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# Influence of footwear on postural sway: A systematic review and meta-analysis on barefoot and shod bipedal static posturography in patients and healthy subjects

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## ABSTRACT

*Background:* Bipedal static posturography is widely used to assess postural control. However, standardized methods and evidence on the influence of footwear on balance in comparison to barefoot stance is sparse.
*Research questions:* Is bipedal static posturography applied in a standardized way with respect to demographics and the experimental set-up (systematic review)? Does habitual footwear influence postural control in comparison to barefoot condition during bipedal static posturography in adult patients and healthy subjects (meta-analysis)?
*Methods:* For this systematic review and meta-analysis, a comprehensive follow-up literature search was conducted from March 2009 until January 2020 according to the PRISMA guidelines. Original, research articles reporting on bipedal, unsupported, static posturography in adults ($\geq$18 years) were included according to inclusion criteria (age, sex, height, weight, duration, repetitions, visual/foot condition, sampling frequency). Studies comparing habitual footwear with barefoot condition during bipedal static posturography were included for the meta-analysis. Center of pressure parameters (sway velocity, range, root mean square, paths lengths) with subjects having eyes closed (EC) or open (EO) were analyzed using random effects models.
*Results:* For this systematic review and meta-analysis, 207 and eight out of 5189 studies with 12'341 and 156 subjects, respectively, were eligible. Most studies (89%) reported barefoot, 5% shod, and 6% barefoot and shod measurements. Less than half of studies (44%) included patients of which the minority (13%) suffered from neurological disease. Sway velocity in the anterior-posterior direction was higher in habitual shoes compared to barefoot with EC (SMD: 1.08; 95% CI: 0.68–1.48; $p < 0.01$; $I^2 = 0\%$), with EO (SMD: 0.68; 95% CI: 0.11–1.26; $p = 0.02$; $I^2 = 1\%$), and in the medio-lateral direction with EC (SMD: 1.30; 95% CI: 0.76–1.85, $p < 0.01$; $I^2 = 37\%$).
*Significance:* Methodical heterogeneity of bipedal static posturography hampers studies' comparability. Thus, we provide a standardized approach to increase knowledge whether habitual footwear decrease postural control in comparison to barefoot stance.

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*Abbreviations:* BMI, Body-Mass-Index; CI, Confidence Interval; CoP, Center of Pressure; EC, Eyes Closed; EO, Eyes Open; Hz, Hertz; $I^2$, Heterogeneity; RMS, Root Mean Square; SMD, Standardized Mean Difference; SD, Standard Deviation.

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## 1. Introduction

Bipedal static posturography is widely used to assess postural control and is mostly applied during bipedal static stance measuring the center of pressure (CoP) [1]. CoP is defined as the global ground reaction force vector that accommodates the body sway [2]. It is well-known that postural control is highly influenced by several factors such as age [3], sex distribution [3,4], anthropometry [5], foot placement [5], physical activity status [6–8], and the subject's health status, which might be hampered e.g. by low back pain, falls, or stroke [9–13]. Hence, it is necessary to control for these factors in principle when assessing postural control—indicating the need of large sample sizes or pooled data analyses that both require a standardized methodology of bipedal, static posturography. However, methodological inconsistency on bipedal static posturography including demographics, experimental set-up, and statistical analysis presently hamper studies comparability in general and particularly with respect to the subject's health status, and thus pooled data analysis [1,14]. To overcome this major limitation with consecutive lack of knowledge, we follow-up the previous work and attempt to standardize bipedal static posturography by Ruhe and colleagues [2], who performed a systematic review on test-retest reliability including studies from 1980 until 2009. They found that bipedal static posturography with measuring CoP parameters is a reliable outcome instrument for assessing postural control when using a standardized experimental set-up. Particularly, age, sex distribution, body weight and height were described to influence CoP outcome [2–5,14,15], and were thus recommended for a standardized approach [2]. Optimal reliability has been suggested with the following parameters: *i)* a measurement duration of at least 90 s, *ii)* averaging three to five repetitions, *iii)* a measurement on a firm surface, *iv)* having eyes closed (EC) is more reliable than having eyes open (EO), and *v)* a sampling frequency of 100 Hz with a cut-off filter at 10 Hz [2]. In addition, foot position should be defined [5], but precise knowledge regarding its test-retest reliability is still lacking [2]. Despite these well-defined demographics, anthropometric and methodological parameters, standardized bipedal static posturography has not yet been established [1], and were thus defined among others as inclusion criteria in the presented systematic review and meta-analysis.

Another widely disregarded parameter during bipedal static posturography is the influence of habitual footwear on the participants' postural control in comparison to their barefoot stance. This is particularly important as earlier studies revealed that shoes impair postural control by altered sensory and proprioceptive inputs during bipedal static posturography [16,17]. In contrast, motion analysis systems elucidated better postural control during shod compared to barefoot bipedal, static, quiet stance [18]. Thus, evidence on the influence of footwear on postural control is still controversial and is in turn of major clinical relevance as patients at risk of falls commonly receive the recommendations to wear shoes [19].

Furthermore, evidence in terms of comparing postural control during barefoot and shod stance measured by bipedal, quiet, and unsupported static posturography is overall sparse, namely in healthy subjects and patients. Therefore, we decided to include all original research articles published in English that fulfilled demographics and the appropriate experimental set-up irrespective from health or disease status to provide the maximal available data—knowing that results on mixed groups would be preliminary and a first step to highlight this relevant topic and lack of data in the field.

To advance knowledge in the field of standardized postural control outcome measure for pooled data analysis in the future, we therefore tackled the following two research question by performing a systematic review and meta-analysis:

(1) Is bipedal static posturography applied in a standardized way with respect to demographics and experimental set-up (systematic review)?

(2) Does habitual footwear influence postural control in comparison to barefoot condition during bipedal static posturography in adult patients and healthy subjects (meta-analysis)?

**Table 1**
Inclusion and exclusion criteria of the systematic review and meta-analysis.

| Inclusion criteria | Exclusion criteria |
|---|---|
| ***Systematic review*** | |
| Peer-reviewed original research articles in English | Any supported stance |
| Adult healthy subjects or patients aged ≥ 18 years | Any perturbed stance |
| | Any influenced visual input |
| Static posturography | Any amputation of lower extremities |
| Information on demographics: | Use of prosthesis or orthosis |
| Age, sex, body weight and height | Spinal cord injury |
| Information on experimental set-up: | Obesity |
| Bipedal, quiet, and unsupported stance | Pregnancy |
| Firm surface | |
| Foot position | |
| Foot condition (barefoot or shod or both conditions) | |
| Visual condition (EC/ EO) | Wii balance board |
| Duration of measurement (s) | |
| Number of trials per condition | |
| CoP parameters | |
| Force plate | |
| Sampling rate (Hz) | |
| ***Meta-analysis*** | |
| Criteria for systematic review except foot condition | Criteria for systematic review |
| Foot condition: barefoot and habitual[a] shoes | Non-habitual shoes (e.g. MBT shoes)<br>Minimalist shoes |

[a] habitual shoes: shoes that are comparable with flat shoes, walking, running, or conventional shoes.

Answering these questions and providing evidence is relevant to improve comparability within groups stratified for age, sex, anthropometry, foot placement, physical activity, health status and foot condition (barefoot/ shod) and will help to advance prediction of patients' postural control outcome trajectories by pooled data analyses in the future.

## 2. Methods

This study follows the PRISMA statement for preferred reporting items for systematic review and meta-analysis, and the population, intervention, comparison, and intervention process (PICO). Eligibility was assessed according to predefined criteria (Table 1 and Section 2.1). Whilst for the systematic review peer-reviewed original research articles on bipedal static posturography in barefoot or shod or both foot conditions were eligible, for the meta-analysis, studies were included investigating healthy adult subjects or patients (P), that underwent bipedal static posturography (I) comparing barefoot to shod (habitual footwear) conditions during bipedal, quiet, unsupported stance (C) to elucidate differences of postural control between both conditions (barefoot/ habitual footwear) measured by CoP outcome parameters (O).

Habitual footwear was defined when shoes were comparable with flat shoes, walking, running, or conventional shoes. Conventional shoes were shown in original articles as having flat soles. Minimalist shoes usually count as habitual shoes and were excluded for the meta-analysis due to barefoot-like characteristics. Non-habitual shoes were unstable shoes, e.g. Masai Barefoot Technology (MBT), or high-heeled shoes.

