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Effects of Wearable Sensor-Based Balance and Gait Training on Balance, Gait, and Functional Performance in Healthy and Patient Populations: A Systematic Review and Meta-Analysis of Randomized Controlled Trials

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Keywords

Inertial measurement unit · Force sensor · Postural balance · Gait · Biofeedback · Exergame · Systematic review

Abstract

Background: Wearable sensors (WS) can accurately measure body motion and provide interactive feedback for supporting motor learning. ***Objective:*** This review aims to summarize current evidence for the effectiveness of WS training for improving balance, gait and functional performance. ***Methods:*** A systematic literature search was performed in PubMed, Cochrane, Web of Science, and CINAHL. Randomized controlled trials (RCTs) using a WS exercise program were included. Study quality was examined by the PEDro scale. Meta-analyses were conducted to estimate the effects of WS balance training on the most frequently reported outcome parameters. ***Results:*** Eight RCTs were included (Parkinson n = 2, stroke n = 1, Parkinson/stroke n = 1, peripheral neuropathy n = 2, frail older adults n = 1, healthy older adults n = 1). The sample size ranged from n = 20 to 40. Three types of training paradigms were used: (1) static steady-state balance training, (2) dynamic steady-state balance training, which includes gait training, and (3) proactive balance training. RCTs either used one type of training paradigm (type 2: n = 1, type 3: n = 3) or combined different types of training paradigms within their intervention (type 1 and 2: n = 2; all types: n = 2). The meta-analyses revealed significant overall effects of WS training on static steady-state balance outcomes including mediolateral (eyes open: Hedges' g = 0.82, CI: 0.43–1.21; eyes closed: g = 0.57, CI: 0.14–0.99) and anterior-posterior sway (eyes open: g = 0.55, CI: 0.01–1.10; eyes closed: g = 0.44, CI: 0.02–0.86). No effects on habitual gait speed were found in the meta-analysis (g = –0.19, CI: –0.68 to 0.29). Two RCTs reported significant improvements for selected gait variables including single support time, and fast gait speed. One study identified effects on proactive balance (Alternate Step Test), but no effects were found for the Timed Up and Go test and the Berg Balance Scale. Two studies reported positive results on feasibility and usability. Only one study was performed in an unsupervised setting. ***Conclusion:*** This review provides evidence for a positive effect of WS training on static steady-state balance in studies with usual care controls and studies with conventional balance training controls. Specific gait parameters and proactive balance measures may also be improved by WS training, yet limited evidence is available. Heterogeneous training paradigms, small sample sizes, and short intervention durations limit the validity of our findings. Larger studies are required for estimating the true potential of WS technology.

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Background

Several diseases as well as the advancement of age can adversely affect postural control [1, 2]. Limited balance ability can have considerable consequences on physical functioning in everyday life and constitutes a leading risk factor for falls [3]. Balance and gait training are together considered to be an important aspect of fall prevention [4]. Several studies have demonstrated the positive effects of conventional exercise training for gait and balance [5]. Incorporating technology such as wearable sensors (WS) has been repeatedly discussed as a promising option for improving balance and gait training regimes [6–8]. WS capabilities include physiological (e.g., muscle activity), biochemical (e.g., blood composition) and motion sensing (e.g., joint movement) systems [9]. This review focuses on WS technology for motion sensing by measuring kinetic or kinematic motion data during balance and/or gait training either with inertial measurement units (IMUs) measuring velocity, acceleration, and direction of body movements [8] or with wearable plantar pressure sensors [10].

WS training can have several advantages in comparison with conventional training, including targeted intervention in an interactive environment, immediate and sensitive feedback about the user's performance, a motivating effect due to game-based features, and the option for virtually supervised home exercises [7, 11, 12].

WS-based immediate external feedback about movement performance and motor errors may enhance motor learning and facilitate the successful execution of daily tasks. Studies suggest that focusing on movement results is more effective for motor learning than focusing on movement performance [13]. Augmenting movement results with external feedback can supplement internal feedback and serve as a "sixth sense" [7]. This seems to be particularly important for patients with an impaired internal feedback, for instance those related to polyneuropathy, stroke or Parkinson's disease (PD) [7]. Consequently, a WS training approach may provide advantages for these patient groups.

WS systems also have practical advantages. Unlike commercial camera systems such as Kinect, WS systems do not require a continuous sightline, enabling the user to use a chair in front to receive support during exercising. Such safety features are of the utmost importance, particularly under unsupervised conditions [14]. Other balance training technologies such as force platforms restrict the base of support which may increase risk of falling [15]. In contrast, WS training allows the possibility of standing naturally or walking on the ground. The small size of WS enables joint motion measurements at various body segments in order to provide real-time feedback for the user [16].

Table 1. Search strategy

	Sensor [tiab] OR sensors [tiab] OR "inertial measurement unit" [tiab] OR "IMU" [tiab] OR Accelerometry [mh] OR acceleromet* [tiab] OR gyroscope* [tiab] OR magnetometer* [tiab]
AND	"Postural balance" [mh] OR Balanc* [tiab] OR posture [mh] OR postur* [tiab] OR gait [mh] OR gait [tiab] OR walking [mh] OR walk* [tiab] OR Proprioception [mh:noexp] OR propriocepti* [tiab] OR sensorimotor [tiab] OR neuromuscular [tiab]
	Training[tw] OR program*[tw] OR exercise*[tw] OR "exercise" [mh] OR intervention* [tiab]
	Randomized controlled trial [pt] OR "randomized controlled trials as topic" [mh] OR random* [tiab]

In summary, WS systems seem to have several advantages when compared with conventional training and other technologies, which make these devices interesting and promising for clinical applications. Overview articles have repeatedly discussed the potential of WS training paradigms for improving clinically relevant motor performances such as postural stability or gait, which are important for safe ambulation and mobility-related quality of life [7, 9, 17]. However, to our knowledge, a systematic review and meta-analysis of WS balance and gait training programs does not exist.

The objectives of this systematic review of randomized controlled trials (RCTs) were: (1) to describe the characteristics of currently published WS training paradigms in terms of sensor placements, training modalities, and types of sensor feedback; (2) to estimate the effect of WS balance and gait training on balance, gait and functional performance in comparison with conventional training or usual care in patient populations and healthy adults; and (3) to evaluate the feasibility of and adherence to WS training.

