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Flavien Quijoux, Aliénor Vienne-Jumeau, François Bertin-Hugault, Philippe Zawieja, Pierre-Paul Vidal, et al.. Center of pressure displacement characteristics differentiate fall risk in older people: A systematic review with meta-analysis. Ageing Research Reviews - ARR, 2020, 62, pp.101117. 10.1016/j.arr.2020.101117. hal-03190290

HAL Id: hal-03190290

<https://hal.science/hal-03190290>

Submitted on 6 Apr 2021

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Center of pressure displacement characteristics differentiate fall risk in older people: A systematic review with meta-analysis

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ARTICLE INFO

Keywords:

Older fallers
Quiet standing
Balance
Center of pressure (COP)
Prediction
Risk of falling

ABSTRACT

Falling is the second most prevalent cause of accidental death in the world. Currently available clinical tests to assess balance in older people are insufficiently sensitive to screen for fall risk in this population. Laboratory tests that record the center of pressure (COP) trajectory could overcome this problem but despite their widespread use, the choice of COP trajectory features for use as a biomarker of fall risk lacks consensus. This systematic review and meta-analysis aimed at identifying the best COP characteristics to predict risk of falling in older adults. More than 4000 articles were screened; 44 (7176 older adults) were included in this study. Several COP parameters emerged as good indices to discriminate fallers from non-fallers. From sensitivity analysis, Sway area per unit time, anteroposterior mean velocity, and radial mean velocity were the best traditional features. In this study, identification of older people with a high fall risk was demonstrated using quiet-standing recordings. Such screening would also be useful for routine follow-up of balance changes in older fallers in clinical practice.

1. Introduction

Falls in older people are a major issue, representing one of the main causes of injury deaths in this age-group (“WHO global report on falls prevention in older age,” 2008). A non-fatal fall can lead to severe injuries such as hip fracture or traumatic brain injury, especially in a population who often also suffer from confounding conditions such as osteoporosis (Resnick et al., 2014) or brain atrophy (Seidler et al., 2010; Sheridan and Hausdorff, 2007; Yamada et al., 2013). The risk of falling is approximately 15 % for people older than age 65, rising to 25 % for those older than age 80 (HAS, 2009; Rubenstein, 2006). Falls also result in a fear of falling again in the future (Arfken et al., 1994; Murphy and Isaacs, 1982; Vellas et al., 1997) and consequently physiological deconditioning (Iaboni et al., 2015; Malini et al., 2016; Prabhakaran et al., 2019), which itself creates substantial financial healthcare costs (HAS, 2009). For patients, reduced independence increases anxiety, social isolation, psychomotor problems related to the fall, and the subsequent development of any otherwise preventable chronic diseases that result from the traumatic consequences that limit physical activity (Lee et al.,

2007; Pereira et al., 2008).

Estimating the risk of falling could provide guidance for adapting rehabilitation programs and provision of care. The occurrence of falls depends on extrinsic factors in the environment such as insufficient lighting or obstacles, for example, as well as intrinsic factors related to the physical capacities of the individual (Datta et al., 2018; Deandrea et al., 2013). Intrinsic precipitating causes have been associated with up to 80 % of falls recorded in institutionalized older people, with the highest prevalence amongst the oldest people (Bueno-Cavanillas et al., 2000). Intrinsic precipitating causes include a past history of falls (Gerdhem et al., 2005), dementia (Scherder et al., 2007), degeneration and lesions of the visual, vestibular and proprioceptive systems (Goble et al., 2009), gait and balance disorders (Seidler et al., 2010), sarcopenia (Landi et al., 2012), and other musculoskeletal modifications (Álvarez Barbosa et al., 2016; Kinney, 2004), all of which can lead to instabilities in different contexts (Bock and Schneider, 2002; Horak, 2006; Li et al., 2018).

Individual fall-risk factors can be monitored longitudinally and the results used in predictive risk-score calculations (Wihlborg et al., 2015).

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<https://doi.org/10.1016/j.arr.2020.101117>

Received 26 November 2019; Received in revised form 7 June 2020; Accepted 15 June 2020

Available online 19 June 2020

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However, all fall prevention efforts face the problem that postural control is dependent on the functioning of many underlying interacting systems: vestibular, proprioceptive and visual information merge to provide people with an internal, sensory representation of their body's movement (Horak, 2006; Ricci et al., 2009) while biomechanical properties, such as reflexive mechanisms (Ho and Bendrup, 2002; Srulijes et al., 2015; Suzuki and Geyer, 2018), and cognitive processing (Borel and Alescio-Lautier, 2014; Mahboobin et al., 2008) are factors that are involved in the maintenance of body equilibrium.

The detection of intrinsic fall-risk factors is complicated, especially before any fall has occurred. Solutions are needed, however, to help more easily detect larger numbers of 'future fallers' either in the field (such as at home or in an institution) or in a clinical setting. For this review we have chosen to explore one such potential method: the use of quiet standing posturography. This study was based on our clinical experience to date which led us to believe that routine, detailed and automatic quantification of motor control using posturography at rest, and the monitoring of locomotion by inertial sensors in an elderly population may provide an accessible and reliable indicator of fall risk (Howcroft et al., 2013; Truong et al., 2019).

The possibility that static posturography could detect future fallers before they fall is particularly attractive because, to date, existing clinical tests to detect those at fall risk have only shown limited success (Horak, 1987) and have not provided better identification of future fallers than practitioners' subjective clinical judgments (da Costa et al., 2012) or the fall history questionnaire (Gates et al., 2008). The reasons given for these test failures include: (1) a lack of objectivity and experimenter bias; (2) an inability to identify balance disorders (Mancini and Horak, 2010); (3) an insensitivity to minor changes in balance ability (Downs et al., 2013; Pajala et al., 2008); (4) poor sensitivity or specificity (depending on the particular test) (da Costa et al., 2012); (5) inconsistent test cut-off values between studies (Beauchet et al., 2011; Lima et al., 2018; Schoene et al., 2013; Shumway-Cook et al., 2000); (6) a susceptibility to ceiling effects (Balasubramanian, 2015); (7) test results being unrelated to fall incidence (Barry et al., 2014; Brodie et al., 2017) and (8) the fact that tests take a long time because they are often complicated (Langley et al., 2007; Perell et al., 2001; Vassallo et al., 2008; Zampieri et al., 2010).

Therefore, a test is needed to provide clinicians with objective and reliable measures of balancing abilities, especially for the frailest older adults, which would complement the functional tests already used in clinical practice. We believe that quantitative posturographic tests, which assess balance by recording center of pressure (COP) oscillations (Błaszczyk, 2016), could provide this useful information to complement the functional tests (Mancini and Horak, 2010; Muir et al., 2010).

Sway parameters extracted from posturography data have been shown to correlate with both fall risk factors (Nardone and Schieppati, 2010; Bauer et al., 2010) and deficient postural strategies (Dueñas et al., 2016; Kręćisz and Kuczyński, 2018). In addition, posturography has been proposed as a means of detecting age-related alterations of postural control at sensory (Alcock et al., 2018), central (Nandi et al., 2018; Ozdemir et al., 2018) musculoskeletal levels (King et al., 2019). Among healthy older people who live in the community, balance and sway measurements have been found to be strong predictors of fall risk (Audiffren et al., 2016; Johansson et al., 2017; Piirtola and Era, 2006; Watt et al., 2018). Finally, an objective, instrumental assessment of sway may also be helpful to guide and evaluate the efficiency of rehabilitation programs aiming at reducing the risk of falling (HAS, 2007).