### 2.1. Inclusion and exclusion criteria

For the systematic review, we included peer-reviewed original

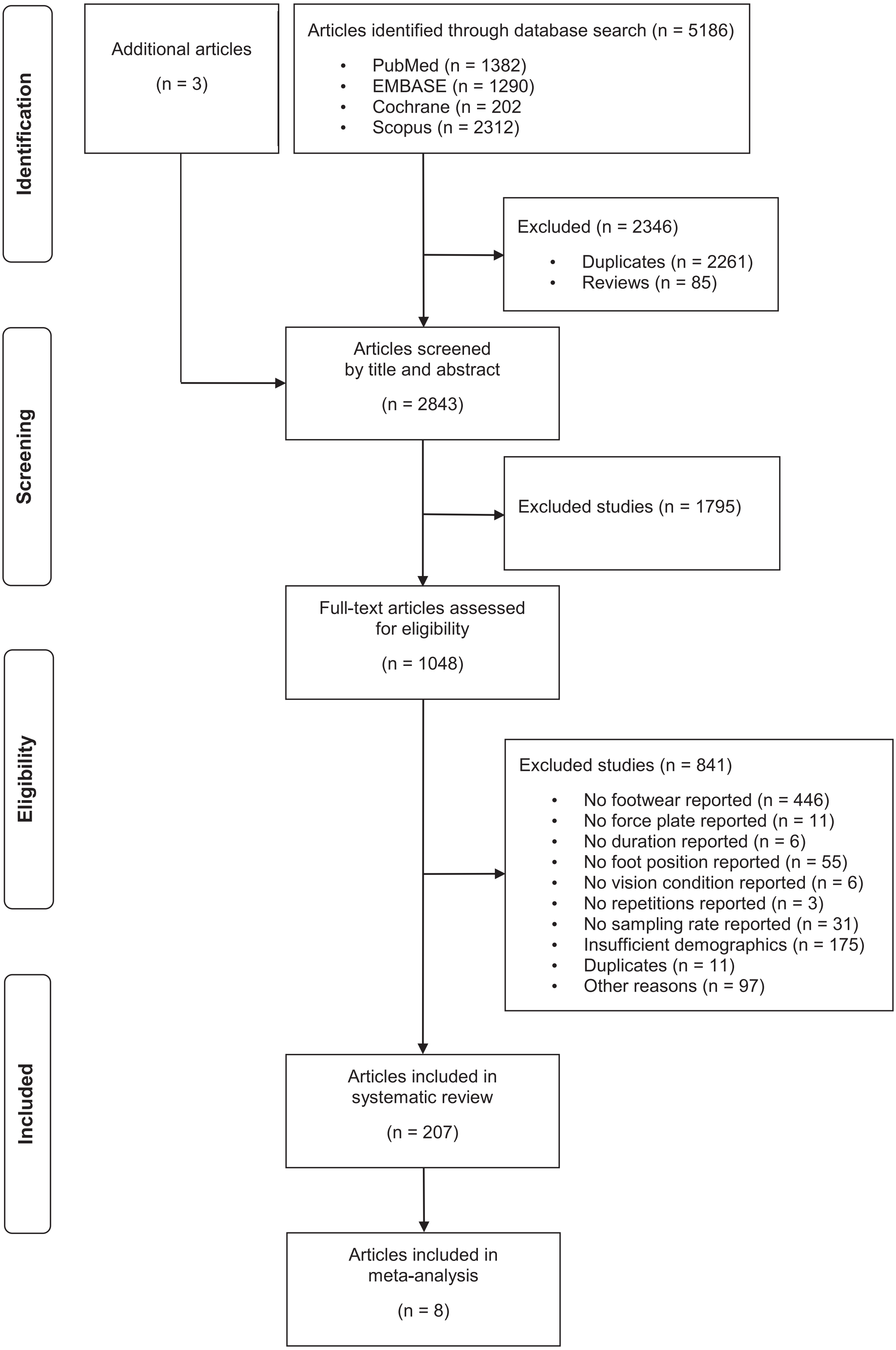


**Fig. 1.** Flowchart depicting studies for the systematic review and meta-analysis with the latter comparing postural control during barefoot and shod (habitual footwear) bipedal, static posturography.

research articles published in English language that reported on studies of bipedal static posturography in adult healthy subjects or patients aged $\geq$ 18 years (Table 1). Further requirements for inclusion were full information on (1) demographic data including age, sex, body weight and height as well as on (2) the experimental set-up regarding static posturography with information on *i)* bipedal, quiet, and unsupported stance, *ii)* whether a firm surface was used, *iii)* the foot position, *iv)* the foot condition (barefoot or shod or both conditions), *v)* the visual condition (EC/ EO), *vi)* the duration of measurement (s), *vii)* the number of trials per condition, *viii)* the CoP parameters *ix)* the force plate, and *x)* the sampling rate (Hz). Reasons for study exclusion were any support during standing, e.g. holding a grip, any perturbed stance or influenced visual input, any amputation of lower extremities, any use of prosthesis or orthosis, spinal cord injury, obesity, pregnancy or a Wii balance board.

For the meta-analysis, those studies of the systematic review were eligible when having compared barefoot to habitual shoe condition; studies comparing barefoot to non-habitual or minimalist shoes were excluded.

### 2.2. *Research questions*

(1) Is bipedal static posturography applied in a standardized way with respect to demographics and experimental set-up (systematic review)?

(2) Does habitual footwear influence postural control in comparison to barefoot condition during bipedal static posturography in adult patients and healthy subjects (meta-analysis)?

### 2.3. *Literature search strategy and selection process*

A professional librarian (MG) conducted a systematic literature search on PubMed, EMBASE, Cochrane and Scopus for the period from March 1, 2009 until January 8, 2020, thus following-up the systematic review by Ruhe and colleagues [2]. The search terms are given (Supplementary Table S1). Thereafter, an additional search was conducted with the added terms “barefoot” and “shoe” for retrieving eligible studies comparing barefoot with shod condition. Based on the predefined inclusion criteria, one reviewer (KR) screened titles and abstracts from 2009 until 2016, a second reviewer (SR) screened titles and abstract from 2016 until 2020. Four reviewers (KR, SR, MH, CK) independently evaluated full texts. Disagreements on inclusion between reviewers were resolved for final decision through a detailed discussion with the senior author (KR).

### 2.4. *Data collection process*

For the systematic review the following parameters regarding full information on (1) demographic data including age, sex, body weight and height as well as on (2) the experimental set-up regarding static posturography with information on *i)* bipedal, quiet, unsupported stance, *ii)* whether a firm surface was used, *iii)* the foot position, *iv)* the foot condition (barefoot/ shod), *v)* the visual condition (EC/ EO), *vi)* the duration of measurement (s), *vii)* the number of trials per condition, *viii)* the CoP parameters, *ix)* the force plate, and *x)* the sampling rate (Hz) were assessed. Study characteristics are given: first author, journal, year of publication, footwear, or barefoot condition, posturography plate, sample rate (Hz), measurement duration (s), eye condition (EC/ EO), number of repetitions, sample size of subjects (healthy/ patients), and kind of disease.

For the meta-analysis, data of studies comparing barefoot with habitual footwear condition was analyzed. Two reviewers (MH, SR) extracted data on study population regarding health status, sample size, demographics (age, sex, height, weight, body-mass-index (BMI)), interventions (barefoot/ shod), shoe type, force plate, sampling rate (Hz), filter cut-off frequency (Hz), duration (s) and repetitions of measurements, foot position, eye condition (EC/ EO), CoP outcome parameters, statistical analysis, and main results. Authors were contacted for completing missing data and/or for raw data.

### 2.5. *CoP outcome parameters*

CoP outcome parameters were compared between barefoot and shod foot condition within the meta-analysis when analyzed in at least two of the included original articles, which was the case for *i)* anterior-posterior and medio-lateral sway (with sway being interchangeable with range or path or excursion), *ii*) the anterior-posterior and medio-lateral sway velocity, *iii)* the anterior-posterior root mean square, and *iv)* the total range length independent from plane.

### 2.6. *Statistical analysis*

The meta-analysis was performed using the meta package in RStudio (Version 1.2.5001, Boston, MA, USA) for each CoP outcome variable given in at least two studies. Due to the wide range of sample characteristics that might influence balance per se, we separately analyzed each CoP outcome variable by the subjects’ health status and performed a meta-analysis for those CoP outcome variables with original data from at least two studies per health status.

Given the large study variations, a random effects model was chosen. Effect sizes are presented as standardized mean difference (SMD) due to continuous data with different scales, and 95% confidence intervals (CI) are given. SMD were calculated using Cohen’s d values and effects are considered small, medium, and strong between 0.2 and 0.5, between 0.5 and 0.8 or higher than 0.8, respectively. Heterogeneity ($I^2$) considering Cochrane’s Q (given as chi-squared statistic) is presented to describe the percentage of variability due to heterogeneity rather than to chance for effect estimates. We considered $I^2$ between 0% and 40% as not important, 30–60% as moderate, 50–90% as substantial, and 75–100% as considerable heterogeneity. The z-test significance level was set at $p <$ 0.05. Forrest plots with 95% CI are given. Funnel plots and Egger’s test describe publication bias. The risk of bias assessment was judged based on the Cochrane collaboration’s tool using the online tool robvis for assessing risk of bias within studies and across studies by two independent reviewers (SR, KR). A study quality rating was used with scores of “poor”, “fair” and “good” for each of the following parameters: sampling rate, the measurement duration, the number of trials per condition, the foot position and the eye condition according to previous recommendations [2]. In addition, the sample size was assessed based on whether a power calculation was performed. Finally, an overall study quality rating is provided (for details see Supplementary Table 2).

## 3. Results

The systematic database search returned 5186 and three further identified articles through additional search terms (Fig. 1). After removing duplicates and reviews, 2843 articles were screened by title and abstract. Thereafter, 207 (20%) out of 1048 full-text articles were included for the systematic review of which eight studies [17,20–26] were eligible for the meta-analysis based on the defined inclusion criteria indicated in Table 1. Reasons for exclusion are specified in Fig. 1. Thus, 207 studies addressed the first research question (systematic review). Only eight out of these 207 studies addressed the second research question (meta-analysis) by reporting the required demographics, experimental set-up and comparing barefoot to habitual footwear condition.