Methods

Search Strategy

The review was performed according to the PRISMA statement and registered at PROSPERO (CRD42016049323) [18]. PubMed, the Cumulative Index to Nursing and Allied Health Literature (CINAHL), Web of Science, and the Cochrane Central Register of Controlled Trials have been searched for articles with publication dates between January 2006 and June 2016 (English and German language). Relevant search terms were combined with Boolean operators (OR/AND) (Table 1, online suppl. Table S1; for all online

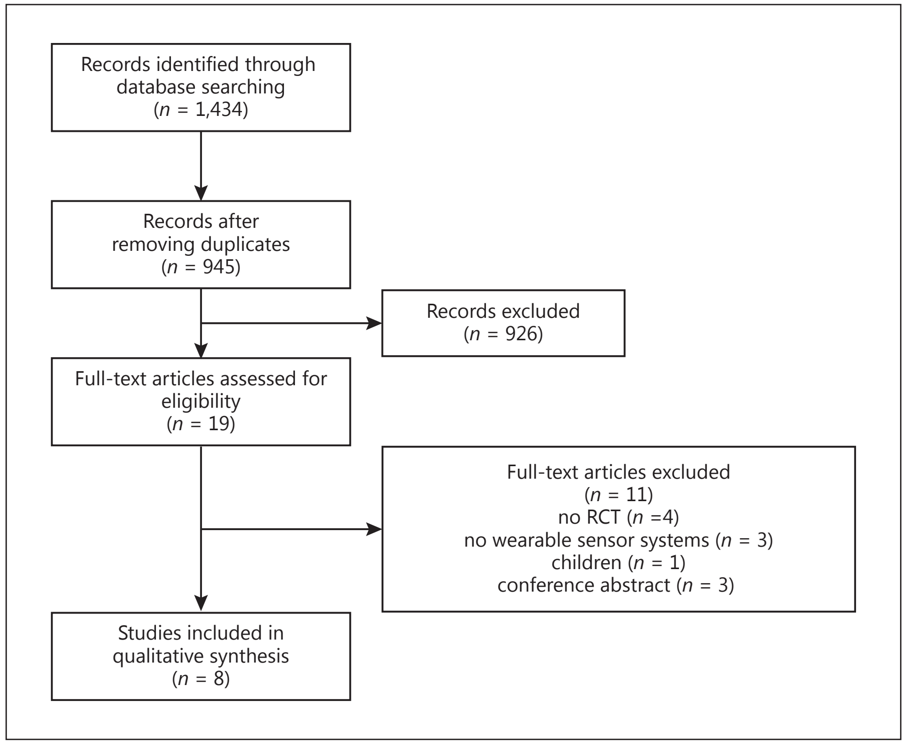

Fig. 1. Flowchart of the process of literature search and extraction of studies meeting the inclusion criteria.

suppl. material, see www.karger.com/doi/10.1159/000481454). Reference lists of relevant articles were subsequently searched by hand in order to identify additional relevant papers. Inclusion criteria were: (1) participants: healthy adults or patients; (2) intervention: WS balance and/or gait training; (3) comparators: conventional balance and/or gait training, usual care; (4) outcomes: balance, gait, functional performance; and (5) study design: RCT. WS was defined as any kind of motion sensor device attached to the participant's body that measured kinetic or kinematic motion data [10], including IMUs (also smartphone-based) and wearable plantar pressure sensors. Excluded from this review were studies using WS sensors for measuring physiological (e.g., muscle activity) or biochemical outcomes [9].

Study Selection and Data Extraction

Study selection was performed by 2 independent reviewers (K.G., T.G.). In the case of disagreements, the articles were discussed with the other authors. Titles and abstracts of retrieved references were screened for inclusion and the full texts of potential articles were further analyzed to determine whether they met the inclusion criteria. Case reports, letters, and systematic reviews were excluded. After inclusion, the study characteristics, research goals, and main findings with respect to balance, gait, and functional performance were extracted and summarized.

Study quality was assessed using the PEDro scale [19]. Studies scoring 9–10 were classified as excellent, 6–8 as good, 4–5 as fair, and less than 4 as poor quality [20].

In the present study, we have used the balance framework of Shumway-Cook and Woollacott [21] to categorize training paradigms and outcome measures. According to Shumway-Cook and Woollacott [21], balance is a complex composite of multiple body systems including the ability to align different body segments and to generate multi-joint movements to effectively control the body position and movement. Balance is highly task-specific and can be categorized into static steady-state balance (i.e., maintaining a steady position in sitting or standing), dynamic steady-state balance (i.e., walking), proactive balance (i.e., anticipating a predicted disturbance such as crossing or walking around an obstacle), and reactive balance (i.e., compensating a disturbance). Training paradigms identified in the present study were linked to the specific categories of the Shumway-Cook and Woollacott framework in the results section. Likewise, outcome parameters reported in the articles included in this review were classified according to the Shumway-Cook and Woollacott model as follows: the category static steady-state balance included measures of postural sway obtained during quiet standing (e.g., center of mass sway), the category dynamic steady-state balance included measures of gait (e.g., habitual gait speed, spatiotemporal gait parameters), and the category proactive balance included measures analyzing the anticipation of a predicted disturbance (e.g., Timed up and Go test [22], Alternate Step Test [23]). No reactive balance measurements were used in the articles included. Results of balance test batteries are reported in a separate section.

In order to compute the effect of WS training compared with controls, random-effect meta-analyses on the most frequently reported outcome parameters for static steady-state balance, dynamic steady-state balance, and proactive balance were applied [21]. No study reported on reactive balance. The outcome of the meta-analyses was Hedges' g (g) calculated as $g = [1 - 3/(4(n_1 + n_2 - 2) - 1)] \times [(mean_1 - mean_2)/\text{standard deviation}_{\text{within groups}}]$ [24]. A positive g-value indicates improvements in favor of the intervention group. g-values between 0.00 and 0.49 indicate small, 0.50–

0.79 medium, and ≥0.80 large effects [25]. Heterogeneity was assessed using Cochran's Q and I^2 (Cochran's $Q < 0.05$, $I^2 > 75\%$) [26]. Q was calculated to determine whether a weighted mean effect size characterized a common effect size. According to the Cochrane recommendations, it is not recommended to test for funnel plot asymmetry when there are fewer than 10 studies in a meta-analysis [26]. The meta-analyses were performed using Comprehensive Meta-Analysis V3 (version 3.3.070).

Results

In total, 1,434 potentially relevant articles were found (Fig. 1). After removing duplicates, 945 article titles and abstracts were screened for relevance. Nineteen full texts were further checked for suitability, of which 8 were finally included. Table 2 illustrates study characteristics, types of training paradigms, WS configuration, type of feedback, training modalities, and results.

