med Rep,* 4(3), 179-83.
19. Panjabi, M. M. (1992). The stabilizing system of the spine. Part I. Function, dysfunction, adaptation, and enhancement. *Journal of spinal disorders,* 5(4), 383-9, discussion 97.
20. Willson, J. D., Dougherty, C. P., Ireland, M. L. & Davis, I. M. (2005). Core stability and its relationship to lower extremity function and injury. *J Am Acad Orthop Surg,* 3(5), 316-25.
21. Suri, P., Kiely, D. K., Leveille, S. G., Frontera, W. R. & Bean, J. F. (2009). Trunk muscle attributes are associated with balance and mobility in older adults: a pilot study. *PM & R: the journal of injury, function, and rehabilitation,* 1(10), 916-24.
22. Baker, M. K., Kennedy, D. J., Bohle, P. L., Campbell, D. S., Knapman, L. & Grady J. (2007). Efficacy and feasibility of a novel tri-modal robust exercise prescription in a retirement community: a randomized, controlled trial. *Journal of the American Geriatrics Society,* 55(1), 1-10.
23. Borghuis, J., Hof, A. L. & Lemmink, K. A. (2008). The importance of sensory-motor control in providing core stability: implications for measurement and training. *Sports medicine (Auckland, NZ),* 38(11), 893-916
24. Carson, R. G. (2006). Changes in muscle coordination with training. *J Appl Physiol,* 101(5), 1506-13.
25. Kang, K. Y. (2015). Effects of core muscle stability training on the weight distribution and stability of the elderly. *J Phys Ther Sci,* 27(10), 3163-5.
26. Martuscello, J. M., Nuzzo, J. L., Ashley, C. D., Campbell, B. I., Orriola, J. J. & Mayer, J. M. (2013). Systematic review of core muscle activity during physical fitness exercises. *J Strength Cond Res*, 27(6), 1684-98.
27. Kim, N. J., Kim, J. S., Wang, J. S., Park, J. H. & Choi, J. H. (2015). The effects of isometric trunk exercises and dynamic trunk exercises on gait in elderly people. *J Phys Ther Sci,* 27(6), 1685-9.

28. Haefeli, J., Vogeli, S., Michel, J. & Dietz, V. (2011). Preparation and performance of obstacle steps: interaction between brain and spinal neuronal activity. *Eur J Neurosci,* 33(2), 338-48.
29. Merchant, R. A., Banerji, S., Singh, G., Chew, E., Poh, C. L. & Tapawan, S. C. (2016). Is Trunk Posture in Walking a Better Marker than Gait Speed in Predicting Decline in Function and Subsequent Frailty? *J Am Med Dir Assoc,* 17(1), 65-70.
30. Radebold, A., Cholewicki, J., Polzhofer, G. K. & Greene, H. S. (2001). Impaired postural control of the lumbar spine is associated with delayed muscle response times in patients with chronic idiopathic low back pain. *Spine (Phila Pa 1976),* 26(7), 724-30.
31. Thabane, L., Thomas, T., Ye, C. & Paul, J. (2009). Posing the research question: not so simple. *Can J Anaesth,* 56(1), 71-9
32. Hodges, P. W. (2003). Core stability exercise in chronic low back pain. *Orthop Clin North Am,* 34(2), 245-54.
33. Wells, C., Kolt, G. S. & Bialocerkowski, A. (2012). Defining Pilates exercise: a systematic review. *Complement Ther Med,* 20(4), 253-62
34. Moher, D., Liberati, A., Tetzlaff, J., Altman, D. G. & Group, P. (2009). Preferred reporting items for systematic reviews and meta-analyses: the PRISMA statement. *PLoS Med,* 6(7), e1000097
35. Wright, R. W., Brand, R. A., Dunn, W. & Spindler, K. P. (2007). How to write a systematic review. *Clin Orthop Relat Res,* 455:23-9.
36. Cohen, J. (1988). Statistical power analysis for the behavioral sciences. *Hillsdale, New Jersey: Lawrence Erlbaum Associates.*
    Harris, J. D., Quatman, C. E., Manring, M. M., Siston, R. A. & Flanigan, D. C. (2014). How to write a systematic review. *Am J Sports Med,* 42(11), 2761-8.
37. Downs, S. H. & Black, N. (1998). The feasibility of creating a checklist for the assessment of the methodological quality both of randomised and non-randomised studies of health care interventions. *J Epidemiol Community Health,* 52(6), 377-84.
38. Landis, J. R. & Koch, G. G. (1977). An application of hierarchical kappa-type statistics in the assessment of majority agreement among multiple observers. *Biometrics,* 33(2), 363-74.
39. Bergamin, M., Gobbo, S., Bullo, V., Zanotto, T., Vendramin, B. & Duregon, F. (2015). Effects of a Pilates exercise program on muscle strength, postural control and body composition: results from a pilot study in a group of post-menopausal women. *Age (Dordr),* 37(6), 118.
40. Kim, S. G., Yong, M. S. & Na, S. S. (2014). The effect of trunk stabilization exercises with a swiss ball on core muscle activation in the elderly. *J Phys Ther Sci,* 26(9), 1473-4.
41. Krist, L., Dimeo, F. & Keil, T. (2013). Can progressive resistance training twice a week improve mobility, muscle strength, and quality of life in very elderly nursing-home residents with impaired mobility? *A pilot study. Clin Interv Aging,* 8:443-8.