### 3.1. *Systematic review*

Study characteristics of each study are presented in Appendix Table 2. Most of the 207 included studies, namely 183 (88%), investigated postural control in barefoot, 11 (5%) shod and 13 (6%) in barefoot and

**Table 2**
Demographics and main characteristics of included studies for the meta-analysis.

| Study | Brenton-Rule et al., 2011 | Cho et al., 2014 | Cudejko et al., 2020 | Demura et al., 2015 | Ferreira et al., 2017 | Landry et al., 2010 | MacRae et al., 2016 | Plom et al., 2014 |
|---|---|---|---|---|---|---|---|---|
| **Population** | Healthy subjects (n = 21) | Chronic stroke patients[a] (n = 32) | Healthy subjects (n = 22) | Healthy subjects (n = 10) | Chronic stroke patients[b] (n = 20) | Healthy subjects (n = 28) | Subjects with chronic low back pain (n = 20) for meta-analysis (n = 7) | Healthy subjects (n = 16) |
| **Age in years (mean ± SD)** | 74 (5) | 63.5 (4.7) | 55.4 (7.8) | 23.9 (3.6) | Baseline 1 (control group): 60.3 (13.3)<br>Baseline 2 (experimental group): 59.2 (10.4) | Men: 53.6 (10.2)<br>Women: 53.2 (6.9) | 37.9 (13.0) | 20 (1.3) |
| **Sex distribution (male/ female)** | 6 / 15 | 16 / 16 | 11 / 11 | 10 / 0 | 14 / 6 | 9 / 19 | 3 / 4 | 0 / 16 |
| **Height in cm (mean ± SD)** | not given | 163.3 (6.7) | not given[c] | 171.8 (4.1) | Baseline 1 (control group): 161 (6)<br>Baseline 2 (experimental group): 166 (8) | Men: 171.7 (4.5)<br>Women: 162.3 (6.0) | 173.8 (7.3) | 166.4 (5.5) |
| **Weight in kg (mean ± SD)** | not given | 62.5 (6.1) | not given[c] | 67.6 (4.9) | Baseline 1 (control group): 63.6 (11.9)<br>Baseline 2 (experimental group): 69.1 (10.7) | Men: 85.8 (15.3)<br>Women: 76.0 (14.3) | 82.4 (22.0) | 65 (9.9) |
| **BMI in kg/m$^2$ (mean ± SD)** | 25.4 (4.2) | not given | 26.7 (4.9) | not given | Baseline 1 (control group): 24.4 (4.1)<br>Baseline 2 (experimental group): 24.9 (3.6) | not given | not given | not given |
| **Intervention** | Barefoot versus 2 different shoe types | Barefoot versus 4 different shoe types | Barefoot versus 12 different shoe types | Barefoot versus 4 different shoe types | Barefoot versus habitual shoes | Barefoot versus 2 different shoe types | Barefoot versus rocker-sole or flat shoes | Barefoot versus 3 unstable shoes or 1 standard shoe |
| **Shoe type included for meta-analysis** | Walking shoes | Flat shoes | Conventional shoes for women and men[e] | Conventional shoes | Habitual shoes not further specified | Habitual shoes not further specified | Walking shoes | Standard shoes |
| **Force plate** | MatScan plate Tekscan Inc, South Boston, USA | Good Balance force platform Metitur Ltd., Jyvaskyla, Finland | FootWork Pro, AM CUBE Berkshire, UK | Stabilometer G5500 Anima, Japan | Kistler model 9286BA Kistler Group, Winterthur, Switzerland | Kistler force plate Kistler Group, Winterthur, Switzerland | FP5000 AMTI, Massachusetts, USA | Kistler force plate Kistler Group, Winterthur, Switzerland |
| **Sampling rate (Hz)** | 40 | 50 | 20 | 20 | 100 | 2400 | 10[c] | 40 |
| **Filter cut off frequency (Hz)** | not given | not given | Low-pass filter at 2 Hz | not given | not given | Low-pass filter at 50 Hz | Low-pass filter at 10 Hz | not given |
| **Duration of static posturography (s)** | 30 | 30 | 30 | 60 | 30 | 30 | 30 out of 90 | 10 |
| **Trials per condition** | 3 | 3 | 3 | 3 | 1 | 3 | 3 | 3 |
| **Foot position** | Individually standardized in the "angle-of-base-of-gait" | Legs apart shoulder width | Marked stance position | Feet together | Schematic representing a 30° angle within the sagittal plane | Feet aligned in the sagittal plane and 15 cm apart | Feet approximately pelvis width apart | Feet 15 cm apart |
| **Eye condition** | Eyes open and eyes closed | Eyes open and eyes closed | Eyes closed | Eyes open | Eyes open and eyes closed | Eyes open | Eyes open and eyes closed meta-analysis: eyes open[f] | Eyes open |

(*continued on next page*)

**Table 2** (*continued*)

| Study | Brenton-Rule et al., 2011 | Cho et al., 2014 | Cudejko et al., 2020 | Demura et al., 2015 | Ferreira et al., 2017 | Landry et al., 2010 | MacRae et al., 2016 | Plom et al., 2014 |
|---|---|---|---|---|---|---|---|---|
| **Center of Pressure outcome parameters** | Anterior-posterior and medio-lateral sway[d] | Anterior-posterior and medio-lateral sway velocity | Anterior-posterior and medio-lateral sway[d] and sway velocity | Anterior-posterior and medio-lateral sway velocity and its sum indicated as mean path length, and root mean square;<br>total area, total root mean square | Anterior-posterior and medio-lateral sway[d] and sway velocity;<br>maximal and minimal oscillation, trace length, equivalent area | Anterior-posterior and medio-lateral sway[d] | Anterior-posterior root mean square and anterior-posterior sway velocity | Anterior-posterior and medio-lateral sway[d] |
| **Statistics** | Two-way ANOVA<br>post-hoc: Tukey | One-way repeated ANOVA<br>post-hoc: least significant difference | log10 transformation<br>linear mixed-effects model<br>Bonferroni corrections | One-way repeated ANOVA<br>Bonferroni correction | Multivariate analysis of variance | Two-way repeated ANOVA<br>Bonferroni correction | Two-way mixed model ANOVA | Repeated measure ANOVA<br>Bonferroni correction |
| **Main results** | Anterior-posterior sway increased in common walking shoes compared to barefoot in both visual conditions<br>$p \leq 0.006$ | Anterior-posterior and medio-lateral sway velocity increased in flat shoes compared to barefoot in both visual conditions<br>$p < 0.05$ | Anterior-posterior and mediol-lateral sway and sway velocity were increased in conventional shoes compared to barefoot<br>$p < 0.05$ | No significant increase of all parameters in conventional shoes compared to barefoot | No significant increase of all parameters in habitual shoes compared to barefoot in both visual conditions | No significant difference between habitual shoes and barefoot | No significant difference between flat shoes and barefoot at baseline | No significant difference in all parameters between standard shoes and barefoot |

[a] Chronic stroke patients: more than 6 months after single stroke (mean 300.6 days) with the ability to stand independently.

[b] chronic stroke patients: 6 months to 5 years after ischemic or hemorrhagic stroke (mean 3.7 ± 1.4 years), independent gait.

[c] received from author on request.

[d] sway is interchangeable with range or path or excursion.

[e] conventional shoes for women (Go Walk 4.0-Pursuit, Skechers, USA) and for men (Superior 2.0-Jeveno shoe, Skechers, USA).

[f] for meta-analysis: sway velocity and root mean square in anterior-posterior direction in eyes open condition were included as only those were reported for barefoot compared to flat shoes.

**Table 3**
Study quality rating of the studies included into the meta-analysis.

| Study | Sampling rate | Measurement duration | Trials per condition | Foot position | Eye condition | Sample sitze | Overall rating |
|---|---|---|---|---|---|---|---|
| **Brenton-Rule et al., 2011** | fair | fair | good | good | good | poor | **good** |
| **Cho et al., 2014** | fair | fair | good | good | good | poor | **good** |
| **Cudejko et al., 2020** | poor | fair | good | good | good | poor | **good** |
| **Demura et al., 2015** | poor | fair | good | good | poor | poor | **poor** |
| **Ferreira et al., 2017** | good | fair | poor | good | good | good | **good** |
| **Landry et al., 2010** | good | fair | good | good | poor | good | **good** |
| **MacRae et al., 2016** | poor | good | good | fair | good | poor | **good** |
| **Plom et al., 2014** | fair | poor | good | good | poor | poor | **poor** |

shod foot condition during bipedal static, quiet and unsupported posturography. The total sample size amounted to 12’341 subjects with a mean of 60 and a mode of 16 participants. Less than half of studies (44%) included patients of which the minority (13%) suffered from neurological diseases: seven trials (3.4%) incorporated stroke patients, eight trials (3.9%) analyzed patients with Parkinson’s disease, six trials (2.9%) patients with multiple sclerosis, and five trials (2.4%) patients having neuropathy. Articles had a large heterogeneity regarding their experimental set-up. Sample frequency varied from 5 Hz to 4000 Hz (mean: 284 Hz; mode and median: 100 Hz), whereby 69% of studies used a frequency of 100 Hz or more. Likewise, measurement duration varied widely from 10 s to 15 min, with a mean of 46 s and a mode of 30 s. Whereas 9% of included studies measured for less than 30 s, 44% for 30 s, 18% between 30 and 60 s, 22% for 60 s, 7% for more than 60 s, and 5% for equal or beyond 90 s. Trials per condition ranged from one to ten repetitions (mean: 2.6 trials; mode and median: 3 trials) with 55% of measurements being repeated three or more times. A higher consistency was observed regarding vision, particularly 62% of the studies measured postural control with EC and EO, 27% measured patients merely with EO and 11% exclusively with EC. Furthermore, investigated trials revealed a large heterogeneity regarding foot positions as follows: 26% measured participants with feet together, 11% with parallel feet shoulder width apart and 28% with parallel feet and other distances. Moreover, there was a large heterogeneity with respect to feet angles and the heel-to-heel distances. The minority of studies, namely 6% allowed self-selected stance position, whereas 11% used a standardized marked foot position.