Study Characteristics

RCTs were performed in patients with PD (n = 2) [27, 28], stroke (n = 1) [29], PD/stroke (n = 1) [30], peripheral neuropathy, either relating to diabetes (n = 1) [31] or chemotherapy (n = 1) [32], and healthy (n = 1) [33], or frail older adults with confirmed fall risk (n = 1) [14]. The average age of the samples ranged from 52.1 to 84.9 years. Sample sizes ranged from 20 to 40. Dropouts were reported in 5 studies with similar rates in WS and control group [14, 27, 29, 31, 32]. One unsupervised study reported 1 dropout specifically relating to handling problems with the WS system [27].

The median PEDro score for all RTCs included was 7 points (out of maximum of 10 points, range 4–8) (Table 3). The majority of the studies were rated as "good" (score 6–8), and 1 study was rated as "fair quality" (score 4–5). The most frequent methodological limitations were a lack of blinding of subjects or study personnel, as well as unconcealed group allocation. One study did not report any inclusion/exclusion criteria and lacked in a between-group comparison statistics [33].

WS Training Paradigms Used

Types and Placements of WS

Six studies used IMUs (incorporating accelerometers, gyroscopes, and magnetometers) [14, 27, 28, 31–33], of which 3 studies used 5 IMUs (1 at the lower back, 1 at each shank, 1 at each thigh) [14, 31, 32], 1 study used 2 IMUs (1 on each shoe) [27], and 2 studies used 1 IMU at the lower back [28, 33]. One study used wearable plantar pressure sensors [29] and another one combined wearable plantar pressure sensors and IMUs [30] (Table 2). IMUs were used for measuring kinematic data of body segments in order to provide feedback about center of mass [14, 28, 31–33] or lower extremity movement [14, 27, 30–32]. Wearable plantar pressure sensors were used to cue weight symmetry distribution between feet while standing (i.e., % body weight loading on the paretic leg) or weight variation during stance phase while walking (i.e., single support time asymmetry ratio) [29, 30]. In all studies, the information from sensors was translated into a visual, audio, vibratory, or combination of 2 or more feedbacks. These feedbacks were used to assist users to better perceive motor errors and/or to improve accuracy of execution of each exercise task, as described below.

Types and Modalities of Exercise Interventions

Intervention duration ranged from 1 day (one session) to 8 weeks (15 sessions in total) (Table 2). Training frequency ranged from 2 to 5 times per week. In 5 studies, the controls received the same training as the intervention group, however without WS feedback [27–30, 33]. In 3 studies, the controls received routine care only [14, 31, 32]. According to the framework of Shumway-Cook and Woollacott [21], training paradigms used in RCTs were subdivided into the following 3 categories:

(a) Static steady-state balance training. Four studies used static stance tasks for balance training [28–30, 33]. The level of the task challenge was increased by reducing the base of support and increasing sensorimotor demand (i.e., by standing with feet together, on one leg, with eyes open or closed). During training, either the postural sway was measured by IMUs [28, 33] or the weight distribution was measured by wearable plantar pressure sensors [29, 30].

(b) Dynamic steady-state balance training. Four studies used progressively challenging walking tasks including normal walking, walking with a reduced base of support, or with additional sensorimotor tasks such as turning the head [28–30, 33]. One study used regular walking [27]. During training, postural sway was measured by IMUs [28, 33]. Gait parameters were measured either by IMUs [27] or by wearable plantar pressure sensors [29, 30].

(c) Proactive balance training. Five studies used weight distribution tasks for proactive balance training [14, 29–32]. These tasks included leaning forwards, backwards and sideways repeatedly. In 3 studies, participants had to navigate a cursor towards different targets on the screen by leaning the body appropriately. During training, either the leaning angle was measured by IMUs [14, 31, 32] or

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Table 2. Study characteristics

First author [Ref.], year	Aim	Sample	Intervention	Sensor type and placement	Type of feedback	Training modalities	Assessment time points	Results	
Inactive control group									
Grewal [31], 2015	To investigate the effect of WS interactive balance training on postural stability	*n* = 35 Diabetic patients with peripheral neuropathy IG: *n* = 19 Mean age: 62.6±7.9 years Female: *n* = 11 (57.9%) CG: *n* = 16 Mean age: 64.9±8.5 years Female: *n* = 8 (50.0%)	IG: WS tasks: – ankle point-to-point reaching task – virtual obstacle-crossing task CG: no training intervention	IMUs: – shank (right, left) – thigh (left, right) – lower back	Auditory Visual	D: 4 weeks T: 45 min F: 2×/week	Baseline Posttest	Balance: EO: – CoM sway area – CoM sway (ML) –CoM sway (AP) –hip sway – ankle sway EC: – CoM sway area – CoM sway (ML) – CoM sway (AP) – hip sway – ankle sway FES-I SF-12: mental score physical score	 ↓ ↓ – ↓ ↓ – – – – ↓ – ↑ –
Schwenk [14], 2014	To evaluate the effectiveness and user experience of a WS balance training program	*n* = 31 Older adults living in a senior living community IG: *n* = 17 Mean age: 84.3±7.3 years Female: *n* = 10 CG: *n* = 16 Mean age: 84.9±6.6 years Female: *n* = 11	IG: WS tasks: – ankle point-to-point reaching task – virtual obstacle-crossing task CG: no training intervention	IMUs: – shank (right, left) – thigh (left, right) – lower back	Auditory Visual	D: 4 weeks T: 45 min F: 2×/week	Baseline Posttest	Balance: EO: – CoM sway area – CoM sway (ML) – CoM sway (AP) – hip sway – ankle sway EC: – CoM sway area – CoM sway (ML) – CoM sway (AP) – hip sway – ankle sway Alternate Step Test Timed Up and Go Gait: normal: – gait speed – gait variability fast: – gait speed – gait variability	 ↓ ↓ ↓ ↓ ↓ ↓ ↓ – ↓ ↓ ↑ ↑ – – ↑ –

Table 2 (continued)