Before continuing with this review, however, it should be noted that the aim is not to establish posturography as a sole means of predicting falls. Despite its encouraging results, posturography also has several shortcomings to detect future fallers. The first is that rather than occurring during quiet standing, most falls actually happen during locomotor tasks (Talbot et al., 2005) and activities of daily living (van Emmerik and van Wegen, 2002), a fact which limits the wider

applicability of COP recordings (Doyle et al., 2005; Ruhe et al., 2010). Secondly, while averaged parameters of the whole COP trajectory have moderate-to-high reliability (Jeter et al., 2015, 2015; Lafond et al., 2004; Li et al., 2016; Lin et al., 2008; Moghadam et al., 2011), the necessary data collection requires long recording periods and several repetitions (Doyle et al., 2007; Lafond, 2006; Ruhe et al., 2010) which would probably make the method inconvenient for everyday clinical practice. Thirdly, to date, the neurophysiological determinants of the various COP parameters are ill-defined (Palmieri et al., 2002; Visser et al., 2008).

In summary, therefore, although there is room for improvement in the use of quiet standing posturography as a tool for the detection the risk of future falls in patients, it is nevertheless worthy of further consideration especially since, at present, it appears to outperform many other tests that are currently being used clinically. The objective of this systematic review, therefore, is to identify the most relevant parameters, conditions and caveats that will allow posturography at rest to be used with the greatest level of confidence to identify fall risk in elderly people.

2. Methods

The literature search and analysis followed the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) (Moher et al., 2009) and Meta-analysis of Observational Studies in Epidemiology (MOOSE) (Stroup et al., 2000) guidelines.

2.1. Literature search strategy

The search strategy can be found in (Quijoux et al., 2019) and is described in the registration on PROSPERO (International Prospective Register of Systematic Reviews) (Registration: CRD42018098671 on June 19, 2018; last edited on January 17, 2020). The methods for the meta-analysis were specified prior to the completion of the inclusion of studies and the full method has been previously published (Quijoux et al., 2019). Between March 2017 and July 2019, a systematic literature review was conducted to identify COP characteristics that best distinguish older fallers from older non-fallers. Four electronic databases were searched: PubMed, ScienceDirect, EMBASE, and the Cochrane Library. The search was performed for all articles published (without date restriction) until July 1, 2019. In addition, a search of 'gray' literature (Conn et al., 2003) was performed which included items like reports, theses and studies that were found online using Google Scholar, ClinicalTrials.gov sources, Google, theses.fr, HAL, ResearchGates and ethos.bl.uk.

All reference lists from included studies were reviewed for additional relevant studies. Many different types of studies were included, because the aim was not to find a fall reduction intervention but to investigate the discriminative abilities of bipedal quiet stance tests. From all of the sources found, data which related to fall risk in older people (defined as being aged 60 years and older) who had undergone quiet-standing measurement of their balance was used provided that the researchers had used stabilometry to quantify postural control. Sources came from both retrospective and prospective clinical trials (randomization was not a requisite), and observational studies (time series, longitudinal or cross-sectional). The papers had to be written in a language understood by the authors (i.e. English, French, Italian, Spanish or German).

2.2. Screening process

Research was considered for inclusion if it contained: (1) a comparison of older fallers and older non-fallers; (2) a record of the number of falls in each group; (3) an analysis of COP recordings during quiet standing for people who had both feet on the ground; (4) an evaluation of the risk of falling using the number of falls retrospectively or

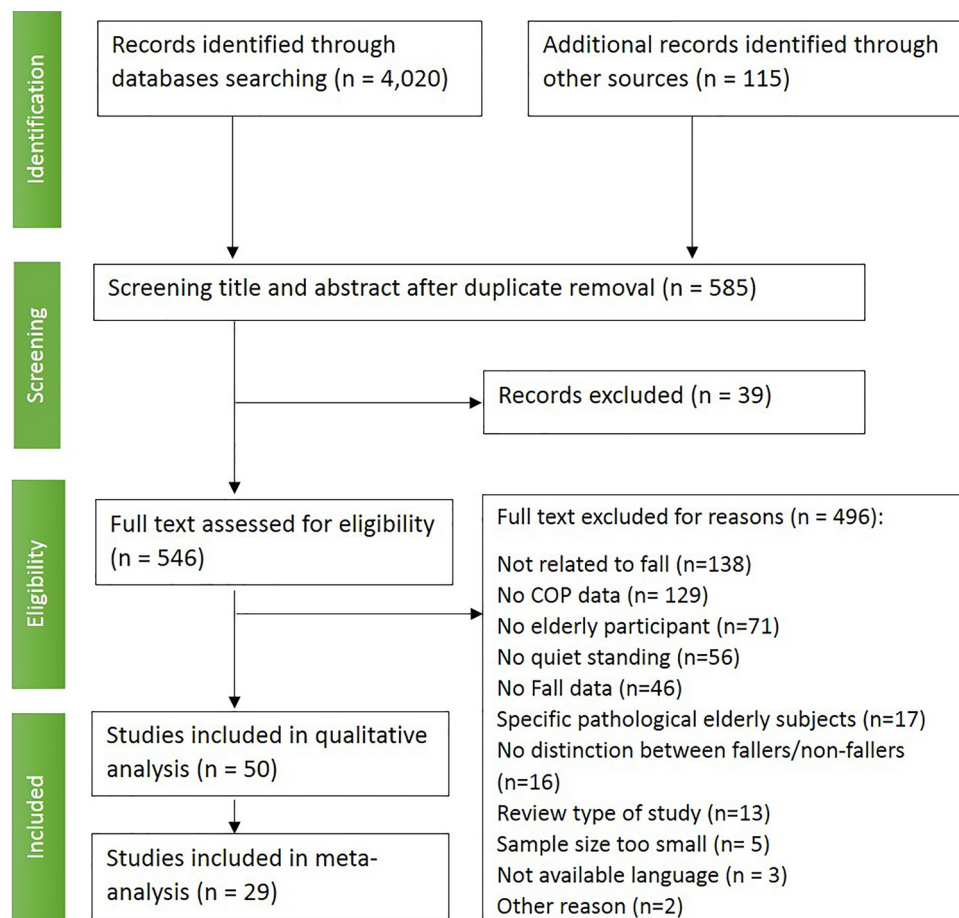


Fig. 1. Flowchart of the systematic review process.
COP: center of pressure

prospectively. Two authors (FQ and AV) independently screened potentially eligible studies for inclusion on the basis of their title, abstract and full text.

FQ and AV performed the risk of bias assessment by using a 26-item checklist based on [Downs and Black \(1998\)](#) (Risk of bias assessment checklist - Supplementary material). This score out of 32 evaluates the risk of bias, with a high value representing low risk. Then, one author (FQ) extracted and collated the data, following the recommendations of the Joanna Briggs Institute Reviewers' Manual ([The Joanna Briggs Institute, 2015](#)) while another author (AV) verified the data extracted from the included articles to confirm their suitability. If any study lacked data or information regarding the participants (even after contacting the authors) it was excluded from the meta-analysis.