### *3.2. Meta-analysis*

Thirteen out of the 207 studies of the systematic review met the compared barefoot to shod condition. Eight [17,20–26] out of these 13 studies were eligible for the meta-analysis as they compared barefoot to habitual footwear condition with a total of 156 participants (69 males; 87 females), and thus addressed the second research question (Table 2). One [17] out of these eight studies was included after discussion due to the good overall study quality rating although only the BMI and not the raw data of the subject’s weight and height were reported (Table 3). Five studies were excluded due to exclusively comparing postural control of subjects wearing non-habitual shoes, such as high-heel shoes, ski boots, unstable shoes, or insoles, to barefoot condition. For two studies, raw data on body height, weight, and sampling rate (Hz) was received on request [21,25].

Five studies [17,21,22,24,26] analyzed 97 healthy subjects (36 males; 61 females). Two studies [22,26] measured young adults with a mean age (± SD) of 20 (± 1.3) and 23.9 (± 3.6) years of which one [22] described regular exercise habits, while the other one [26] gave no information on the participants’ physical activity status. Two studies [21,24] included middle-aged adults with a mean age of 55.4 (± 7.8) and a mean age of 53 years (males: 53.6 years (± 10.2), females: 53.2 years (± 6.9)). One study included elderly subjects with a mean age of 74 years (± 5),[17] indicating the heterogeneity of studies with respect to age, a relevant factor when measuring postural control, that might have confound results, and pinpoints the need to standardize applied bipedal, static posturography—allowing pooled data collection and analysis in the future.

Regarding patients, two studies [20,23] investigated 52 chronic stroke patients (30 males; 22 females), and one study [25] compared bipedal static posturography in a subgroup of seven (3 males; 4 females) out of 20 subjects with chronic low back pain. Details on chronic stroke patients are summarized in the Supplementary Table S3. It is worth noting, Ferreira et al. [23] performed a randomized controlled trial (RCT) comparing barefoot and habitual shoe condition with insoles in a longitudinal design of which we incorporated baseline data without insoles, which are indicated as baseline 1 (control group: n = 8) and baseline 2 (experimental group: n = 12) (Table 2 and Supplementary Fig. S1). Regarding body weight and height, Brenton-Rule et al. [17] indicated the BMI (raw data was not received) but was included due to

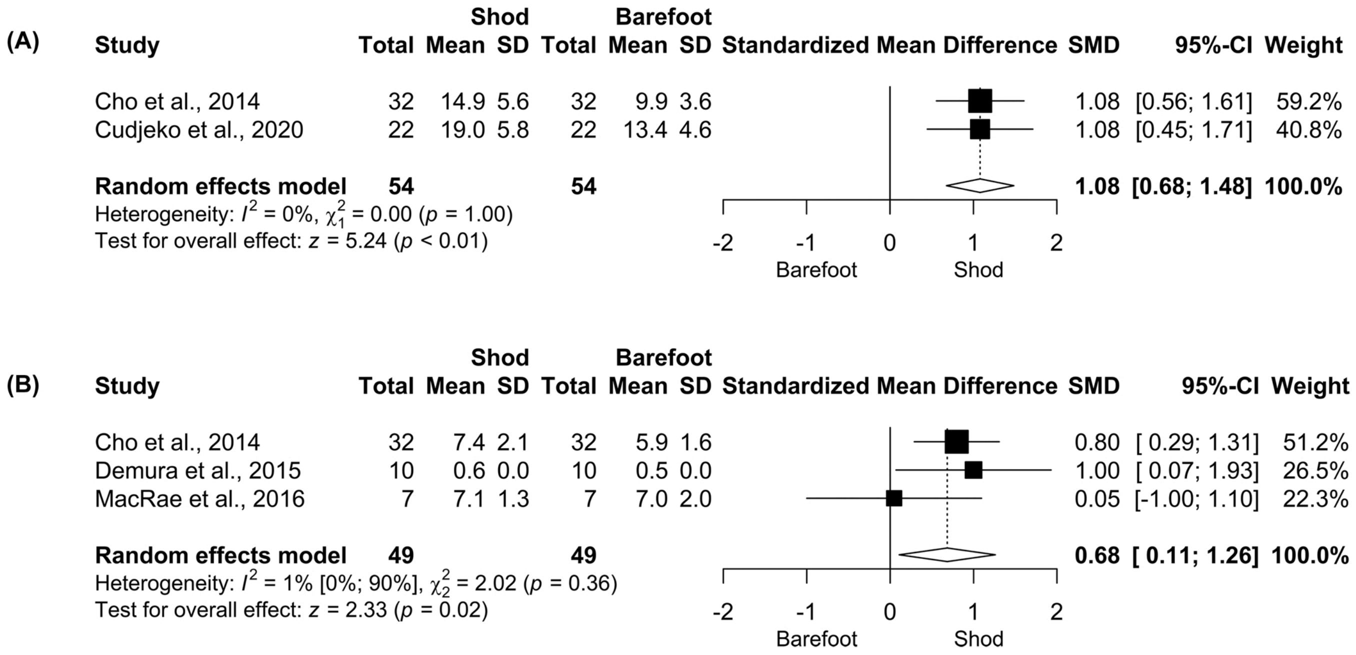


**Fig. 2.** Sway velocity in the anterior-posterior plane was increased in shod compared with barefoot condition with (A) eyes closed and (B) eyes opened in stroke and healthy subjects, indicating decreased postural control during shod bipedal static posturography.

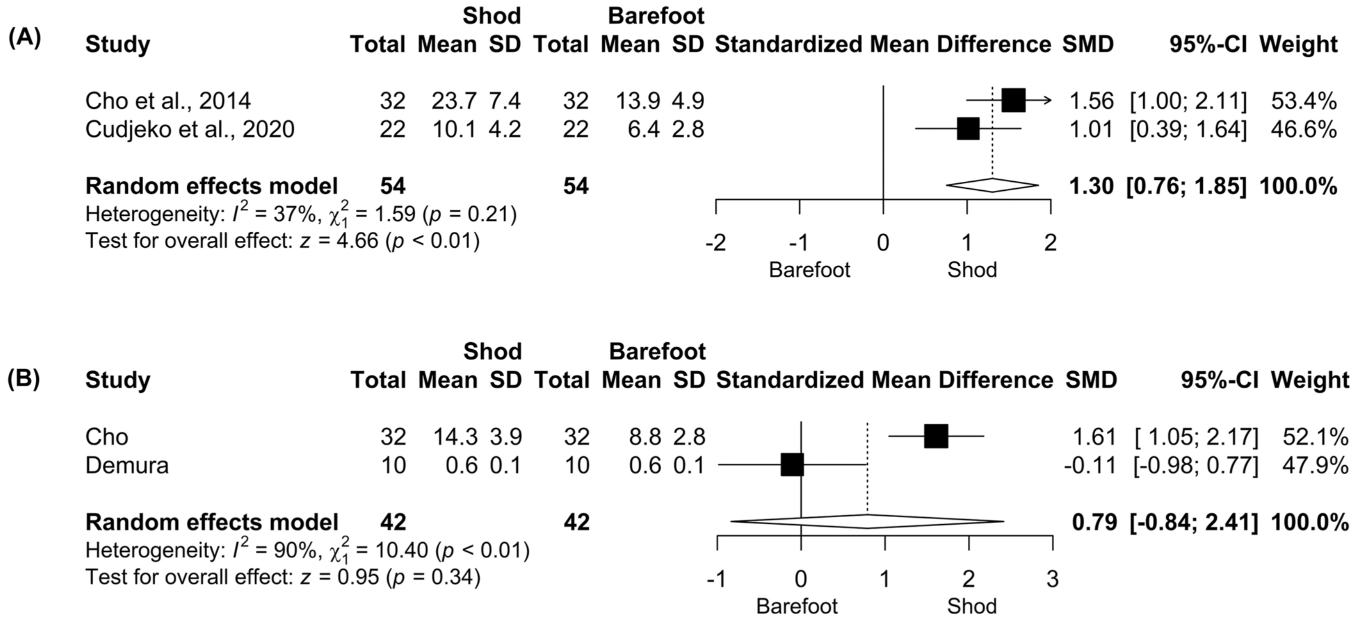


**Fig. 3.** Sway velocity in the medio-lateral plane was increased in shod compared with barefoot condition with (A) eyes closed and (B) eyes opened in stroke and healthy subjects, indicating decreased postural control during shod bipedal static posturography.

its good overall quality rating as indicated in Table 3.