First author [Ref.], year	Aim	Sample	Intervention	Sensor type and placement	Type of feedback	Training modalities	Assessment time points	Results
Schwenk [32], 2016	To investigate the effect of an interactive WS motor adaption balance training program	n = 22 Cancer patients with chemotherapy induced peripheral neuropathy IG: n = 11 Mean age: 68.7±8.7 years Female: n = 7 (63.6%) CG: n = 11 Mean age: 71.8±8.9 years Female: n = 6 (54.4%)	IG: WS tasks: – ankle point-to-point reaching task – virtual obstacle-crossing task CG: no training intervention	IMUs: – shank (right, left) – thigh (left, right) – lower back	Auditory Visual	D: 4 weeks T: 45 min F: 2×/week	Baseline Posttest	Balance: EO, feet closed: – CoM sway (ML) ↓ – CoM sway (AP) – – hip sway ↓ – ankle sway ↓ EO, semi-tandem: – CoM sway (ML) ↓ – CoM sway (AP) ↓ – hip sway ↓ – ankle sway – EC, feet closed: – CoM sway (ML) – – CoM sway (AP) – – hip sway – – ankle sway – Gait: – gait speed – – gait variability – FES-I –
Active control group								
Byl [30], 2015	To evaluate the effectiveness of a supervised gait training with and without visual kinematic biofeedback to improve mobility, balance, strength and flexibility	n = 24 Patients with stroke or PD IG: n = 12 Stroke: n = 5 Mean age: 66.2±5.0 years Female: n = 3 PD: n = 7 Mean age: 68.5±3.6 years Female: n = 4 CG: n = 12 Stroke: n = 7 Mean age: 60.8±5.4 years Female: n = 5 PD: n = 5 Mean age: 70.0±2.9 years Female: n = 1	IG: WS tasks: – sit-to stand – walk – walk + dual task – stairs – plyometric activities – integrated strength training – integrated flexibility activities CG: same tasks as IG but without WS feedback	Smart shoes: – toe – 1, 2, 4, 5 metatarsophalangeal joint – heel IMUs: – shank (left, right) – thigh (left, right)	Visual	D: 6–8 weeks T: 45 min F: 2×/week + daily walking at home	Baseline Posttest	Gait: – gait speed-10 m – – step length – – 6-min walk – – Dynamic Gait Index – – Tinetti Gait assessment – – Timed Up and Go – – Berg Balance scale – – strength – – range of motion –
Ginis [27], 2016	To test the feasibility and effects of WS home-based training vs. conventional home-based gait training on gait, balance and quality of life	n = 40 Patients with PD IG: n = 20 Mean age: not specified Female: not specified CG: n = 18 Mean age: not specified Female: not specified	IG: WS tasks: walking with audio-biofeedback-gait-app Patients with freezing of gait: Freezing-of-Gait-cue app CG: same tasks as IG but without WS feedback	Two IMUs (on the shoes) + Smartphone	Auditory	D: 6 weeks T: 30 min F: min. 3×/week	Baseline Posttest 1: immediately after the intervention Posttest 2: 4 weeks after the intervention	Gait: – gait speed – – stride length – – double support time – Dual task gait: – gait speed – – stride length – – double support time – Balance: – MiniBESTest ↑ –Four Square Step Test – – FES-I – Physical capacity: – 2-min walk test – – Physical Activity scale for the elderly – SF-36 ↑

Table 2 (continued)

First author [Ref.], year	Aim	Sample	Intervention	Sensor type and placement	Type of feedback	Training modalities	Assessment time points	Results	
Lim [33], 2016	To determine if multi-session balance training with and without biofeedback leads to changes in balance performance	n = 36 Healthy community-dwelling older adults IG: n = 18 Mean age: 69±7 years Female: n = 11 CG: n = 18 Mean age: 70±6 years Female: n = 14	IG: WS tasks: Stance tasks: – 1-leg-stance, EO – stand feet together, EC, firm surface – stand feet together, EC, foam – tandem stance, EC Walking tasks: – walking 8 m – walking 8 m turning head from side to side – 8 tandem steps, EC CG: same tasks as IG but without WS feedback	IMUs: – lower back	Vibrotactile Auditory Visual	D: 2 weeks T: not specified F: 3×/week	Baseline Posttest 1: immediately after the 3rd training session Posttest 2: immediately after the intervention Posttest 3: 1 week after the intervention Posttest 4: 1 month after the intervention	Balance 1-leg, EO: CoM angle (ML) CoM angle (AP) EC: CoM angle (ML) CoM angle (AP) EC on foam: CoM angle (ML) CoM angle (AP) Tandem, EC: CoM angle (ML) CoM angle (AP) Task duration Gait: Walk 8 m: CoM angle (ML) CoM angle (AP) Task duration Walk Head turn: CoM angle (ML) CoM angle (AP) Task duration 8 tandem steps: CoM angle (ML) CoM angle (AP) Task duration	 – – – – ↓ ↓ – – ↑ – ↑ ↓ – – – ↓ ↓ ↓
Nanhoe-Mahabier [28], 2012	To investigate the short-term carry-over effects of one training session involving WS real-time vibrotactile biofeedback	n = 20 Patients with PD IG: n = 10 Mean age: 59.3±2.0 years Female: n = 2 (20%) CG: n = 10 Mean age: 58.6±2.5 years Female: n = 2 (20%)	IG: WS tasks: – standing feet together, EC – standing on one leg, EO – tandem stance, EC – standing feet together, EC, on foam – walking 9 m at preferred speed, EO – 15 tandem steps, EC CG: same tasks as IG but without WS feedback	IMUs: – lower back (L1, L3)	Vibrotactile	D: not specified T: not specified F: one training session	Baseline Posttest	Balance: – CoM sway (ML) – CoM sway (AP) – sway angular velocity (ML) – sway angular velocity (AP) Gait: – CoM sway (ML) – CoM sway (AP) – sway angular velocity (ML) – sway angular velocity (AP) Untrained tasks: – CoM sway (ML) – CoM sway (AP) – sway angular velocity (ML) – sway angular velocity (AP)	 – – – ↓ ↓ – – – – – – ↓

Table 2 (continued)

First author [Ref.], year	Aim	Sample	Intervention	Sensor type and placement	Type of feedback	Training modalities	Assessment time points	Results	
Sungkarat [29], 2011	To determine whether external feedback of weight distribution during standing and walking improves gait and balance performance	n = 35 Patients with stroke IG: n = 18 Mean age: 53.8±11.2 years Female: n = 6 CG: n = 17 Mean age: 52.1±7.2 years Female: n = 5	IG: WS tasks: Gait retraining: – weight-bearing/-shifting – stepping – strengthening of the lower extremities – walking over ground with/without manual + verbal guidance Conventional stroke rehabilitation: – neuromuscular facilitation technique – therapeutic exercises – balance – functional training CG: same tasks as IG but without WS feedback	Nonparetic shoe: – Insole shoe Wedge – foot switch Paretic shoe: – pressure sensor	Auditory	D: 3 weeks T: 60 min F: 5×/week	Baseline Posttest	Gait: – gait speed – step length – single support time – Berg Balance scale – Timed Up and Go – loading on paretic leg during stance	 ↑ – ↑ – – ↑