2.3. Data pooling strategy

For pooling predictive data from COP recordings, at least three studies must have computed the same COP feature in similar, quiet-standing conditions. This meant that they used the same type of study and that participants were asked to maintain the same foot position and eye conditions (i.e. open, closed or blindfolded) in order to reduce inter-study inconsistency as far as possible. The algorithm to compute the pooled results was developed under Python Language Reference v3.7.2 (Python Software Foundation) to allow a sensitivity analysis regarding the experimental conditions ([Quijoux et al., 2020](#)).

2.4. Overall quality of the evidence

The overall quality of the evidence per outcome was evaluated by a

rating system ([Quijoux et al., 2019](#)) adapted from the GRADE system ([Ryan and Hill, 2016](#)) for longitudinal follow-up studies. This assessment estimated the overall risk of bias for each variable by rating (i) the number of studies using this variable, (ii) their average risk of bias score, (iii) data heterogeneity, as measured by I^2 ([Higgins et al., 2003](#)) and (iv) the cumulative sample size. To visualize possible publication biases, funnel diagrams were used; they represented the estimated effect size of each article in relation to the average standard error mean as plotted on the vertical axis. A symmetrical inverted funnel shape indicated that there was no publication bias.

2.5. Dataset duplication

One important factor we encountered which affected our analysis was dataset duplication. This was where certain authors appeared to have used the same data set for several different (published) studies. For example, [Baloh et al. \(1998a\)](#) used the same sample as [Baloh et al. \(1994, 1998b\)](#) used some of the same data as [Baloh et al. \(1995\)](#); [Merlo et al. \(2012\)](#) used the same data set as [Maranesi et al. \(2016\)](#); [Topper et al. \(1993\)](#), as reported by ([Piirtola and Era, 2006](#)), used data from two studies published by [Maki et al. \(Maki, 1993; Maki et al., 1991\)](#) while [Lajoie and Gallagher \(2004\)](#) used a part of the dataset from a previous article ([Lajoie et al., 2002](#)). In all of these cases, we used the most recent report for data extraction and the other studies were reviewed as sources of complementary information. For [Hur et al. \(2009a\)](#), we used information from [Leveille et al. \(2008\)](#) to define the inclusion criteria and used ([Hur, 2011](#)) for participants' demographics and ([Hur et al., 2009b](#)) as a reference for data extraction.

3. Results

The original search identified more than 4000 publications as potentially relevant for addressing the question of discriminating fallers from non-faller based on quiet stance testing. After reading all of their titles and abstracts, 546 articles were subsequently screened in more detail for possible inclusion. These reviews led to a total of 50 studies being eligible for qualitative analysis but after removing reports that used duplicate datasets from other articles, a total of 44 articles ($n = 7176$ participants) remained for final analysis (Fig. 1) (List of included studies - Supplementary material).

3.1. Qualitative analysis

3.1.1. Risk of bias assessment

From the 26-item check list, the risk of bias evaluation revealed a moderate risk of bias, with a mean score of $15 \pm 4/32$ [range: 8–23]. To assess the overall methodological quality of each article, the criteria assessed with the checklist awarded one point if it was met or zero if it was not, except for two criteria. One assessing the generalizability of the results (awarding up to 2 points) and the other assessing the statistical power of the study (awarding up to 5 points). The score is therefore the sum of the points obtained. Only 18 studies reported the number of falls and the COP features computed for each group of participants. Otherwise, studies reported recording conditions well ($n = 38$) and used appropriate statistics ($n = 34$). The studies included in the quantitative analysis had a mean score of $16 \pm 3/32$ and the excluded studies $13 \pm 3/32$.

3.1.2. Demographics data

From the total pooled population of 7176 older participants, 4842 were older non-fallers (NFs), 1554 were occasional fallers (OFs; defined as having fallen at least once) and 640 were frequent fallers (FFs; defined as having had two or more falls). There was also a group of 140 people who were described as unrecorded fallers (UFs), since records about how many times they fell were unavailable. Some studies grouped FFs (who had ≥ 2 falls during follow-up) with OFs (who had one recorded fall during the same period).

Only 28 of 44 studies reported sufficient information regarding participants' characteristics and inclusion criteria, the most common issue was the pooling of demographic data for fallers and non-fallers. Of the data available, the mean age of the NFs was 76 ± 5 years. For the fallers group, the average age was 77 ± 6 years (OFs) and 77 ± 4 (FFs), although these data came from the 31 studies who reported the mean ages of each group separately. The studies lacked data regarding weight, height or body mass index (BMI). Ten studies reported data regarding cognitive evaluation (Mini Mental State Evaluation [MMSE]), although this information was used as an inclusion criterion. For example, Hur et al. (2009a); Laughton et al. (2003) and Park et al. (2014) used a cognitive test and participants were excluded below a certain score (24/30, 24/30 and 18/30, respectively) but none reported clear values of the cognitive evaluation.

Among the 7176 participants, most (80 %) were not institutionalized. Overall, 3495 (49 %) were community-dwelling people and 2234 (31 %) lived independently. Only 349 (5%) lived in a nursing home and 338 (10 %) were patients seen in medical settings. Therefore, although the average age of the population was over 75 years, for more than two thirds of the subjects there were no indications in the data of any existing pathology that would have affected their balance and therefore it could not be assumed that these people were fragile. Demographic information was not clear for 10 % of the pooled population and so could not be used.

3.1.3. Fall evaluation

One issue that was identified from the studies examined was that the definition of 'a fall' differed between authors. This was an important

point, since it influenced the number of falls that each research group recorded and the final classification of a patient as either a faller or a non-faller. In total, 23 studies used a referenced definition for classification of a fall; most chose either the definition from the Kellogg International Work Group (Kellogg International Work Group, 1987) and or from Tinetti et al. (Tinetti et al., 1988). In terms of classification, falls were often not associated with their consequences (e.g. a sustained injury or hospitalization). Among the 44 studies reviewed, the authors of the 26 retrospective papers based their identification of fallers on a history of falls following a physical interview and fall questionnaires or ($n = 1$) incident reports. For prospective studies ($n = 15$), the usual way to follow participants was to ask them to send back a calendar recording falls or postcards with ($n = 10$) or without ($n = 2$) phoning the person for complementary information. Thirteen (54 %) retrospective studies defined the faller group based on the presence of ≥ 1 falls in the previous 12 months before assessment. Similarly, six (40 %) prospective studies classified older people as fallers when they had a fall in the 12 months of follow-up. The period of interest was rarely longer than 12 months because of the difficulty following older participants.

3.1.4. Measurement conditions

Information regarding COP recording protocols was usually adequately detailed ($n = 38/44$). We noted some variability in the recording methodologies regarding the quiet-standing position (Fig. 2). Protocols included recording without a dual task (84 %), with one with eye open using a blindfold or with eyes closed (77 %). When information was available about recording conditions such as gaze direction (43 %) or posture (43 %), the most frequently used assessment technique was to ask the participant to look at a target that had been placed at eye level < 4 m away ($n = 12$), to stand as still as possible ($n = 15$) with arms at the sides ($n = 21$), barefoot ($n = 23/44$; 3 studies accepted flat shoes and 18 provided no information) and with feet placed in a comfortable position ($n = 21$) or in a narrow position with toes and heels touching ($n = 10$). In six studies, a condition using a foam pad was also set in addition to recording on the firm surface of the COP measurement tool. Most of the recording durations were < 35 s ($n = 34$). About half of the protocols ($n = 21$) specified several recordings [range: 2–10] to average the results or use only one of them.