Bipedal static posturography using CoP differed between studies with seven different predefined foot positions in the eight included studies (Table 2). Four studies [17,20,23,25] measured CoP with EC and EO, one study [21] with EC, and three studies [22,24,26] with EO. MacRae et al. [25] measured during EC and EO but reported data comparing barefoot to habitual shoes only with EO. Length of measurement ranged from 10 to 90 s with one study [25] using the middle 30 s for analysis, thus net duration ranged from 10 to 60 s. Ferreira et al. [23] measured chronic stroke patients once, while all other studies [17,20–22,24–26] averaged three measurements for their analysis. Six studies [17,20–22,25,26] gave exact information on type of the footwear: five [17,21,22,25,26] used running and walking shoes, respectively, indicated as walking, conventional, habitual or standard shoes, and one study [20] analyzed flat sole shoes. CoP parameters were *i)* sway velocity in the anterior-posterior (Fig. 2) and medio-lateral (Fig. 3) plane each with EC or EO, *ii)* range (interchangeable with sway, path or excursion) in the anterior-posterior and medio-lateral plane each with

EC and EO (Supplementary Fig. S1A-D), *iii)* root mean square in the anterior-posterior direction with EO (Supplementary Fig. S1E), and *iv)* path length with EO indicating the total range length independent from plane (Supplementary Fig. S1F).

### 3.2.1. *Habitual footwear might influence postural control*

The meta-analysis of the heterogeneous samples regarding the subjects' health status, i.e. patients with chronic stroke, chronic low back pain and healthy subjects, revealed a significant strong effect towards increased sway velocity in the anterior-posterior direction with EC [20,21] (SMD=1.08 [random]; 95% CI: 0.68;1.48; $p < 0.01$; $I^2 = 0\%$) (Fig. 2A) and EO [20,22,25] (SMD = 0.68 [random]; 95% CI: 0.11;1.26; $p = 0.02$; $I^2 = 1\%$) (Fig. 2B) in shod compared to barefoot condition with low heterogeneity of both analyses indicating better postural control during barefoot quiet stance in the sagittal plane with or without visual control. Likewise, a significant strong effect was elucidated towards increased sway velocity wearing habitual shoes compared to barefoot quiet stance in the medio-lateral direction with EC [20,21] (SMD = 1.30 [random]; 95% CI: 0.76; 1.85; $p < 0.01$; $I^2 = 37\%$) (Fig. 3A) with low heterogeneity indicating better postural control of barefoot condition in the frontal plane without visual control. In contrast, postural control displayed as medio-lateral sway velocity with EO [20,22] did not differ between subjects whilst quietly standing barefoot or shod with large studies' heterogeneity ($I^2 = 90\%$) (Fig. 3B). All other CoP parameters, namely range in the anterior-posterior plane with EC [17,21,23] or EO [17,23,24,26] and medio-lateral plane with EC [17,21,23] or EO [17,23,24,26], the root mean square in the anterior-posterior plane with EO [22,25], and the total path length with EO [22,23] did not differ (Supplementary Fig. S1A-F).

### 3.2.2. *CoP outcome variables per health status*

Four out of the total of 13 CoP outcome variables, namely sway in the anterior-posterior and medio-lateral plane with EC and EO, were analyzed in healthy subjects within at least two out of the eight eligible studies as indicated in Table 4, and thus additional meta-analyses for healthy subjects are provided. No meta-analyses were feasible for the health status of chronic stroke and chronic low back pain patients due to the lack of original data.

Healthy subjects had an extended sway in the anterior-posterior plane with EC while wearing habitual shoes in comparison to barefoot condition as indicated by a significant medium effect [17,27] (SMD = 0.61 [random]; 95% CI: 0.17; 1.05; $p < 0.01$; $I^2 = 0\%$) (Fig. 4A), while sway in the anterior-posterior direction with EO remained non-significant with a moderate heterogeneity [17,24,26] (SMD=0.27 [random]; 95% CI: −0.20; 0.75; $p = 0.25$; $I^2 = 41\%$) (Fig. 4B). Healthy subjects also had an extended sway in the medio-lateral plane with EC when wearing habitual shoes in comparison to barefoot stance with a significant small to moderate effect [17,27] (SMD = 0.50 [random]; 95% CI: 0.04; 0.96; $p = 0.03$; $I^2 = 0\%$) (Fig. 5A), while the analysis of sway in the medio-lateral direction with EO did not differ between both foot conditions [17,24,26] (SMD = 0.18 [random]; 95% CI: −0.22; 0.59; $p = 0.37$; $I^2 = 0\%$) (Fig. 5B).

### 3.2.3. *Risk of bias*

Risk of bias assessment for each study and across studies resulted in a moderate to high risk of bias for each study due to the items of performance, reporting and other biases using the Cochrane Collaboration's tool (Supplementary Fig. S2A-B). There are concerns regarding the blinding of outcome assessment and the experimental set-up with the lack of a power calculation in six out of eight included studies. We assume no publication bias relying on the Funnel plots and Egger's test for publications with respect to sway velocity in the anterior-posterior plane with EC (Fig. 6A) or EO (Fig. 6B), nor in all other analyzed parameters, except sway velocity in the medio-lateral direction with EO with considerable heterogeneity (data not shown).

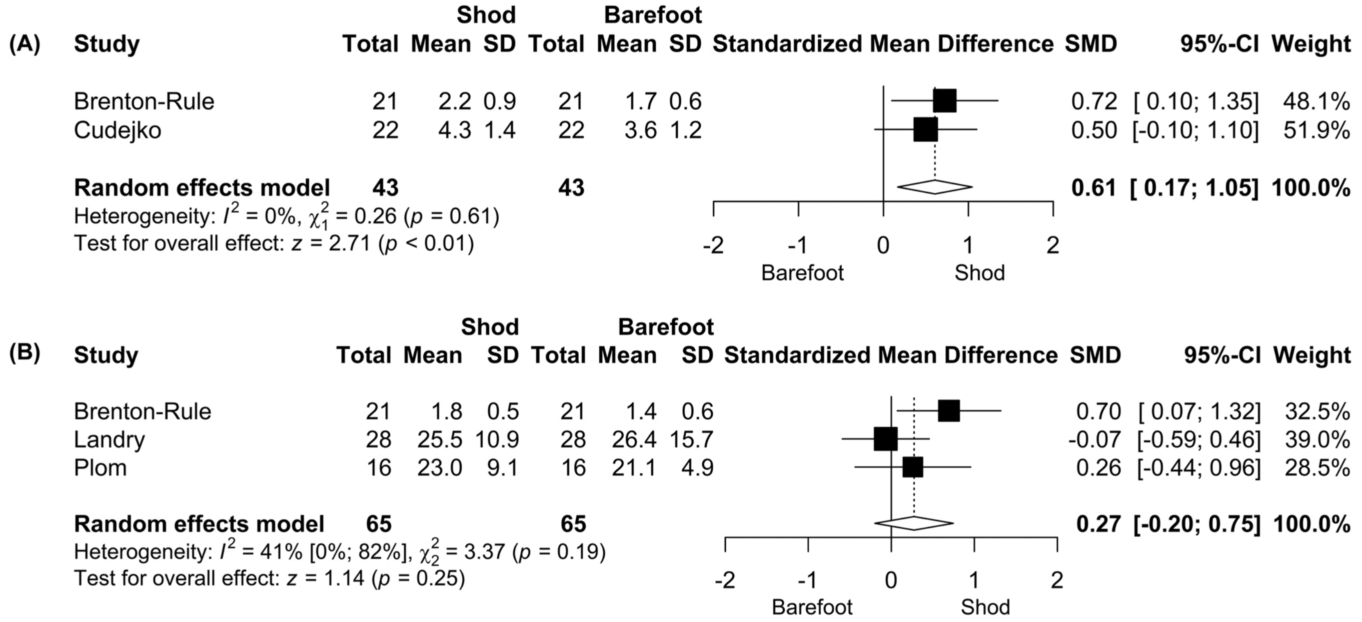
**Table 4**

Overall, 13 CoP outcome variables were analyzed within the eight studies of the meta-analysis of which only four CoP outcome variables were analyzed at least in two studies per health status as indicated in green. These CoP outcome variables were sway in the anterior-posterior and medio-lateral plane with eyes closed and eyes open in healthy subjects. All other CoP parameters did not meet the minimum of two studies per health status, and thus separate meta-analyses for chronic stroke and chronic low back pain patients are currently not available due to the lack of standardized methodology across studies using bipedal, static posturography. Abbreviations: AP: anterior-posterior, ML: medio-lateral, EC: eyes closed, EO: eyes opened, CoP: Center of pressure, RMS: Root Mean Square.

| Health status<br>CoP parameter | Healthy subjects | Chronic stroke | Chronic low back pain |
|---|---|---|---|
| **Velocity AP EC** | 1 | 1 | 0 |
| **Velocity AP EO** | 1 | 1 | 1 |
| **Velocity ML EC** | 1 | 1 | 0 |
| **Velocity ML EO** | 1 | 1 | 0 |
| **Sway AP EC** | 2 | 1 | 0 |
| **Sway AP EO** | 3 | 1 | 0 |
| **Sway ML EC** | 2 | 1 | 0 |
| **Sway ML EO** | 3 | 1 | 0 |
| **RMS AP EO** | 1 | 0 | 1 |
| **Path length EC** | 0 | 1 | 0 |
| **Path length EO** | 1 | 1 | 0 |
| **Equivalent area EC** | 0 | 1 | 0 |
| **Equivalent area EO** | 0 | 1 | 0 |

### 3.2.4. *Study quality rating*

The study quality rating is indicated in Table 3. The overall rating revealed a good study quality for six studies [17,20,23–25,27], while two studies [22,26] had a poor study quality rating. In detail, only two studies [25] used the suggested measurement duration of 90 s, two studies [23,24] applied the recommended sampling rate of 100 Hz, five studies [17,20,21,23,25] measured with EC. Regarding the sample size, two studies [23,24] reported a power analysis for sample size calculation.