AP, anterior-posterior; CG, control group; CoM, centre of mass; D, duration; EC, eyes closed; EO, eyes open; F, frequency; FES-I, falls efficacy scale-international version; IG, intervention group; IMU, inertial measurement unit; L, lumbar vertebra; ML, medio-lateral; SF, short form health survey; T, time bout; WS, wearable sensor; PD, Parkinson's disease.

the weight bearing was measured by wearable plantar pressure sensors [29, 30]. The above-mentioned studies additionally used obstacle-avoidance tasks. In 3 studies participants had to cross virtual obstacles appearing on a screen [14, 31, 32], and IMUs attached to shanks, thighs, and lower back measured lower extremity motion including height and length of the step while crossing the obstacle. Different obstacle heights including 5, 10 and 15% of the leg length were practiced alternately with the left or the right foot. In 2 other studies, participants had to step over differently-sized obstacles [29, 30].

One of these studies additionally used strengthening, stretching (heel cord, hip, and hamstrings), plyometric activities (jumping), and walking up and down a set of stairs [30]. Training was completed indoors and outdoors, over ground and on the treadmill. No study included could be categorized as reactive balance training.

WS Real-Time Feedback Provided during Training

Different types of feedback were provided by WS, depending on the training paradigm used:

(a) Static steady-state balance training. Corrective feedback about postural sway was provided either by lights mounted on a headband [30, 33], by acoustic transducers [29, 33], or by vibrating sensors [28, 33], when postural sway exceeded the predetermined threshold during baseline assessment.

(b) Dynamic steady-state balance training. A study in PD and poststroke patients provided positive and corrective visual feedback about foot loading, step length, and stride widths during walking, which was projected onto a screen [30]. An engineer and a therapist helped the participants to interpret the visual feedback. A study in stroke patients provided positive auditory feedback for each successful trial relating to the amount of weight bearing on the paretic leg and the duration of the swing phase of the nonparetic limb [29]. A study in PD patients using a smartphone app provided positive verbal feedback when gait speed and stride length remained within an individually predetermined range (±5% of the median value of a supervised reference walk of the respective participant) and corrective verbal feedback when parameters fell outside of this range. Furthermore, auditory cues during walking were provided when freezing of gait was detected [27]. Another study in PD patients provided corrective feedback using vibrotactile sensors mounted on a headband if postural sway during walking fell outside the predetermined range, which was derived during the baseline assessment [28]. One study combined feedback [33].

Table 3. Results of the quality scoring using the PEDro scale

	Byl et al. [30], 2015	Ginis et al. [27], 2016	Grewal et al. [31], 2015	Lim et al. [33], 2016	Nanhoe-Mahabier et al. [28], 2012	Schwenk et al. [14], 2014	Schwenk et al. [32], 2016	Sungkarat et al. [29], 2011
Eligibility criteria specified	×	×	×	–	×	×	×	×
Random allocation	×	×	×	×	×	×	×	×
Concealed allocation	–	–	×	–	–	×	×	×
Groups similar at baseline	×	×	×	–	×	×	×	×
Subject blinding	–	–	–	–	–	–	–	–
Therapist blinding	–	–	–	–	–	–	–	–
Assessor blinding	–	–	×	–	–	×	×	×
Less than 15% dropouts	×	×	×	×	×	×	×	×
Intention-to-treat analysis	×	×	×	×	×	×	×	×
Between-group statistical comparison	×	×	×	×	×	×	×	×
Point measures and variability data	×	×	×	×	×	×	×	×
Sum score	6	6	8	4	6	8	8	8

×, criterion is evidenced in article; –, criterion is not evidenced, not applicable, not coded, or could not be determined in article.

(c) Proactive balance training. Studies using leaning tasks included both positive visual (circle exploded) and auditory (positive sound) feedback for each correct execution, which was provided on a computer [14, 31, 32]. Additionally, corrective visual feedback (if circle changed color) was provided if the exercise was executed too slowly. Two other studies using leaning tasks provided feedback about weight distribution either visually (with the help of different colors on a screen) [30] or auditory (i.e., through an audio signal) for each successful trial [29]. For obstacle-avoidance tasks, a lower-extremity avatar provided visual feedback about the height and length of the step and whether the obstacle was negotiated. Additionally, audio feedback about crossing or hitting the obstacle was provided [14, 31, 32].

Training Effects

Effects on Static Steady-State Balance Measures

Four studies compared training effects on postural sway while standing with eyes open between the WS and the control group [14, 28, 31, 32] (Table 2). A meta-analysis of these studies revealed a significant overall effect of WS training when compared with controls on mediolateral sway during standing with eyes open (g = 0.82, CI: 0.43–1.21; Fig. 2) and eyes closed (g = 0.57, CI: 0.14–0.99; Fig. 3). Likewise, the meta-analysis for anterior-posterior sway also showed significant effects for eyes open (g = 0.55, CI: 0.01–1.10; Fig. 4) and eyes closed (g = 0.44, CI: 0.02–0.86; Fig. 5). Homogeneity criteria were met for all the analyses (Q = 0.35–1.51, p = 0.12–0.84, I^2 = 0.00–47.82%). Effects were present for studies comparing WS training to usual care [14, 31, 32] and to conventional training [28]. Effects were found in studies using proactive training paradigms [14, 31, 32] and in the study which combined static and dynamic steady-state balance training paradigms [28] (Fig. 2–5). All studies used IMUs.

One study in healthy older reported a significant pre-post reduction in postural sway while standing on foam with eyes closed in the WS group [33]. However, between-group differences were not reported. One study in PD patients specifically evaluated the transfer from trained to untrained steady-state balance tasks [28]. A significantly greater decrease in sway angular velocity in anterior-posterior direction was found in the WS group in comparison with the controls.

All of the above mentioned effects were measured immediately after the intervention. One study in healthy older adults performing a follow-up measurement after 1 week and 1 month did not report effects [33]. In this study, results were reported in a bar chart, but no exact values were provided in the text or tables. Since authors did not respond to our request to provide these data, we were unable to calculate effect sizes.