3.1.5. Features computed

The diversity of the parameters derived from the COP trajectory can be confusing for practitioners. We classified the extracted features following Prieto et al. (1996) to summarize the use of the most common variables (List of center of pressure features and their definition - Supplementary material). The most common feature was 'COP mean velocity' ($n = 29$) in either the anteroposterior (AP) and mediolateral (ML) direction or in the radial direction (a combination of the two planes). 'Surface', defined as the area containing the COP trajectory (Rasku et al., 2012), was also widely used and 17 studies used it for their classification of fallers and non-fallers. Few studies shared the same recording conditions and similar COP features (Fig. 3). Surface was expressed in multiple ways, depending on the authors. Given this lack of information on calculation methods, different statokinesiogram surface values were grouped together without distinction being made between either the percentage of points included or the shape of the surface (which was generally circular or elliptical). As a result of these assumptions, therefore, our quantitative analysis excluded variables from several complex features which were included in only a few studies, such as time-frequency analysis of the COP time series as they could not be included in the meta-analysis.

The included studies mainly concluded on the inability of these features to find differences between fallers and non-fallers (Aufauvre et al., 2005; Maranesi et al., 2016; Muir et al., 2013), but some inconsistency was seen across studies (Bauer et al., 2010, 2016; Hur et al., 2009b; Lajoie et al., 2002; Lajoie and Gallagher, 2004). On the other

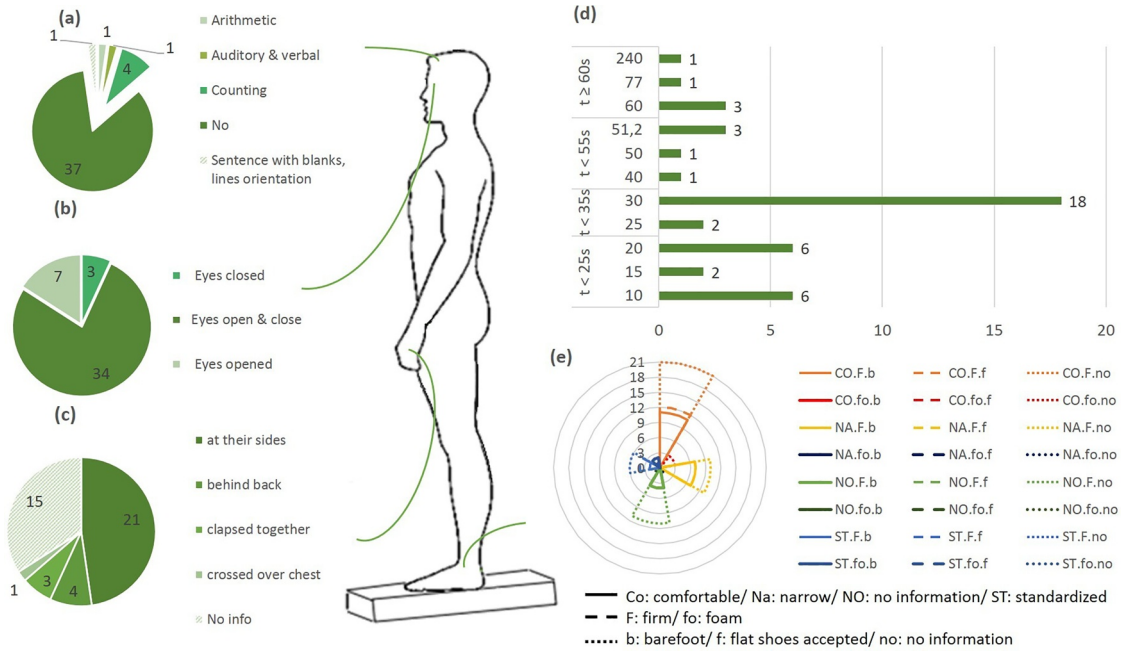


Fig. 2. Conditions of recordings.

- (a) Dual-task
 - (b) Eyes open or closed
 - (c) Hand position
 - (d) Duration of recording
 - (e) Feet position and surface
- Co: comfortable/ Na: narrow/ NO: no information/ ST: standardized
 - -F: firm/ fo: foam
 ——— b: barefoot/ f: flat shoes accepted/ no: no information

Recording conditions varied in order to increase the difficulty of the quiet stance tasks. These included the addition of (a) a dual task, (b) visual sensory deprivation or foot position and the addition of a foam cushion (e). The most frequently reported foot position was a comfortable position (as defined either by the researchers or the test subject). A standardized position orientates the feet and defines the distance between the heels and metatarsals. Arms are generally positioned in a relaxed manner next to the body but often too little information was given (c). Recording duration also varied; there were more short recordings of less than 35 s (d).

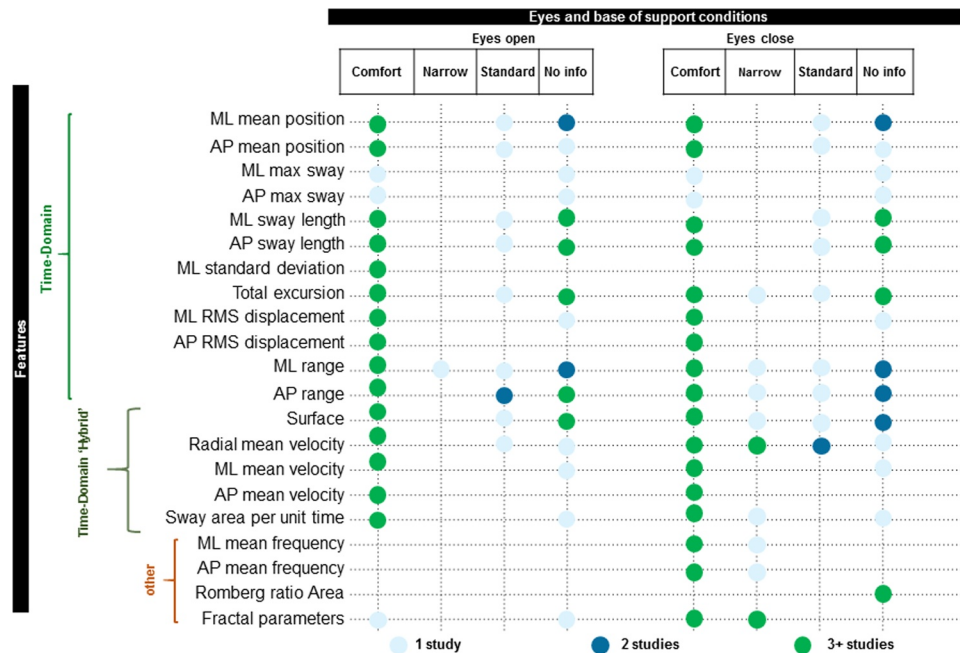


Fig. 3. Number of studies using COP features per condition.

ML: mediolateral; AP: anteroposterior; RMS: root mean square

The majority of the parameters are from the time domain. It was not possible to combine data from complex analyses due to the small number of studies that used the same recording conditions.