(A)

| Study | Shod Total | Shod Mean | Shod SD | Barefoot Total | Barefoot Mean | Barefoot SD | SMD | 95%-CI | Weight |
|---|---|---|---|---|---|---|---|---|---|
| Brenton-Rule | 21 | 2.2 | 0.9 | 21 | 1.7 | 0.6 | 0.72 | [ 0.10; 1.35] | 48.1% |
| Cudejko | 22 | 4.3 | 1.4 | 22 | 3.6 | 1.2 | 0.50 | [-0.10; 1.10] | 51.9% |
| **Random effects model** | **43** | | | **43** | | | **0.61** | **[ 0.17; 1.05]** | **100.0%** |

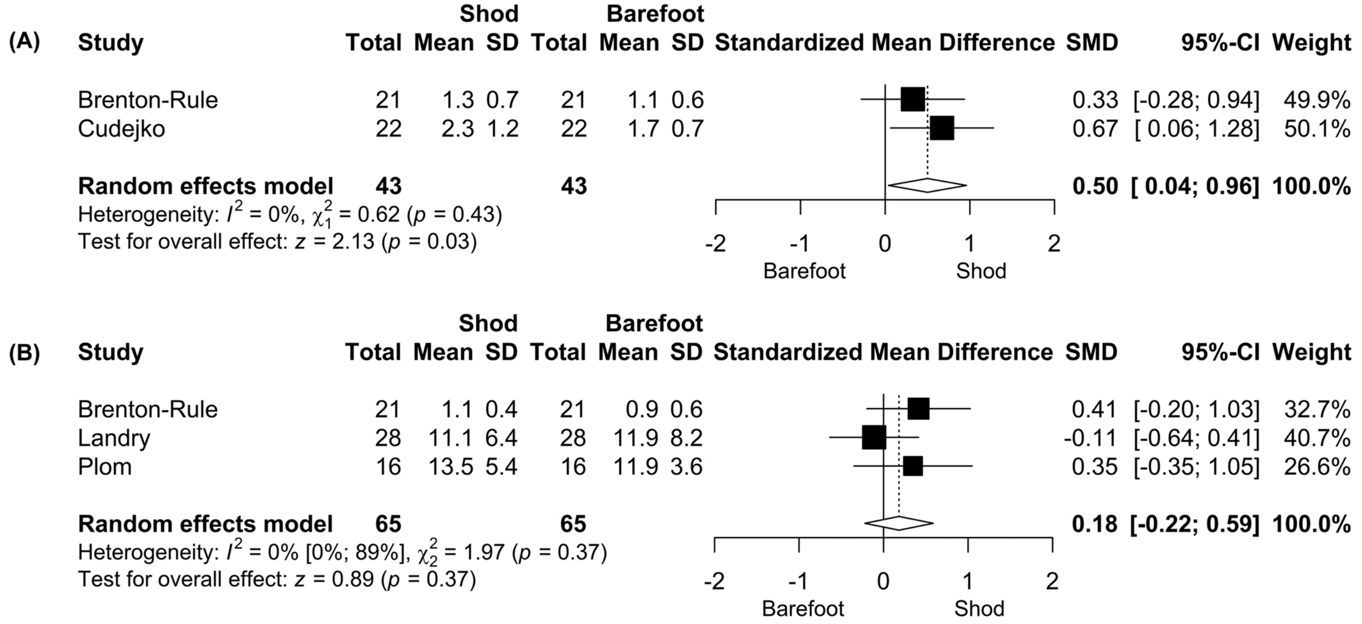
Heterogeneity: $I^2 = 0\%$, $\chi^2_1 = 0.26$ ($p = 0.61$)
Test for overall effect: $z = 2.71$ ($p < 0.01$)

(B)

| Study | Shod Total | Shod Mean | Shod SD | Barefoot Total | Barefoot Mean | Barefoot SD | SMD | 95%-CI | Weight |
|---|---|---|---|---|---|---|---|---|---|
| Brenton-Rule | 21 | 1.8 | 0.5 | 21 | 1.4 | 0.6 | 0.70 | [ 0.07; 1.32] | 32.5% |
| Landry | 28 | 25.5 | 10.9 | 28 | 26.4 | 15.7 | -0.07 | [-0.59; 0.46] | 39.0% |
| Plom | 16 | 23.0 | 9.1 | 16 | 21.1 | 4.9 | 0.26 | [-0.44; 0.96] | 28.5% |
| **Random effects model** | **65** | | | **65** | | | **0.27** | **[-0.20; 0.75]** | **100.0%** |

Heterogeneity: $I^2 = 41\%$ [0%; 82%], $\chi^2_2 = 3.37$ ($p = 0.19$)
Test for overall effect: $z = 1.14$ ($p = 0.25$)

**Fig. 4.** Four out of eight eligible studies allowed meta-analyses per CoP outcome variable in healthy subjects. (A) In these healthy subjects with a mean age of 74 and 55, respectively, sway in the anterior-posterior plane with eyes closed was increased in shod compared with barefoot condition, indicating a decreased postural control during shod bipedal static posturography. (B) In contrast, sway in the anterior-posterior direction with eyes opened did not differ between foot conditions. These results support the benefit of measuring subjects with eyes closed during bipedal static posturography.



(A)

| Study | Shod Total | Shod Mean | Shod SD | Barefoot Total | Barefoot Mean | Barefoot SD | SMD | 95%-CI | Weight |
|---|---|---|---|---|---|---|---|---|---|
| Brenton-Rule | 21 | 1.3 | 0.7 | 21 | 1.1 | 0.6 | 0.33 | [-0.28; 0.94] | 49.9% |
| Cudejko | 22 | 2.3 | 1.2 | 22 | 1.7 | 0.7 | 0.67 | [ 0.06; 1.28] | 50.1% |
| **Random effects model** | **43** | | | **43** | | | **0.50** | **[ 0.04; 0.96]** | **100.0%** |

Heterogeneity: $I^2 = 0\%$, $\chi^2_1 = 0.62$ ($p = 0.43$)
Test for overall effect: $z = 2.13$ ($p = 0.03$)

(B)

| Study | Shod Total | Shod Mean | Shod SD | Barefoot Total | Barefoot Mean | Barefoot SD | SMD | 95%-CI | Weight |
|---|---|---|---|---|---|---|---|---|---|
| Brenton-Rule | 21 | 1.1 | 0.4 | 21 | 0.9 | 0.6 | 0.41 | [-0.20; 1.03] | 32.7% |
| Landry | 28 | 11.1 | 6.4 | 28 | 11.9 | 8.2 | -0.11 | [-0.64; 0.41] | 40.7% |
| Plom | 16 | 13.5 | 5.4 | 16 | 11.9 | 3.6 | 0.35 | [-0.35; 1.05] | 26.6% |
| **Random effects model** | **65** | | | **65** | | | **0.18** | **[-0.22; 0.59]** | **100.0%** |

Heterogeneity: $I^2 = 0\%$ [0%; 89%], $\chi^2_2 = 1.97$ ($p = 0.37$)
Test for overall effect: $z = 0.89$ ($p = 0.37$)

**Fig. 5.** In healthy subjects, sway in the medio-lateral plane was increased in shod compared with barefoot condition with (A) eyes closed, indicating decreased postural control during shod bipedal static posturography. (B) The meta-analysis of sway in the medio-lateral plane of healthy subjects with eyes opened revealed no difference between both foot conditions.