42. Petrofsky, J. S., Cuneo, M., Dial, R., Pawley, A. K. & Hill, J. (2005). Core Strengthening and Balance in the Geriatric Population. *The Journal of Applied Research,* 5(3), 423-33.
43. De Vos, N. J., Singh, N. A., Ross, D. A., Stavrinos, T. M., Orr, R. & Fiatarone Singh, M. A. (2005). Optimal load for increasing muscle power during explosive resistance training in older adults. *J Gerontol A Biol Sci Med Sci,* 60(5), 638-47.
44. Granacher, U., Lacroix, A., Muehlbauer, T., Roettger, K. & Gollhofer, A. (2013). Effects of core instability strength training on trunk muscle strength, spinal mobility, dynamic balance and functional mobility in older adults. *Gerontology,* 59(2), 105-13.
45. Hamacher, D., Hamacher, D., Rehfeld, K. & Schega, L. (2016). Motor-cognitive dual-task training improves local dynamic stability of normal walking in older individuals. *Clin Biomech (Bristol, Avon),* 32:138-41
46. Kahle, N., & Tevald, M. A. (2014). Core muscle strengthening's improvement of balance performance in community-dwelling older adults: a pilot study. *J Aging Phys Act,* 22(1), 65-73.
47. Markovic, G., Sarabon, N., Greblo, Z. & Krizanic, V. (2015). Effects of feedback-based balance and core resistance training vs. Pilates training on balance and muscle function in older women: a randomized-controlled trial. *Arch Gerontol Geriatr,* 61(2), 117-23.
48. Sullivan, D. H., Roberson, P. K., Smith, E. S., Price, J. A. & Bopp, M. M. (2007). Effects of muscle strength training and megestrol acetate on strength, muscle mass, and function in frail older people. *J Am Geriatr Soc,* 55(1), 20-8.
49. Villanueva, M. G., Lane, C. J. & Schroeder, E. T. (2015). Short rest interval lengths between sets optimally enhance body composition and performance with 8 weeks of strength resistance training in older men. *Eur J Appl Physiol,* 115(2), 295-308.
50. Wolpert, D. M., Ghahramani, Z. & Flanagan, J. R. (2001). Perspectives and problems in motor learning. *Trends Cogn Sci,* 5(11), 487-94.
51. Phillips, E., Farrow, D., Ball, K. & Helmer, R. (2013). Harnessing and understanding feedback technology in applied settings. *Sports Med,* 43(10), 919-25.
52. Stanmore, E., Stubbs, B., Vancampfort, D., de Bruin, E. D. & Firth, J. (2017). The effect of active video games on cognitive functioning in clinical and non-clinical populations: A meta-analysis of randomized controlled trials. *Neurosci Biobehav Rev,* 78:34-43.
53. Doyon, J. & Benali, H. (2005). Reorganization and plasticity in the adult brain during learning of motor skills. *Curr Opin Neurobiol,* 15(2), 161-7.
54. King, B. R., Fogel, S. M., Albouy, G. & Doyon, J. (2013). Neural correlates of the age-related changes in motor sequence learning and motor adaptation in older adults. *Front Hum Neurosci*, 7:142.