Effects on Dynamic Steady-State Balance Measures

Seven RCTs evaluated training effects on gait performances by reporting on different gait parameters [14, 27–32] (Table 2). A meta-analysis including 5 studies did not reveal an overall effect on habitual gait speed (g = –0.19, CI: –0.68 to 0.29) (Fig. 6) [14, 27, 29, 30, 32]. The homo-

Study	Control group type	Training paradigm	Type of sensor	Control group, *n*	Intervention group, *n*	Effect size: Hedges' *g*	SE	95% CI	Weight, %
Nanhoe-Mahabier et al. [28]	active	stat., dyn.	IMUs	10	10	1.34	0.48	0.40, 2.27	17.4
Grewal et al. [31]	inactive	proactive	IMUs	16	19	0.63	0.34	–0.04, 1.30	34.4
Schwenk et al. [14]	inactive	proactive	IMUs	15	15	0.79	0.37	0.07, 1.52	29.1
Schwenk et al. [32]	inactive	proactive	IMUs	10	9	0.75	0.46	–0.15, 1.64	19.2
Overall				**51**	**53**	**0.82**	**0.20**	**00.43, 1.21**	**100**
Heterogeneity: $Q = 1.51$ ($p = 0.68$) $I^2 = 0.00\%$									

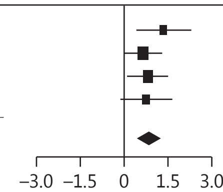

Fig. 2. Effects of wearable sensor-based balance and gait training on mediolateral sway with eyes open.

Study	Control group type	Training paradigm	Type of sensor	Control group, *n*	Intervention group, *n*	Effect size: Hedges' *g*	SE	95% CI	Weight, %
Grewal et al. [31]	inactive	proactive	IMUs	16	19	0.42	0.34	–0.24, 1.08	41.9
Schwenk et al. [14]	inactive	proactive	IMUs	15	15	0.65	0.36	–0.07, 1.36	35.3
Schwenk et al. [32]	inactive	proactive	IMUs	10	9	0.72	0.45	–0.17, 1.61	22.8
Overall				**41**	**43**	**0.57**	**0.22**	**00.14, 0.99**	**100**
Heterogeneity: $Q = 0.35$ ($p = 0.84$) $I^2 = 0.00\%$									

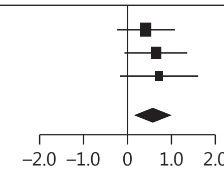

Fig. 3. Effects of wearable sensor-based balance and gait training on mediolateral sway with eyes closed.

Study	Control group type	Training paradigm	Type of sensor	Control group, *n*	Intervention group, *n*	Effect size: Hedges' *g*	SE	95% CI	Weight, %
Nanhoe-Mahabier et al. [28]	active	stat., dyn.	IMUs	10	10	1.32	0.48	0.39, 2.25	20.5
Grewal et al. [31]	inactive	proactive	IMUs	16	19	0.06	0.33	–0.59, 0.71	29.9
Schwenk et al. [14]	inactive	proactive	IMUs	15	15	0.79	0.37	0.07, 1.08	27.1
Schwenk et al. [32]	inactive	proactive	IMUs	10	9	0.22	0.44	–0.64, 1.08	22.5
Overall				**51**	**53**	**0.55**	**0.28**	**0.01, 1.10**	**100**
Heterogeneity: $Q = 5.74$ ($p = 0.12$) $I^2 = 47.82\%$									

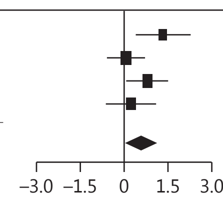

Fig. 4. Effects of wearable sensor-based balance and gait training on anterior-postural sway with eyes open.

geneity criteria were met ($Q = 8.62$, $p = 0.07$, $I^2 = 53.59\%$). Figure 6 suggests that negative effects were not related to a specific type of training paradigm or the sensor type that was used.

Single studies reported that WS training led to significant improvements of specific gait parameters, including single support time and loading on the paretic leg in post-stroke patients [29], decreased mediolateral postural sway during walking in PD patients [28], and fast gait speed in healthy older [14]. No effects were found for the freezing of gait in patients with PD [27].

Another study in PD patients evaluating the transfer from trained to untrained gait tasks reported a significantly greater decrease in anterior-posterior sway angular

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Study	Control group type	Training paradigm	Type of sensor	Control group, *n*	Inter-vention group, *n*	Effect size: Hedges' *g*	SE	95% CI	Weight, %
Grewal et al. [31]	inactive	proactive	IMUs	16	19	0.22	0.33	–0.44, 0.87	42.0
Schwenk et al. [14]	inactive	proactive	IMUs	15	15	0.53	0.36	–0.18, 1.24	35.5
Schwenk et al. [32]	inactive	proactive	IMUs	10	9	0.73	0.45	–0.16, 1.62	22.5
Overall				**41**	**43**	**0.44**	**0.20**	**00.02, 0.86**	**100**
Heterogeneity: $Q = 0.35$ ($p = 0.84$) $I^2 = 0.00\%$									

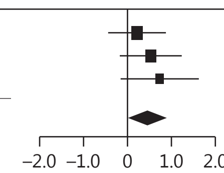

Fig. 5. Effects of wearable sensor-based balance and gait training on anterior-postural sway with eyes closed.

Study	Control group type	Training paradigm	Type of sensor	Control group, *n*	Inter-vention group, *n*	Effect size: Hedges' *g*	SE	95% CI	Weight, %
Byl et al. [30]	active	stat., dyn., pro.	IMUs + force sensors	12	11	0.00	0.40	–0.79, 0.79	18.6
Ginis et al. [27]	active	dynamic	IMUs	18	20	0.05	0.32	–0.57, 0.67	22.9
Schwenk et al. [14]	inactive	proactive	IMUs	15	15	–0.51	0.36	–1.25, 0.20	20.6
Schwenk et al. [32]	inactive	proactive	IMUs	10	9	0.19	0.46	–0.15, 1.72	16.3
Sungkarat et al. [29]	active	stat., dyn., pro.	pressure sensors	18	17	–0.76	0.34	–1.43, –0.09	21.7
Overall				**73**	**72**	**–0.19**	**0.25**	**–0.68, 0.29**	**100**
Heterogeneity: $Q = 0.24$ ($p = 0.63$) $I^2 = 53.59\%$									

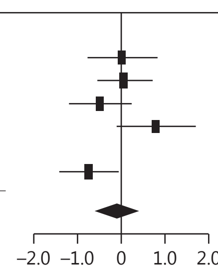

Fig. 6. Effects of wearable sensor-based balance and gait training on gait speed.

velocity in the WS group in comparison with the controls [28]. One study did not find effects after a 4-week follow-up assessment [27].