## 4. Discussion

In this systematic review, 207 (4%) out of 5189 original articles were eligible based on the recommended methodology reporting full information on demographics and applied standardized experimental set-ups during bipedal static posturography. The vast majority, namely 88% of studies, assessed postural control barefoot, while only 5% measured participants with shoes and 6% in both conditions, namely barefoot and with any kind of shoe. According to the large research effort of 12'341 analyzed subjects within the included studies of the systematic review, our first research question whether bipedal static posturography is applied in a standardized way with respect to demographics and experimental set-up is "no". Thus, methodologic inconsistencies in bipedal static posturography persist and hamper studies' comparability and pooled data analysis. Particularly, the duration of measurement varied largely as only one third of studies measured for a duration of at least 60 s. Besides that, methodological inconsistencies were specifically found regarding the foot position and sampling frequency, while two

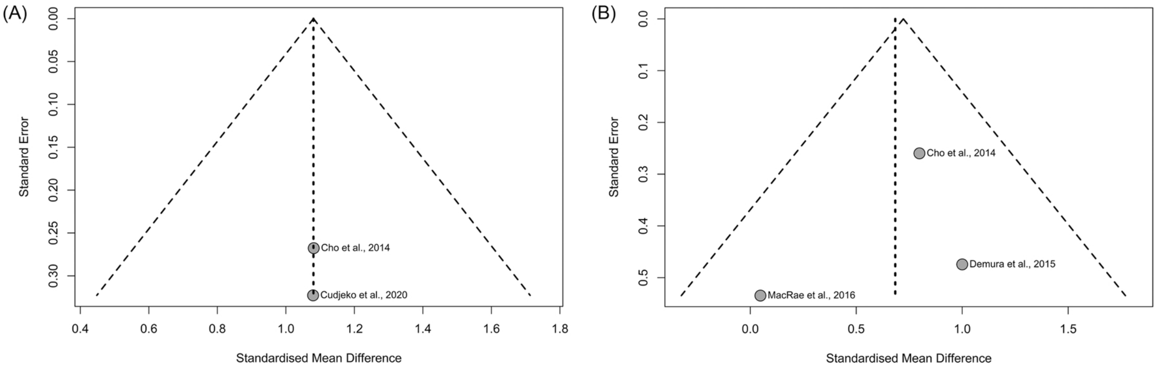


**Fig. 6.** Sparse but not biased publications comparing barefoot to shod (habitual footwear) condition analyzing sway velocity in the anterior-posterior plane with (A) eyes closed and (B) eyes opened.

thirds of studies measured subjects with EC and EO as recommended. This discrepancy between a huge research effort without data allowing pooled data analysis underline that we are currently far-out from standardized posturography albeit its wide use for five decades since its implementation in the early 1970s by Nashner et al. [28]. Moreover, standardized static posturography is particularly lacking in patients suffering from neurological diseases as indicated by 13% of included studies in the systematic review.

### *4.1. Meta-analysis with a limited number of studies comparing foot condition*

Regarding the meta-analysis on whether habitual footwear influence postural control in comparison to barefoot condition during bipedal static posturography in adult patients and healthy subjects allow merely preliminary conclusions. In detail, eight studies with heterogeneous study populations, namely with chronic stroke, low back pain or healthy subjects, met the inclusion criteria, of which only part of studies reported the same COP parameters—disclosing the lack of standardized bipedal static posturography. Based on this sparse evidence comparing habitual footwear with barefoot bipedal, quiet, and unsupported stance on a firm static posturography force plate, we assume that habitual footwear might decrease postural control in chronic stroke and healthy subjects that needs further investigation in larger cohorts with particular focus on subgroup analyses regarding the subjects' age, physical activity, and health status in the future. Largest effect sizes were found for the CoP parameter *sway velocity* in the anterior-posterior and medio-lateral plane with EC followed by *sway velocity* in the anterior-posterior plane with EO within the heterogenous study samples indicating better postural control during barefoot compared to shod stance. Why postural control did not differ between habitual footwear and barefoot conditions in chronic low back pain patients remains unclear and might indicate a decreased lumbar sensory transmission that needs further investigation. These preliminary findings due to the sparse available standardized data and the wide range of sample characteristics were supported by our meta-analyses of healthy subjects regarding the CoP outcome variable *sway in the anterior-posterior* and *medio-lateral plane with EC*. These analyses pinpoints that wearing habitual shoes increases the length of sway in both planes with EC in comparison to barefoot condition, emphasizing the benefit of measuring subjects with EC.

### *4.2. Postural control in patients and healthy subjects over the adult life span*

Sway velocity in the anterior-posterior plane was increased in shod compared with barefoot condition with EC and EO in young and middle aged healthy subjects and chronic stroke patients, indicating that shoes might decrease postural control. Furthermore, sway velocity in the medio-lateral plane was increased in shod compared with barefoot condition with EC in middle aged healthy subjects and chronic stroke patients, suggesting again that shoes decrease postural control. Beyond that, sway was increased in healthy subjects with EC wearing habitual shoes in comparison to barefoot stance, thus indicating decreased balance whilst wearing habitual shoes. However, current evidence suggests

**Box 1**
Standardized methodology for assessing postural control by bipedal, static posturography.

1. Demographics (age, sex distribution)
2. Arthrometry (body weight, body height)
3. Physical activity status
4. Health status
5. Sample size with power calculation
6. Experimental set-up with defined
    - bipedal, quiet and unsupported stance
    - foot position (self-selected foot placement and traced foot position by using templets for repetitions and/ or follow-up measurements)
    - foot condition (barefoot and habitual footwear)
    - visual condition (EC and EO); no perturbed visual input
    - duration of measurement (90 s)
    - number of trials per condition (3–5 repetitions)
    - CoP parameters (sway velocity in the anterior-posterior and medio-lateral plane, sway (interchangeable with range or path or excursion) in the anterior-posterior and medio-lateral plane, root mean square, total range independent from plane, sway vector)
    - force plate with a firm surface
    - sampling rate (100 Hz), cut-off filter (10 Hz)

that footwear becomes more relevant to ageing in terms of fall risks [29], and optimizing footwear is recommended during ageing to prevent falls [30]. Although, we recommend age-stratified analysis for future analysis based on larger samples, there is evidence footwear impairs foot position awareness in both the young and the elderly [31].

On the neuronal level, past studies showed a significant impact of shoes on the proprioceptive system [32], the joint position sense [33], the sensitivity to foot position [31], and on the tactile system [34]. As the tactile and proprioceptive system are altered during ageing and in neurological diseases e.g. multiple sclerosis [35], stroke [36], and Parkinson's disease [37,38], it seems evident that balance is more affected by shoes in these groups compared to healthy subjects. Data on chronic stroke patients by Cho et al. [20] and by Ferreira et al. [23] could not be pooled as they measured sway velocities and range, respectively. The presented, however preliminary, results due to mixed populations, suggest that barefoot condition provide better postural control in healthy young adults as well as during aging in healthy and chronic stroke patients that needs further research of larger samples allowing for subgroup analyses. Our data underline that advancing the field is relevant as postural deficits during static posturography has been shown to predict gait and balance dysfunction that were not visible through functional tests such as the Timed Up and Go or Timed 25-Foot Walk [39]. Thus, we emphasize the need of complete reporting of demographic and experimental set-up according to the recommended parameters (Box 1).

### 4.3. Limitations

First, included subjects were mixed with respect to diseases and age probably confound results. However, these are the first data available in the field and help to pinpoint the topic's relevance. Second, all included trials for the meta-analysis showed substantial heterogeneity in the experimental set-up including foot position, eye condition, duration, repetitions, sampling rate and cut-offs as well as a moderate to high risk of bias, indicating again the need for applied standardized posturography. Third, two studies [22,26] on young healthy subjects had a poor study quality rating according to our scoring, which emphasizes the current lack of evidence on whether habitual footwear influence postural control in comparison to barefoot condition. Fourth, we excluded studies on patients with spinal cord injury due to the restricted unsupported stance that need additional investigation. Fifth, we excluded all trials using Wii balance boards as CoP outcome measures are at least partly incomparable to force plates having limitations on accuracy, precision, and validity [40,41], and thus current evidence justify its exclusion. Sixth, only a very limited number of CoP parameters could be pooled for meta-analyses due to the limited standardized methodology, and a promising and robust CoP parameter, i.e. the *sway vector*, should be also considered in future research [1]. Seventh, even though the eligible studies for the systematic review investigated a wide range of sample characteristics regarding age and diseases, e.g. Parkinson's disease, multiple sclerosis and neuropathy, these original data could not be pooled for the meta-analysis due to the lack of standardized methodology and the lack of comparing foot conditions.

### 4.4. Future perspective

Here, we endorse the recommendation by Ruhe and colleagues regarding the full information on demographics and the experimental set-up [2]. Therefore, we suggest a measurement duration of 90 s, a sampling frequency of 100 Hz and at least 3 measurement repetitions. To advance knowledge whether habitual footwear decreases postural control measured by bipedal, static posturography, we suggest a measurement duration of 90 s which has not yet been performed comparing habitual footwear to barefoot condition. Moreover, a standardized methodology will be the prerequisite for pooled data analysis and enlarged sample sizes for multivariate regression models controlling for age, sex, body weight, height, and diseases that will help to provide robust evidence and clinical recommendations regarding postural control during barefoot and habitual foot condition.

### 4.5. Conclusion

This systematic work pinpoints the large heterogeneity of applied bipedal static posturography and the sparse evidence comparing habitual footwear with barefoot condition. Our methodological recommendations for standardized bipedal static posturography might pave the way for larger pooled data analyses, and thus better predict patients' outcome trajectories in the future.

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## CRediT authorship contribution statement

**Stefan Reutimann:** Validation, Formal analysis, Investigation, Data curation, Writing – original draft, Visualization. **MaryJane Hill-Strathy:** Validation, Investigation, Writing – review & editing. **Carmen Krewer:** Conceptualization, Methodology, Investigation, Writing – review & editing. **Jeannine Bergmann:** Conceptualization, Methodology, Writing – review & editing. **Friedemann Müller:** Conceptualization, Resources, Writing – review & editing. **Klaus Jahn:** Conceptualization, Resources, Writing – review & editing. **Katrin Rauen:** Conceptualization, Methodology, Validation, Investigation, Resources, Data curation, Writing – original draft, Writing – review & editing, Visualization, Supervision, Project administration.

## Conflict of interest

None.

## Data availability

All data are included in the main manuscript or supplemental files. R code of statistical analysis will be provided upon reasonable request from any qualified investigator.

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## Appendix A. Supplementary material

Supplementary data associated with this article can be found in the online version at doi:10.1016/j.gaitpost.2021.11.022.