55. Milton, J., Solodkin, A., Hlustik, P. & Small, S. L. (2007). The mind of expert motor performance is cool and focused. *Neuroimage,* 35(2), 804-13.
56. Comerford, M. J. & Mottram, S. L. (2001). Movement and stability dysfunction-contemporary developments. *Man Ther,* 6(1), 15-26.
57. Key, J. (2013). 'The core': understanding it, and retraining its dysfunction. *J Bodyw Mov Ther,* 17(4), 541-59.
58. Anderson, K. & Behm, D. G. (2005). The impact of instability resistance training on balance and stability. *Sports Med,* 35(1), 43-53.
59. Di Fabio, R. P., Zampieri, C., Henke, J., Olson, K., Rickheim, D. & Russell, M. (2005). Influence of elderly executive cognitive function on attention in the lower visual field during step initiation. *Gerontology*, 51(2), 94-107.
60. Anacker, S. L. & Di Fabio, R. P. (1992). Influence of sensory inputs on standing balance in community-dwelling elders with a recent history of falling. *Physical therapy*, 72(8), 575-81, discussion 81-4.
61. Bystrom, M. G., Rasmussen-Barr, E. & Grooten, W. J. (2013). Motor control exercises reduces pain and disability in chronic and recurrent low back pain: a meta-analysis. *Spine (Phila Pa 1976)*, 38(6), E350-8.
62. Hodges, P. W. & Richardson, C. A. (1996). Inefficient muscular stabilization of the lumbar spine associated with low back pain. A motor control evaluation of transversus abdominis. *Spine,* 21(22), 2640-50.
63. Ferreira, P. H., Ferreira, M. L. & Hodges, P. W. (2004). Changes in recruitment of the abdominal muscles in people with low back pain: ultrasound measurement of muscle activity. *Spine (Phila Pa 1976),* 29(22), 2560-6.
64. Hides, J. A., Lambrecht, G., Richardson, C. A., Stanton, W. R., Armbrecht, G. & Pruett, C. (2011). The effects of rehabilitation on the muscles of the trunk following prolonged bed rest. *Eur Spine J,* 20(5), 808-18.

Dickx, N., Cagnie, B., Parlevliet, T., Lavens, A. & Danneels, L. (2010). The effect of unilateral muscle pain on recruitment of the lumbar multifidus during automatic contraction. An experimental pain study. *Man Ther,* 15(4), 364-9.

65. Tsao, H., Galea, M. P. & Hodges, P. W. (2008). Reorganization of the motor cortex is associated with postural control deficits in recurrent low back pain. *Brain,* 31(Pt 8), 2161-71.
66. Clark, B. C. & Manini, T. M. (2008). Sarcopenia =/= dynapenia. *J Gerontol A Biol Sci Med Sci,* 63(8), 829-34.
67. Clark, B. C., Taylor, J. L., Hong, S. L., Law, T. D. & Russ, D. W. (2015) Weaker Seniors Exhibit Motor Cortex Hypoexcitability and Impairments in Voluntary Activation. *J Gerontol A Biol Sci Med Sci,* 70(9), 1112-9.
68. Tian, Q., Chastan, N., Bair, W. N., Resnick, S. M., Ferrucci, L. & Studenski, S. A. (2017). The brain map of gait variability in aging, cognitive impairment and dementia-A systematic review. *Neurosci Biobehav Rev,* 74(Pt A), 149-62.
69. O'Connor, S. R., Tully, M. A., Ryan, B., Bradley, J. M., Baxter, G. D. & McDonough, S. M. (2015). Failure of a numerical quality assessment scale to identify potential risk of bias in a systematic review: a comparison study. *BMC Res Notes,* 8:224

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