Behav Res (2017) 49:310–317
DOI 10.3758/s13428-016-0706-4

Statokinesigram normalization method

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Abstract *Stabilometry* is a technique that aims to study the body sway of human subjects, employing a force platform. The signal obtained from this technique refers to the position of the foot base ground-reaction vector, known as the *center of pressure* (CoP). The parameters calculated from the signal are used to quantify the displacement of the CoP over time; there is a large variability, both between and within subjects, which prevents the definition of normative values. The *intersubject* variability is related to differences between subjects in terms of their anthropometry, in conjunction with their muscle activation patterns (biomechanics); and the *intrasubject* variability can be caused by a learning effect or fatigue. Age and foot placement on the platform are also known to influence variability. Normalization is the main method used to decrease this variability and to bring distributions of adjusted values into alignment. In 1996, O'Malley proposed three normalization techniques to eliminate the effect of age and anthropometric factors from temporal-distance parameters of gait. These techniques were adopted to normalize the stabilometric signal by some authors. This paper proposes a new method of normalization of stabilometric signals to be applied in balance studies. The method was applied to a data set collected in a previous study, and the results of normalized and nonnormalized signals were compared. The results showed that the new method, if used in a well-designed experiment, can eliminate undesirable correlations between the analyzed parameters and the subjects' characteristics and show only the experimental conditions' effects.

Keywords Statokinesigram · Normalization · Method · Anthropometry · Stabilometry

Stabilometry is a technique employed to study the body sway of human subjects in a standing position using a force platform (Kapteyn et al., 1983). Similar to a weighing scale, a force platform is a device that uses a set of force transducers to quantify the ground-reaction vector force and its point of application, known as the *center of pressure* (CoP). Usually the device is connected to a computer which records the displacement of the CoP for a preset period, forming the CoP signal. The CoP signal can be visualized as two forms: a *stabilogram*, a representation of CoP displacement in one direction, either anterior–posterior or medial–lateral, presented as a function of time; and a *statokinesigram*, a graphic representation of CoP displacement, presented in the horizontal plane (Prieto, Myklebust, Hoffmann, Lovett, & Myklebust, 1996).

The CoP signal is the source for the extraction of stabilometric parameters, which provide important insights into the process of balance control. The parameters are used to quantify the migration of the CoP in terms of its area, displacement speed, trajectory length, mean position, mean oscillation frequency, and mean power frequency (Prieto et al., 1996). Each of these parameters may help to clarify some aspect of the balance control system from neurophysiological and biomechanical points of view.

Electronic supplementary material The online version of this article (doi:10.3758/s13428-016-0706-4) contains supplementary material, which is available to authorized users.

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There is a large variability in these parameters, both between and within subjects (Chiari, Rocchi, & Cappello, 2002). Repeated measurements on consecutive days of the same individual may show a large spread of values, reflecting high intrasubject variability (Samson & Crowe, 1996). In some cases, this variability can be explained by a learning effect resulting in a progressive reduction in body sway over repeated trials (Tarantola, Nardone, Tacchini, & Schieppati, 1997) or, in extreme cases, long-term trials can lead to fatigue and an increase in body sway (Corbeil, Blouin, Bégin, Nougier, & Teasdale, 2003; Gribble & Hertel, 2004; Nardone, Tarantola, Giordano, & Schieppati, 1997).

The intersubject variability is related to differences between subjects in terms of their anthropometry, in conjunction with their muscle activation patterns (biomechanics) (Alonso et al., 2012; Chiari et al., 2002). Age and foot placement are also known to influence postural stability and may contribute to increased signal variability (Hageman, Leibowitz, & Blanke, 1995; McIlroy & Maki, 1997; Prieto et al., 1996). The variability of all such measures in normal subjects has been widely debated and has prevented the definition of normative values for stabilometric parameters (Ruhe, Fejer, & Walker, 2010; Samson & Crowe, 1996; Yamamoto et al., 2015).

In 2002, Chiari and collaborators highlighted the importance of the application of a normalization method to compensate for the bias that biomechanical factors may introduce in the estimation of stabilometric parameters. Normalization allows the comparison of corresponding normalized values from different datasets in a way that eliminates the effects of certain major influences. Until now, some authors have applied the methods proposed for gait studies by O'Malley to eliminate the effects of age and of anthropometric factors on the stabilometric parameters (O'Malley, 1996). The present article aims to propose a new normalization method to be applied specifically in balance studies. It is a self-normalization technique where each individual is considered separately from all others. No attempt is made to look at trends in the entire data set, resulting in a normalized statokinesigram without measurement units; however, by computing the mean area of the sample before normalization, the new method permits the resulting statokinesigrams to show parameter values around the average of the sample, maintaining the original units. After the statokinesigram normalization, all the other classical parameters cited in this article might be shown more accurately since the normalized signals highlight the experimental effects.