## References

[1] J.W. Blaszczyk, The use of force-plate posturography in the assessment of postural instability, Gait Posture 44 (2016) 1–6.

[2] A. Ruhe, R. Fejer, B. Walker, The test-retest reliability of centre of pressure measures in bipedal static task conditions–a systematic review of the literature, Gait Posture 32 (2010) 436–445.

[3] P.A. Hageman, J.M. Leibowitz, D. Blanke, Age and gender effects on postural control measures, Arch. Phys. Med. Rehabil. 76 (1995) 961–965.

[4] J.W. Blaszczyk, M. Beck, D. Sadowska, Assessment of postural stability in young healthy subjects based on directional features of posturographic data: vision and gender effects, Acta Neurobiol. Exp. 74 (2014) 433–442 (Wars.).

[5] L. Chiari, L. Rocchi, A. Cappello, Stabilometric parameters are affected by anthropometry and foot placement, Clin. Biomech. 17 (2002) 666–677 (Bristol, Avon).

[6] H. Liu, A. Frank, Tai chi as a balance improvement exercise for older adults: a systematic review, J. Geriatr. Phys. Ther. 33 (2010) 103–109.

[7] R. Orr, J. Raymond, M. Fiatarone Singh, Efficacy of progressive resistance training on balance performance in older adults: a systematic review of randomized controlled trials, Sports Med. 38 (2008) 317–343.

[8] S.M. Kim, F. Qu, W.K. Lam, Analogy and explicit motor learning in dynamic balance: posturography and performance analyses, Eur. J. Sport Sci. 21 (2021) 1129–1139.

[9] M.B. Alsufiany, E.B. Lohman, N.S. Daher, G.R. Gang, A.I. Shallan, H.M. Jaber, Non-specific chronic low back pain and physical activity: a comparison of postural control and hip muscle isometric strength: a cross-sectional study, Medicine 99 (2020), e18544 (Baltimore).

[10] S. Phu, S. Vogrin, A. Al Saedi, G. Duque, Balance training using virtual reality improves balance and physical performance in older adults at high risk of falls, Clin. Interv. Aging 14 (2019) 1567–1577.

[11] C.G. Horlings, B.G. van Engelen, J.H. Allum, B.R. Bloem, A weak balance: the contribution of muscle weakness to postural instability and falls, Nat. Clin. Pract. Neurol. 4 (2008) 504–515.

[12] J. Tollár, F. Nagy, B. Csutorás, N. Prontvai, Z. Nagy, K. Török, E. Blényesi, Z. Vajda, D. Farkas, B.E. Tóth, I. Repa, M. Moizs, D. Sipos, A. Kedves, Á. Kovács, T. Hortobágyi, High frequency and intensity rehabilitation in 641 subacute ischemic stroke patients, Arch. Phys. Med. Rehabil. 102 (2021) 9–18.

[13] M. Tramontano, D. Dell'Uomo, A.M. Cinnera, C. Luciani, C. Di Lorenzo, M. Marcotulli, F. Vona, A. Mercuro, S. Abbruzzese, Visual-spatial training in patients with sub-acute stroke without neglect: a randomized, single-blind controlled trial, Funct. Neurol. 34 (2019) 7–13.

[14] F. Scoppa, R. Capra, M. Gallamini, R. Shiffer, Clinical stabilometry standardization: basic definitions–acquisition interval–sampling frequency, Gait Posture 37 (2013) 290–292.

[15] O. Hue, M. Simoneau, J. Marcotte, F. Berrigan, J. Doré, P. Marceau, S. Marceau, A. Tremblay, N. Teasdale, Body weight is a strong predictor of postural stability, Gait Posture 26 (2007) 32–38.

[16] J.M. Hijmans, J.H. Geertzen, P.U. Dijkstra, K. Postema, A systematic review of the effects of shoes and other ankle or foot appliances on balance in older people and people with peripheral nervous system disorders, Gait Posture 25 (2007) 316–323.

[17] A. Brenton-Rule, S. Bassett, A. Walsh, K. Rome, The evaluation of walking footwear on postural stability in healthy older adults: an exploratory study, Clin. Biomech. 26 (2011) 885–887 (Bristol, Avon).

[18] P.A. Federolf, L. Roos, B. Nigg, The effect of footwear on postural control in bipedal quiet stance, Footwear Sci. 4 (2012) 115–122.

[19] Guideline for the Prevention of Falls in Older Persons. American Geriatrics Society, British Geriatrics Society, and American Academy of Orthopaedic Surgeons Panel on Falls Prevention, J. Am. Geriatr. Soc., 49, 2001, pp. 664–672.

[20] K. Cho, W. Lee, Changes in postural sway according to footwear types of hemiparetic stroke patients, J. Phys. Ther. Sci. 26 (2014) 861–864.

[21] T. Cudejko, J. Gardiner, A. Akpan, K. D'Aout, Minimal footwear improves stability and physical function in middle-aged and older people compared to conventional shoes, Clin. Biomech. 71 (2019) 139–145 (Bristol, Avon).

[22] T. Demura, S. Demura, M. Uchiyama, T. Kitabayashi, K. Takahashi, Effect of shoes with rounded soft soles in the anterior-posterior direction on the center of pressure during static standing, Foot 25 (2015) 97–100 (Edinb.).

[23] L.A.B. Ferreira, M. Galli, R.D. Lazzari, A.J.L. Dumont, V. Cimolin, C.S. Oliveira, Stabilometric analysis of the effect of postural insoles on static balance in patients with hemiparesis: a randomized, controlled, clinical trial, J. Bodyw. Mov. Ther. 21 (2017) 290–296.

[24] S.C. Landry, B.M. Nigg, K.E. Tecante, Standing in an unstable shoe increases postural sway and muscle activity of selected smaller extrinsic foot muscles, Gait Posture 32 (2010) 215–219.

[25] C.S. MacRae, D. Critchley, M. Morrissey, A. Shortland, J.S. Lewis, Do rocker-sole shoes influence postural stability in chronic low back pain? A randomised trial, BMJ Open Sport Exerc. Med. 2 (2016), e000170.

[26] W. Plom, S.C. Strike, M.J. Taylor, The effect of different unstable footwear constructions on centre of pressure motion during standing, Gait Posture 40 (2014) 305–309.

[27] T. Cudejko, J. Gardiner, A. Akpan, K. D'Août, Minimal shoes improve stability and mobility in persons with a history of falls, Sci. Rep. 10 (2020) 21755.

[28] L.M. Nashner, A model describing vestibular detection of body sway motion, Acta Oto-Laryngol. 72 (1971) 429–436.

[29] A.L. Hatton, K. Rome, Falls, footwear, and podiatric interventions in older adults, Clin. Geriatr. Med 35 (2019) 161–171.

[30] J.C. Menant, J.R. Steele, H.B. Menz, B.J. Munro, S.R. Lord, Optimizing footwear for older people at risk of falls, J. Rehabil. Res. Dev. 45 (2008) 1167–1181.

[31] S. Robbins, E. Waked, J. McClaran, Proprioception and stability: foot position awareness as a function of age and footwear, Age Ageing 24 (1995) 67–72.

[32] A. Zech, S. Meining, K. Hotting, D. Liebl, K. Mattes, K. Hollander, Effects of barefoot and footwear conditions on learning of a dynamic balance task: a randomized controlled study, Eur. J. Appl. Physiol. 118 (2018) 2699–2706.

[33] K. Sekizawa, M.A. Sandrey, C.D. Ingersoll, M.L. Cordova, Effects of shoe sole thickness on joint position sense, Gait Posture 13 (2001) 221–228.

[34] A.A. Priplata, J.B. Niemi, J.D. Harry, L.A. Lipsitz, J.J. Collins, Vibrating insoles and balance control in elderly people, Lancet 362 (2003) 1123–1124.

[35] P. Rougier, M. Faucher, S. Cantalloube, D. Lamotte, M. Vinti, P. Thoumie, How proprioceptive impairments affect quiet standing in patients with multiple sclerosis, Somatosens. Mot. Res. 24 (2007) 41–51.

[36] L.M. Carey, T.A. Matyas, C. Baum, Effects of somatosensory impairment on participation after stroke, Am. J. Occup. Ther. 72 (2018) 7203205100, 7203205100p7203205101-7203205100p7203205110.

[37] M. Vaugoyeau, S. Viel, C. Assaiante, B. Amblard, J.P. Azulay, Impaired vertical postural control and proprioceptive integration deficits in Parkinson's disease, Neuroscience 146 (2007) 852–863.

[38] B. Pratorius, S. Kimmeskamp, T.L. Milani, The sensitivity of the sole of the foot in patients with Morbus Parkinson, Neurosci. Lett. 346 (2003) 173–176.

[39] N.E. Fritz, S.D. Newsome, A. Eloyan, R.E. Marasigan, P.A. Calabresi, K. M. Zackowski, Longitudinal relationships among posturography and gait measures in multiple sclerosis, Neurology 84 (2015) 2048–2056.

[40] H.L. Bartlett, L.H. Ting, J.T. Bingham, Accuracy of force and center of pressure measures of the Wii Balance Board, Gait Posture 39 (2014) 224–228.

[41] R.A. Clark, B.F. Mentiplay, Y.H. Pua, K.J. Bower, Reliability and validity of the Wii Balance Board for assessment of standing balance: a systematic review, Gait Posture 61 (2018) 40–54.