Table 1
Significant features for each condition with n ≥ 3 number of studies. Overall evidence ranges from very low and low to moderate and high.

Condition	Feature	p-value	Risk of bias score (mean of the 32-score)	Number of studies (n)	Heterogeneity (I ²)	Cumulative sample size	Quality	Overall evidence
			> 22	>10	<30%	>400	High	
			16–22	3-10	30-75%	200-400	Moderate	
			< 16	0-3	>75%	<200	Low	
Retrospective	AP sway length	0.039	13.33	6	45%	420	4	Low
	ML range	0.049	13.80	13	88%	894	4	Low
	AP mean velocity	0.027	16.67	6	27%	617	6	Moderate
	Radial mean velocity	0.003	15.50	16	88%	1531	4	Low
	Sway area per unit time	<0.001	16.40	5	0%	444	6	Moderate
Retrospective x EC x Comfortable	Sway area per unit time	0.012	17.00	3	0%	264	5	Moderate
	Radial mean velocity	0.028	16.50	4	96%	412	4	Low
Prospective	AP mean position	0.006	17.00	4	21%	540	6	Moderate
	ML sway length	0.011	18.00	8	66%	1732	5	Moderate
	Total excursion	0.008	19.00	10	81%	4834	4	Low
	AP RMS displacement	0.005	15.50	4	46%	392	3	Low
	AP mean velocity	0.005	16.33	6	28%	1208	6	Moderate
	Radial mean velocity	<0.001	17.29	7	64%	970	5	Moderate
Prospective x EO x Comfortable	AP mean velocity	0.008	16.33	3	0%	604	6	Moderate
	Radial mean velocity	0.001	16.33	3	40%	436	5	Moderate
Prospective x EC x Comfortable	Radial mean velocity	0.001	16.33	3	28%	436	6	Moderate
EO	AP mean position	0.012	15.80	5	9%	490	5	Moderate
	ML sway length	0.013	16.71	7	77%	1054	4	Low
	Total excursion	0.002	17.11	9	80%	2678	4	Low
	AP RMS displacement	0.006	15.25	4	35%	415	4	Low
	AP mean velocity	0.002	16.50	6	37%	907	5	Moderate
	Radial mean velocity	<0.001	15.60	9	49%	1131	4	Low
	ML Standard Deviation	<0.001	15.67	3	0%	411	5	Moderate
	Sway area per unit time	0.027	16.50	4	52%	788	5	Moderate
EC	ML range	0.040	15.67	9	92%	711	3	Low
	AP mean velocity	0.050	16.50	6	5%	918	6	Moderate
	Radial mean velocity	0.003	16.39	13	91%	1370	5	Moderate

Significantly different parameters for fallers and non-fallers are presented depending on the recording conditions in the selected studies. The p-value is presented for the Z-test evaluating the overall size effect. The cumulative evidence scale ranged from 0 (low) to 2 (high) for each item. The final quality rating is either very low (< 2), low (2–4), moderate (5–6) or high (> 6).

hand, several studies found that performance of a Stabilogram Diffusion Analysis (SDA), a stochastic method based on the auto-correlation of the COP trajectory, was significantly predictive of falling. The SDA could reveal two regimes characterized by their postural behavior, defined as an open-loop and a close-loop reaction on a short and a long-

term respectively (Soangra and Lockhart, 2012). Elderly fallers demonstrated significantly greater short-term coefficients (Kurz et al., 2013; Melzer et al., 2010; Muir et al., 2013), without a specific direction being identified. Other author reported the advantage of SDA to identify fallers from non-fallers (Hur et al., 2009b; Tuunainen et al.,

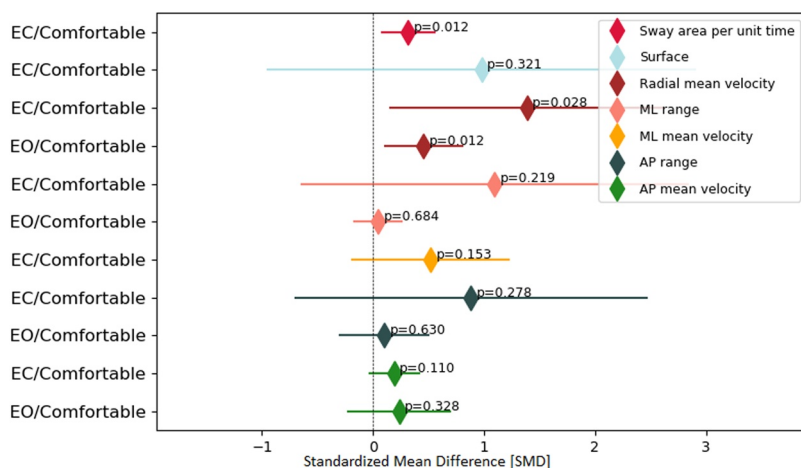


Fig. 4. Forest plot of COP features for retrospective history of fall. The overall effect size (with 95 % confidence intervals) is represented by the horizontal bar. The p-value represents the Z-test results for the approximate mean differences.

(a) AP mean velocity for prospective follow-up and comfortable feet position (EC in red, EO in blue); (b) Radial mean velocity for prospective follow-up and comfortable feet position (EC in red, EO in blue); (c) Radial mean velocity for retrospective history of falls and comfortable feet position (EC in red and EO in blue); (d) Sway area per unit time for retrospective history of falls and comfortable feet position (EC in red).

2014), with various related features.

In contrast, three other studies (Borg and Laxåback, 2010; Laughton et al., 2003; Qiu and Xiong, 2015) did not find that SDA results allowed reliable differentiation between older non-fallers and fallers. It is of note, however, that these 3 studies also showed a higher risk of bias with scores of 11/32, 11/32 and 12/32 (respectively) whereas those studies that reported SDA to be an effective tool had scores from 13 to 23.

This finding may indicate an ability to distinguish fallers from non-fallers with parameters extracted from complex analysis. Unfortunately, we could not combine the results of these studies because of the heterogeneity of the recording conditions and the different directions (AP, ML and radial) in which the features were calculated.

3.1.6. Predictive models

Several authors attempted to use predictive models based on COP features to classify participants as fallers and non-fallers or even to predict the number of falls for a participant. Taken alone, or combined with clinical variables, COP features were reported to have achieved an overall classification accuracy, based on the area under the receiver operating characteristic curve, ranging from 0.43 (Caterino et al., 2009) to 0.77 (Bargiotas et al., 2018). For sensitivity, participants were correctly predicted as fallers, with an accuracy that ranged from 29 % to 82 %. For specificity, participants were correctly predicted as non-fallers, with an accuracy that ranged from 43 % to 92 %. As compared with the standard test with feet in a comfortable position, tests where participants were asked to adopt a narrow stance gave little or no additional information regarding fall risk prediction (Caterino et al., 2009; Mertes et al., 2015). Moreover, this narrow stance was found to be too difficult for some older individuals (Bigelow and Berme, 2011).