Effects on Proactive Balance Measures

Three studies measured the effects on proactive balance function using the Timed Up and Go test [14, 29, 30]. A meta-analysis of these studies did not reveal a significant effect ($g = –0.40$, CI: –0.81 to 0.02, $Q = 1.78$, $p = 0.41$, $I^2 = 0.00\%$, online suppl. Fig. S2). Online Figure S2 suggests that negative results were not related to a specific training paradigm, type of control group or sensor type that was used. One study found significant improvements in the Alternate Step Test by WS training when compared to usual care [14].

Effects on Balance Test Batteries

Two RCTs measuring the effect on the performance of the Berg Balance Scale did not report significant effects ($g = 0.06$, CI: –1.11 to 11.22, $Q = 4.99$, $p = 0.03$, $I^2 = 79.96\%$, online suppl. Fig. S3) [29, 30]. Another study in poststroke and PD patients did not find any improvements in the Tinetti Gait Assessment and the Dynamic Gait Index [30].

Effects on Other Outcomes

Studies which measured muscle strength [30], range of motion [30], and physical activity [27] did not report additional effects of WS training. Two RCTs evaluating health-related quality of life reported significantly greater improvements in the Short-Form Health Survey in the WS group [27, 31]. In contrast, 3 studies did not report effects for fear of falling related to WS training [27, 31, 32].

Adherence to the Training Interventions

Adherence was only assessed in unsupervised programs. In one, 93.3% of the participants completed all 8 training sessions. Another study reported the self-selected time spent on training. While the number of training sessions was identical, the WS group spent less time on training when compared with controls.

Feasibility and Usability of WS Training

Only 2 studies reported on feasibility and usability. A study combining shoe-mounted IMUs and a smartphone had an average of 4 out of maximum 5 points for user-friendliness. The system was well accepted, except for some difficulties with the correct placement of the IMUs and the handling of the touchscreen. The other study rated the usability of a WS system using 5 IMUs for balance training. Most participants said that they had fun while exercising with the system without having safety concerns. Notably, most participants claimed that the WS feedback helped them to learn the exercises more quickly.

Discussion

The aim of this systematic review was to estimate the effect of WS balance and gait training programs in healthy and patient populations. The meta-analysis showed evidence in favor of the effectiveness of WS training in improving static steady-state balance parameters. Studies using usual care controls and studies making comparisons with conventional training reported effects suggesting an added value of WS training for improving specific balance performances. In contrast, the meta-analyses did not reveal effects for dynamic steady-state and proactive balance outcomes. Single studies reported significant effects of WS training on selected gait parameters and selected proactive balance measures.

WS Training Paradigms Used

Types and Placements of WS

IMUs were used most frequently in the studies included, but placement differed across the studies. For example, 2 studies in patients with neuropathy mounted IMUs on the shank in order to compensate for impaired proprioception in the ankle joint related to neuropathy [31, 32]. In contrast, in other studies IMUs were mounted on the lower back in order to provide feedback about sway of the center of mass [28, 33]. Furthermore, some authors used pressure-sensitive insoles for providing specific feedback about weight bearing symmetry in stroke patients [29]. These studies aimed at improving symmetrical weight bearing in order to improve balance and gait performance specifically in stroke patients [29]. In addition, a single study combined IMUs and wearable plantar pressure sensors [30]. Authors argued that a combination of both sensor types allows simultaneous detection of the movement of body segments (IMUs) and foot-floor contact (plantar pressure sensors), which in turn allows a more precise feedback about movement performance. Most authors provided a specific rationale for the choice of the sensor type and the sensor placement such as compensating for a specific proprioceptive deficit [31, 32]. On the same note, the different sensor types and placements limited the comparability of articles included. The number of included studies was too small to perform a subanalysis according to sensor type or placement.

Types and Modalities of Exercise Interventions

A recent systematic review from Lesinski et al. [34] evaluated the dose-response relationship of balance training in older adults. According to their review, a training period of 11–12 weeks, a frequency of 3 sessions per week, a total number of 36–40 training sessions, a duration of 31–45 min of a single training session, and a total duration of 91–120 min of balance training per week induces the largest effect on balance performance. In contrast, our review revealed that none of the WS training studies included had an optimal dosage as proposed by Lesinski et al. [34], but the duration of the training periods was shorter in all studies (from 1 day to 8 weeks), and the frequency was lower in 5 out of 8 studies included (62.5%). This may explain the limited effects found for some outcomes. Future studies on WS training should be designed according to the recommendations of Lesinski et al. [34] in order to ensure an adequate training dosage required for inducing a significant effect on balance control.

WS Real-Time Feedback Provided during Training

The majority of studies translated body motions into visual feedback provided on a screen. The rationale for choosing predominately visual feedback was that other types of feedback such as auditory feedback are difficult to interpret, particularly for specific populations such as those with PD [28].

With respect to motor learning, an important aspect is the differentiation between positive and corrective feedback [35]. While positive feedback fosters motivation, corrective feedback is an essential element during learning processes [35]. RCTs included in this review provided either solely corrective feedback or combined this with the positive feedback. An example of corrective feedback is the study from Sungkarat et al. [29], in which a tone was given to poststroke patients when unequal weight distribution (i.e., standing) or short step length (i.e., walking) exceeded a determined threshold. An example of combined feedback is the postural balance training paradigm from Grewal et al. [31] and Schwenk et al. [14, 32]. In these studies, participants had to navigate a cursor on the screen towards a goal by leaning their body in the appropriate direction. Inaccuracy or low speed was indicated by different colors on the screen, while correct task execution was awarded by the playing of a positive sound. The effects of different feedback paradigms on outcome measures were not compared in any study, and this represents an area of future research in the field of WS training.

Training Effects

Effect on Static Steady-State Balance Measures

Medio-lateral sway during stance tasks has been repeatedly identified as a predictor of future falls risk, whereas eyes closed sway was found to be a stronger predictor in comparison with eyes open [36]. Our meta-analyses revealed positive effects on mediolateral sway during stance tasks when this was measured with eyes open and eyes closed. The authors discussed that the feedback provided from body motion may help participants to reduce specific components of sway related to fall risk. On the same note, our meta-analyses revealed lower effect sizes for eyes closed sway, although this is the more important fall risk measure.