The added value of a blindfolded test was suggested in several studies (Audiffren et al., 2016; Brauer et al., 2000; Caterino et al., 2009; Deschamps et al., 2016; Howcroft et al., 2017; Maki et al., 1994; Panzer et al., 2011). Various authors also reported that ML features data significantly accurately predicted fall status (Audiffren et al., 2016; Bauer et al., 2016) and that their accuracy was superior to results from AP data (Bergland et al., 2003; Bigelow and Berme, 2011; Maki et al., 1994; Stel et al., 2003; Swanenburg et al., 2010). Several authors, however, failed to find predictive ability with COP features alone (Brauer et al., 2000; Buatois et al., 2006; Caterino et al., 2009; Lajoie and Gallagher, 2004; Pajala et al., 2008) and others reported that the predictive value of COP data was improved when nutritional status or anthropomorphic characteristics, for example, were added to clinical data (Bigelow and Berme, 2011; Deschamps et al., 2016). Several studies used results from established clinical tests such as the Berg Balance Scale (Bauer et al., 2016; Brauer et al., 2000), the Tinetti POMA (Bauer et al., 2016; Panzer et al., 2011) and TUG test (Bauer et al., 2016;

Bergland et al., 2003; Buatois et al., 2006; Caterino et al., 2009), clinical tests failed to show predictive quality as compared with COP data. In multivariate models, the quantification of anterior maximal lean excursion, such as in the Functional Reach test, could slightly improve the prediction (Bergland et al., 2003; Panzer et al., 2011).

3.2. Meta-analysis

3.2.1. Quantitative analysis

Twenty-nine studies were included in the quantitative analysis. Using retrospective classification of patients' fall status (based on their fall history) five features differed significantly between non-fallers and fallers in all studies (Table 1): AP sway length (n = 6; p = 0.039; Z = 2.07; I² = 45 %), AP mean velocity (n = 6; p = 0.027; Z = 2.21; I² = 27 %), ML range (n = 13; p = 0.049; Z = 1.96; I² = 88 %), radial mean velocity (n = 16; p = 0.003; Z = 2.92; I² = 88 %) and sway area per unit time (n = 5; p < 0.001; Z = 4.09; I² = 0%), which was defined as the area enclosing the COP trajectory per second.

From prospective classification of fall status, six features significantly differed between (future) non-fallers and fallers in prospective studies: AP mean position (n = 4; p = 0.006; Z = 2.74; I² = 21 %), AP RMS displacement (n = 4; p = 0.005; Z = 2.83; I² = 46 %), AP mean velocity (n = 6; p = 0.005; Z = 2.78; I² = 28 %), ML sway length (n = 8; p = 0.011; Z = 2.55; I² = 66 %), radial mean velocity (n = 7; p < 0.001; Z = 3.59; I² = 64 %) and total excursion (n = 10; p = 0.008; Z = 2.64; I² = 81 %). Because the conditions of recording could change the ability to discriminate between fallers and non-fallers, both foot position and eye condition (open/closed) were taken into account in the sensitivity analysis.

3.2.2. Sensitivity analysis

The visual information could play a major role in the postural strategy to maintain balance, the data were divided into eyes open (EO) and eyes closed (EC) conditions during the recording. Also, foot position may affect the measurement of the COP trajectory. Therefore, we used a sensitivity analysis to select studies classifying fallers with the same recording settings. Both sway area per unit time and radial mean velocity data also allowed discrimination of fallers from non-fallers in the interaction: Retrospective x EC x Comfortable (n = 3; p = 0.012; Z = 2.50; I² = 0% and n = 4; p = 0.028; Z = 2.503; I² = 96 %) (Fig. 4). In prospective studies (Fig. 5), the radial mean velocity was significantly different for both visual conditions (Prospective x EO x Comfortable: n = 3; p < 0.001; Z = 3.366; I² = 40 % and: Prospective x EC x Comfortable: n = 3; p = 0.007; Z = 2.689; I² = 28 %). However, AP mean velocity was significantly different in only the EO condition (Prospective x EO x Comfortable: n = 3; p = 0.008; Z = 2.655; I² = 0%). For the features significantly discriminating fallers and

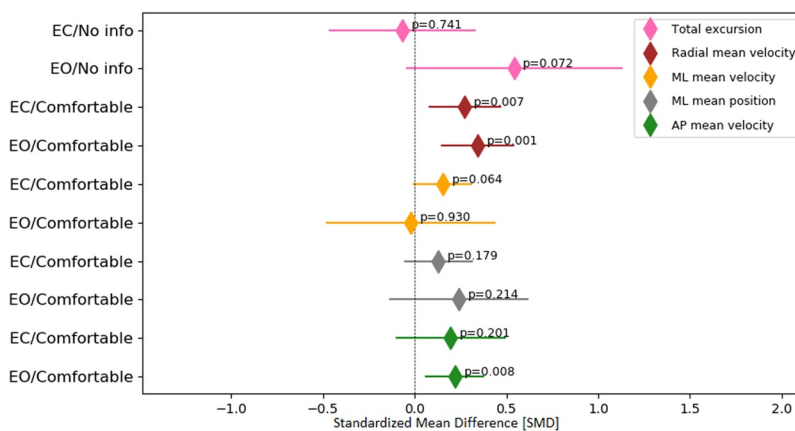


Fig. 5. Forest plot of COP features for prospective fall recording. The overall effect size (with 95 % confidence intervals) is represented by the horizontal bar. The p-value represents the Z-test results for the approximate mean differences.

non-fallers, the study protocols vary on whether or not shoes are worn during recording. Thus, for the sway area per unit time in the interaction Retrospective x EC x Comfortable, the three articles used the three possible footwear conditions (i.e., barefoot, with shoes and without information). There is slightly less variability in the wearing of shoes for the other parameters because the measurements were taken with participants barefoot or the articles did not provide information on this topic. This finding does not seem to be related to the heterogeneity measured because the sway area per unit time had a zero heterogeneity value, whereas other parameters were more heterogeneous, despite the proximity of the protocols concerning this parameter.

Based on the averaged risk of bias score, the number of studies available that examined each parameter, the heterogeneity between studies and the cumulative sample sizes for any given variable, the overall reliability of the parameters in the differentiation of fallers from non-fallers ranged from low to moderate (Table 1). The heterogeneity of the studies is the main cause of the decrease in reliability, thus reducing the possibility of generalizing the results.

Graphical examination of the funnel plots for the studies (Fig. 6) did not reveal publication biases. Unfortunately, this was probably due to the limited number of studies available for each outcome rather than a definite absence of bias. Due to the difficulty of interpreting these graphs, therefore, it was not possible to exclude the possibility of publication bias. This is something that presented a major limitation to the generalization of results across the studies reviewed.

4. Discussion

4.1. Summary of overall evidence

To our knowledge, this systematic review is the first to examine the classification quality of stabilogram features by performing meta- and sensitivity analyses over different COP recording conditions in order to differentiate fallers from non-fallers in an older population. Although several studies had previously agreed that older fallers exhibit higher COP displacements than older non-fallers during a quiet standing task, the best postural markers to distinguish these two groups remained undefined. In order to answer to that question, this review identified several studies out of a corpus of approximately 4000 studies that had been published in both peer-reviewed journals and gray literature (Conn et al., 2003).

Our results highlighted the ability of a simple quiet-standing task (with eyes open or closed in a comfortable position) to distinguish fallers from non-fallers in an elderly population. The interaction of study type, visual and foot position conditions, identified velocity in both anteroposterior and radial directions and the sway area per unit

time as the best features for discriminating between fallers and non-fallers.

Despite the significant capability of some parameters to differentiate between fallers and non-fallers, it is necessary to emphasize that the generalization of these results may be limited by the overall quality of the evidence which ranged from low to moderate. As mentioned, the heterogeneity of the studies led to a low reliability of the ability to differentiate elderly people with a history of falls from the radial mean velocity parameter. The use of these radial mean velocity data therefore seems more relevant for longitudinal follow-ups since future retrospective studies could potentially contradict its efficacy. The other parameters ('AP mean velocity' and 'sway area per unit time'), which were considered moderately reliable, require more testing in larger cohorts in future studies. Nevertheless, it seems reasonable to use 'AP mean velocity' and 'sway area per unit time' in predictive models since they were moderately reliable.

At the time of writing, the diagnosis of the risk of falling remains a subjective clinical approach. Eventually, uni- or multivariate predictive models based on velocity parameters could provide a source of additional information on the effectiveness of therapy in reducing the risk of falling. This development is made possible by the reduced cost of the force platforms, as well as their increased portability and connectivity functions which means that they could be coupled with automatic data processing enabled by machine learning algorithms (Zavoronkov et al., 2019).

The frequency and stochastic analysis of quiet stance posturography data may be relevant to detect persons at risk of falling (Gilfriche et al., 2018; Kouzaki and Masani, 2012; Schumann et al., 1995; Suzuki et al., 2017) or possible neurological impairments (Salsabili et al., 2013). Despite the known benefits of such analyses, however, and the recognition of the additional clinical value they bring (Baratto et al., 2002; Chiari et al., 2000; König Ignasiak et al., 2017; Rasku et al., 2012; Tallon et al., 2013) at present they remain time-consuming and difficult to perform, which explains their scattered presence in the literature. In addition, apart from sway density (Audiffren et al., 2016; Maranesi et al., 2016), other calculated COP parameters are summary measures and do not reflect the dynamic of balance during the quiet stance test. Given the high AUC obtained by Bargiotas et al. (2018) with traditional features applied on local windows over the COP signal, it seems reasonable for future research to continue investigating local dynamic analysis.

Our results have emphasized the discriminative properties of the COP data extracted from the sagittal plane. We also found that results from analysis of ML data were more heterogeneous than AP results under all test conditions. These findings contrast with systematic reviews by Piirtola and Era (2006) and Watt et al. (2018) where ML data were

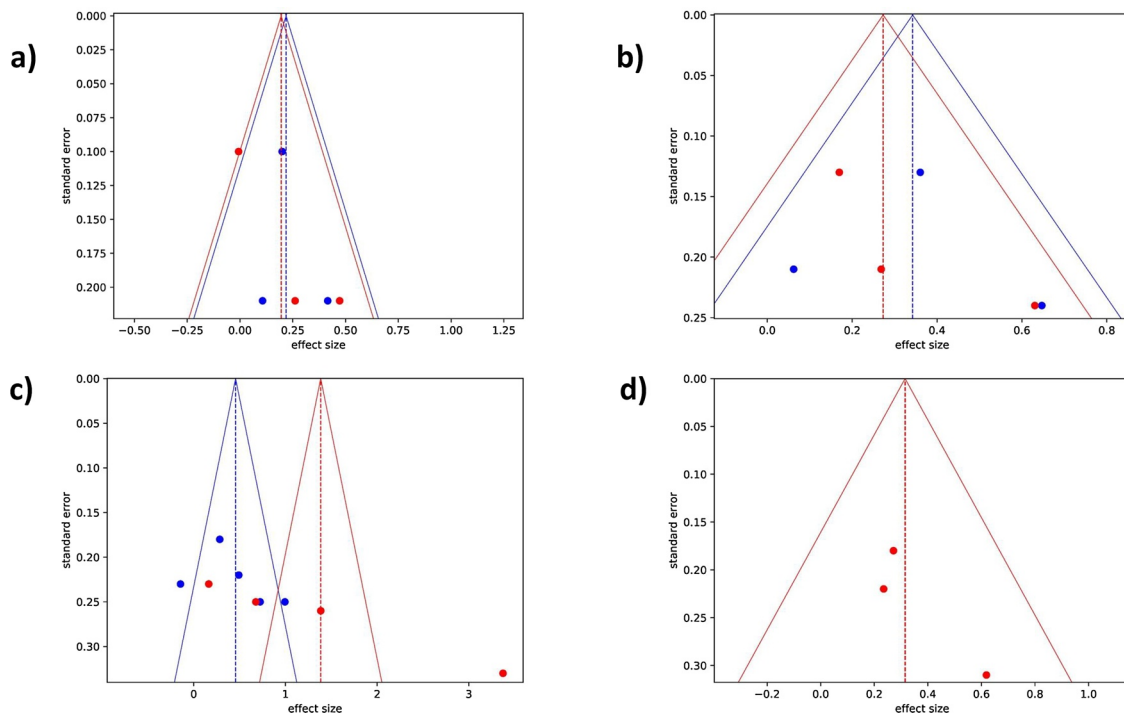


Fig. 6. Funnel plots of COP features significantly different between non-fallers and fallers in various interactions of conditions.

The diagram shows the standardized mean difference plotted against size-based standard error of the mean. a) AP mean velocity for prospective follow-up and comfortable feet condition (EC in red, EO in blue); b) Radial mean velocity for prospective follow-up and comfortable feet condition (EC in red, EO in blue); c) Radial mean velocity for retrospective history of falls and comfortable feet condition (EC in red, EO in blue); d) Sway area per unit time for retrospective history of falls and comfortable feet position (EC in red).

found to be more discriminatory than AP features. Such contradictory conclusions, we believe, can be explained by the fact that we stratified the data into three conditions (namely by study type, whether participants had their eyes open or closed and also the position of their feet). This stratification led to the exclusion of ML data from the set of differentiating COP displacement characteristics and this exclusion highlighted the importance of explicitly controlling test conditions which are currently inconsistently applied between studies (for factors such as what participants are asked to do with their eyes during testing or how and where they should place their feet). In future studies, this standardization would allow stabilographic data to be pooled across studies; this would increase the power of the findings and so enable recommendations to be more reliably drawn between studies.

4.2. Variability in the procedure to record COP displacements

It seemed reasonable to pool data across the studies due to reliability of the parameters across recording protocols (Bauer et al., 2008; Schubert et al., 2012), especially for the COP velocity (Lafond et al., 2004; Li et al., 2016; Lin et al., 2008; Lovecchio et al., 2016; Moghadam et al., 2011; Schmid et al., 2002; Swanenburg et al., 2008). The heterogeneity measured in this meta-analysis could have been explained in part by the variation in the quiet-standing recordings among studies. Recommendations proposed to reduce variability of the COP features include increasing the duration of the recordings (Schmid et al., 2002). However longer durations to increase inter-subject reliability, seem incompatible with physical abilities of older participants. Also, repetitive trials could improve the reliability between participants, but only half of the included studies used more than one recording. Few studies (Hewson et al., 2010; Hur et al., 2009b; Kurz et al., 2013; Laughton et al., 2003; Melzer et al., 2010; Seidler and Martin, 1997) recorded the balance of the participants five or more times, as recommended to improve the robustness of the data (Golriz et al., 2012; Santos et al., 2008). The exception is Hewson et al. (2010), whose

population was community-dwelling people living independently, with a mean age below 80 years old, which argues for some limits regarding the feasibility of repetitive measures for institutionalized older people. It should therefore be noted that the simplicity of the test will serve the most fragile people and should still allow the distinction between those most at risk, without the need to make the test more complex by asking to stay on one foot for example.