Studies using visual feedback reported limited effect on postural balance measured with eyes closed [14, 31, 32]. Visual feedback might have particularly improved the processing of visual information for balance control [37], whereas other balance control systems including somatosensory and vestibular system were not trained [38]. In contrast, studies with vibrotactile feedback [28] or combined auditory and vibrotactile feedback [33] reported significant improvements while standing with eyes closed in healthy older adults [33] and PD patients [28]. However, it remained unclear whether these improvements were related specifically to auditory feedback or, vibrotactile feedback, or the combination of both feedback types. Future WS training studies might be designed to improve specifically eyes closed balance performance, for instance by including eyes closed balance tasks and by providing audio or vibratory feedback.

Single authors discussed potential mechanisms related to the specific feedback provided by WS. For instance, Grewal et al. [31] argued that the visual feedback about ankle joint motion facilitated a sensory remapping during training. Although studies did not evaluate the specific mechanisms of the training, the results demonstrated the potential of WS for providing biofeedback about single body segment motion.

Positive effects were found in studies that compared WS training with usual care [14, 31, 32] as well as in the study comparing WS training with conventional training [28]. Results suggest that WS training has an added value for improving postural sway during stance tasks, when compared with conventional balance and gait training, although more studies are needed. Studies using proactive training (i.e., leaning and obstacle-avoidance) [14, 31, 32] and combined static and dynamic steady-state balance training [28] included positive effects suggesting that different paradigms are useful for improving static steady-state balance.

Conventional balance training studies have shown that a transfer from trained to untrained tasks is limited [39]. Interestingly, a study included in this review reported transfer effects of trained tasks to nontrained tasks after a single training session in PD patients [28]. The authors concluded that the WS training fosters a carry-over effect to more general improvements in balance, but no sustainability of effects could be found.

All studies which reported effects on static steady-state balance used IMUs, suggesting that this sensor type is useful for assisted balance training.

The number of studies was too low for creating meta-analysis subgroups for factors such as type of control group, type of training paradigm, type of sensor, or type of feedback. Further studies are required to estimate the influence of these factors on the effectiveness of the training.

Effects on Dynamic Steady-State Balance Measures

The meta-analysis did not show any effects on habitual gait speed relating to WS training. Although habitual gait speed was the most frequently assessed gait parameter, it might not have been sensitive enough to detect specific WS training-related changes in dynamic steady-state balance. We did not find evidence that factors such as control group (i.e., usual care vs. conventional training), sensor type, and type of training paradigm were related to these negative findings. However, the number of studies is too low to draw definitive conclusions.

Interestingly, we found that those studies using a testing-the-limits paradigm (fast gait speed) in frail older adults or those assessing disease-specific gait parameters such as single support time or loading on the paretic foot in stroke patients found improvements in dynamic steady-state balance related to WS training. Our results may suggest that functionally impaired older adults or patients with a specific deficit such as decreased sensory input would benefit particularly from WS-based training, which is in line with previous studies on biofeedback training [36, 40]. The authors additionally discussed that repeated practice of single leg stance during obstacle-avoidance training was transferred to better walking performance. They concluded that subjects with limited one leg stance ability could particularly benefit from this type of training paradigm.

Effects on Proactive Balance Measures

The meta-analysis did not show effects on functional performance evaluated by the Timed Up and Go test. The authors discussed that a transfer from trained tasks to more general functional tasks such as Timed Up and Go test could not be verified [29]. In contrast, studies using more specific measures of proactive balance such as the Alternate Step Test reported improvements after WS training [14]. The authors discussed that the Alternate Step Test is strongly associated with mediolateral balance control, which was specifically trained by WS technology. Results may suggest that improvements in mediolateral balance have positively impacted on proactive balance [14]. Findings need to be confirmed in future studies.

Effects on Balance Test Batteries

The results of both studies evaluating the performance of the Berg Balance Scale varied widely and showed a high level of heterogeneity. Limited training effects found for balance test batteries and the limited sustainability of effects might be related to limited statistical power in most RCTs, since the sample sizes were relatively small, i.e. <40.

Feasibility and Usability of Sensor-Based Training

Feasibility and usability are major factors for the successful implementation of WS training into routine practice. A sound process evaluation providing detailed insights about the user's opinion was lacking in all studies. Evidence from a single study suggests that the WS support was helpful for learning balance exercises more quickly [41], even though this training was supervised, and it remains unclear whether similar results can be achieved in an unsupervised setting.

A precondition is the unobtrusiveness of WS in order to foster long-term usage in everyday settings. Up until now, 1 RCT has evaluated WS training in an everyday environment of PD patients and reported a generally high user acceptance, as well as some difficulties with sliding IMUs onto the laces of the shoes and pressing the small start button [27]. Future studies that specifically focus on improving usability may help to foster implementation of WS technology into real life settings.

Limitations

Participants, types of training paradigms, control groups, training duration, WS feedback, and WS types and placements differed in the studies included in our meta-analysis. This may limit the validity of our findings and must be taken into consideration when interpreting the overall effect.

The limited number of RCTs did not allow subgroup meta-analysis. On the same note, the main aim of our review was to estimate the effectiveness of WS training in general, regardless of the target population or the type of training paradigm used. Furthermore, we considered the abovementioned factors when reporting and discussing the results in order to provide comprehensive information for designing future studies. Only the articles published during the last 10 years (after 2006) were included in this review. An initial PubMed search did not show any WS training articles published before this date, limiting a risk of bias.

Conclusion and Future Research

To our knowledge, this is the first systematic review of RCTs on WS-based balance and gait training. In summary, our results indicate that there is evidence in favor of a positive effect of WS training in order to improve static steady-state balance in both healthy older adults and patient populations, but more work is needed before a broad conclusive statement on this subject can be made. Despite the limited effects on dynamic steady-state and proactive balance measures found in meta-analyses, there is some evidence that WS training improves selected parameters of gait and stepping performance. Participants reported that WS training is useful for learning and training tasks. No study has trained and assessed the reactive balance. However, reactive balance is important for preventing falls [42] and future WS training paradigms might include this balance component.

We found both positive and negative results in this review, depending on the outcome measure examined. We also found methodological weaknesses in current RCTs, most importantly small sample sizes and short intervention periods, which may have resulted in limited effects.

Future RCTs should be designed with a sound trial design including an adequate sample size, active control group, and an adequate follow-up analysis. Studies should additionally take into account the established guidelines of exercise training in order to ensure adequate training frequency and duration [43]. If a greater number of RCTs exists, important factors such as disease specificity, sensor type, and training modalities can be picked up in subgroup analyses, in order to identify the most effective type of training paradigms.

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