In nursing homes, we believe that access to a simple and reliable measurement of balance would be particularly useful. Although most of the selected studies focused on independent seniors, the issue of falling in people over 80 years of age is of greater concern. Correlated to age, the number of falls per person goes hand in hand with the loss of autonomy, which is itself responsible for new falls (Institut national de la santé et de la recherche médicale (Inserm, 2015)). The absence of clinical test results in predictive models highlights the lack of sensitivity of the tools currently used in daily practice to monitor the physical capacities of institutionalized people. It therefore seems necessary to continue the trials in nursing homes to collect more data and determine parameters that are more specific to this population.

4.3. Co-contractions and COP

The differentiation quality of AP mean velocity could be explained by the fact that participant needed to maintain stiffness because of agonist-antagonist muscle co-contraction around the ankle (Baudry and Duchateau, 2012, 2012; Goble et al., 2009; Papegaaij et al., 2014; Vette et al., 2017). Co-contractions have been shown to produce faster AP COP movements (Benjuya et al., 2004; Carpenter et al., 2001; Ho and Bendrups, 2002; Nelson-Wong et al., 2012). Because radial mean velocity is calculated from a combination of speed in both directions, co-contractions affecting AP velocity would also affect the radial velocity. Therefore, radial mean velocity of the COP (in mm/s) and the sway area per unit time (in mm²/s) may be correlated, but the impact of co-contractions on the latter is less clear. Co-contractions of leg muscles in the

older adult may also lead to inappropriate motor responses (Delignières et al., 2011; Jeka et al., 2004; Le Mouel and Brette, 2017; Masani, 2003), particularly in relation to the inhibitory mechanisms involved in the process of motor response selection (Duque et al., 2014).

4.4. Limitations

The first limitation in our review is that three papers which appeared to be suitable for inclusion had to be rejected as no one could read them (they were written in Portuguese, Japanese and Arabic). We attempted to circumvent this problem by searching the gray literature and other information that was related to these papers, but we could not find anything.

The second limitation of this systematic review is the absence of analysis by number of falls. Older adults who fell once during the follow-up period were not always separated from those who fell frequently (i.e. twice or more) or from those who did not fall at all.

Thirdly, little information was available on the conditions under which the falls occurred; as a result, we were unable to distinguish the number of incidents per participant or the injuries associated with these falls. It would be preferable in future studies to add information on fall injuries as this would allow predictive models to be stratified according to the severity of the fall consequences (James et al., 2018). Because it is easier to distinguish FFs from NFs or from OFs, we can assume that simple predictive models will be more effective in discriminating very high-risk individuals from robust older people.

It also seems necessary to include more institutionalized older people because our review highlighted the lack of studies investigating the COP of dependent people. This could have an impact on the outcomes presented here (Rubenstein et al., 1994). Indeed, with a mean age of 77 years in our study, these results could not be generalized to all frail older people without more data collected from extended care settings. Because of their social (Bloch et al., 2010), cognitive (Kamińska et al., 2015; McMichael et al., 2008; Montero-Odasso et al., 2012) and physical dependence (Deandrea et al., 2013), older adults in residential care are more likely to fall but also more difficult to follow in a longitudinal design. Also, although cognitive disorders can affect both postural strategy and the incurred risk to put individuals in danger, these were not reported in most of the studies. Hence, we were not able to perform a sensitivity analysis on cognitive status.

Dual cognitive tasks or standing on a surface such as foam are used to increase the challenge of balance tests (Al-Yahya et al., 2011; Bergamin et al., 2014; Lacour et al., 2008; Woollacott and Shumway-Cook, 2002). However, an analysis of the interaction: Faller status x Surface x Task was not found to be significant (Shumway-Cook et al., 1997). In the present study, unfortunately, we could not investigate this further since we could not pool data from studies using cognitive dual-task or foam owing to the diversity of the COP variables used and the variety of recording conditions.

Another issue with the reporting of or defined conditions for testing was that many articles did not provide information on whether participants were wearing shoes during recording. Footwear could have a negative impact on the postural balance of older people by reducing the sensory inferences of the skin on the sole of the foot (Hijmans et al., 2007) although heel size has previously been shown to not affect the COP displacement in older adults (Lindemann et al., 2003). In this review, unfortunately, we were unable to sub-stratify the sensitivity analysis because of the small number of tests that stated they allowed footwear.

Finally, other variables such as personal characteristics (BMI, a history of falls or even nutrition) could be relevant to improve the ability to discriminate fallers from non-fallers.

5. Conclusion

Despite a discrepancy between the included studies regarding the

condition of recording, this review suggests that sway area per unit time can differentiate fallers from non-fallers. In addition, prospective studies have shown that the mean velocity in the AP direction and in the radial direction were significantly different between fallers and non-fallers. ML features were less consistent and discriminative than AP features in the present meta-analysis. There is no doubt that current advances in data processing will make it possible to use COP trajectory analysis in routine consultations. The identification of parameters for classifying and predicting people at risk is therefore necessary to create effective tools for longitudinal monitoring of the most vulnerable elderly people. In the future, these markers can then be used to objectify the improvement of balancing capacities in the context of rehabilitation and promote the personalization of care (Rajagopalan et al., 2017). Given the increasing institutionalization of older people in many countries, in the absence of relevant clinical tests, connected technologies will provide support to health professionals for the follow-up of vulnerable people (Siren et al., 2019).

Systematic review registration

This review was registered with PROSPERO (International Prospective Register of Systematic Reviews) on June 19, 2018 (Registration: CRD42018098671). Both the search strategy and study protocol are available at https://www.crd.york.ac.uk/prospero/display_record.php?RecordID=98671

CRedit authorship contribution statement

Flavien Quijoux: Conceptualization, Methodology, Software, Formal analysis, Investigation, Data curation, Writing - original draft, Visualization. **Aliénor Vienne-Jumeau:** Methodology, Software, Validation, Formal analysis, Investigation, Data curation, Writing - original draft, Writing - review & editing, Visualization. **François Bertin-Hugault:** Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition. **Philippe Zawieja:** Methodology, Resources, Writing - review & editing, Supervision. **Marie Lefèvre:** Resources, Supervision. **Pierre-Paul Vidal:** Conceptualization, Methodology, Resources, Writing - review & editing, Supervision, Project administration. **Damien Ricard:** Conceptualization, Methodology, Validation, Resources, Writing - review & editing, Supervision, Project administration, Funding acquisition.

Acknowledgements

This study has been funded in the context of a PhD program in partnership with ORPEA SA. This collaboration between Cognac-G laboratory of Centre Giovanni Alfonso Borelli, Université de Paris - ENS Saclay - CNRS - SSA UMR 9010 and ORPEA group is framed in the French conventions for Industrial Training by the Research (CIFRE 2016/0437) managed by the National Association Research-Technology (ANRT).

Appendix A. Supplementary data

Supplementary material related to this article can be found, in the online version, at doi:<https://doi.org/10.1016/j.arr.2020.101117>.

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