Method

Statokinesigram normalization

The normalization is based on conversion from the Cartesian into the polar coordinate system, where normalization is performed, and the data are then reconverted back to the Cartesian system. It is applied to each subject, on statokinesigrams containing CoP coordinates for the whole period of the experiment. The normalization procedure follows these five steps:

1. ***Centralization*** Centralization of the statokinesigram to the origin of the Cartesian axes (0, 0) by subtracting the average value of medial–lateral displacement (*X*) and anterior–posterior displacement (*Y*) of the CoP:

$$x_i = X_i - \overline{X}$$
$$y_i = Y_i - \overline{Y}$$

2. ***System conversion*** Conversion from the Cartesian system (*x*, *y*) to the polar system of coordinates (modulus/angle):

$$\text{Modulus}_i = \sqrt{x_i^2 + y_i^2}$$
$$\text{Angle}_i = \arctan\left(\frac{y_i}{x_i}\right)$$

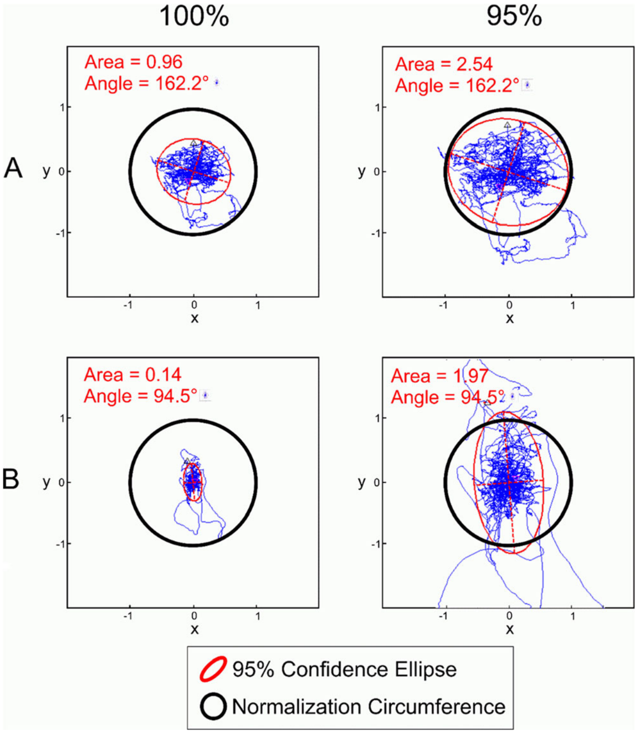

Fig. 1 Above, the statokinesigram of subject "A"; below, the statokinesigram of subject "B." In the left column, 100 % of the statokinesigrams' points were enclosed in circumferences of radius equal to 1; in the right column, 95 % of the statokinesigrams' points were enclosed in similar circumferences. Note that the confidence ellipse area is highly dependent on the magnitude of loops when adopting the 100 % circumference

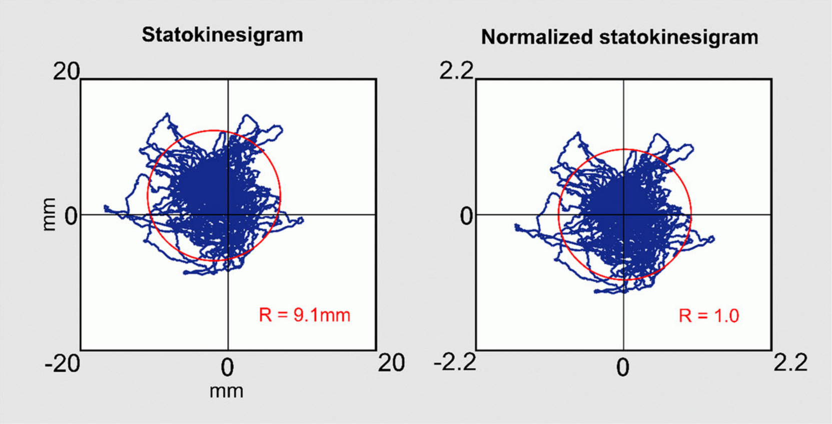

Fig. 2 Example of a subject's statokinesigram, before and after normalization. The red circumferences contain 95 % of the points

3. ***Determination of the farthest point from the origin*** To remove any interference that may be caused by areas of spurious loops in the CoP path, only 95 % of the original statokinesigram's points are taken into account in the normalization procedure. If all the points were taken into account, the normalized area would be affected by the amplitude of any large loops present in the CoP path: The larger the magnitude of the loop, the smaller the confidence ellipse area (see Fig. 1).

$$R_{max} = \max\left(\mathrm{Modulus}_{(95\%)}\right)$$

4. ***Normalization***

$$\mathrm{Mod}_{\mathrm{norm}_i} = \frac{\mathrm{Modulus}_i}{R_{\max}}$$

By using $\mathrm{Mod}_{\mathrm{norm}_i}$ above, the resulting statokinesigram will be confined in a circumference of a radius equal to 1, with no measurement unit. To make its area assume a value equal to the average of the sample, maintaining the measurement unit, this modulus has to be multiplied by $\sqrt{\bar{A}/_{\pi}}$:

$$\mathrm{Mod}_{\mathrm{norm}_i} = \frac{\mathrm{Modulus}_i}{R_{\max}} \times \sqrt{\bar{A}/_{\pi}}$$

where $\bar{A}$ is the average area of the sample.

5. ***System conversion*** Conversion of the normalized values back to Cartesian coordinates:

$$x_{\mathrm{norm}_i} = \mathrm{Mod}_{\mathrm{norm}_i} \times \cos(\mathrm{Angle}_i)$$
$$y_{\mathrm{norm}_i} = \mathrm{Mod}_{\mathrm{norm}_i} \times \sin(\mathrm{Angle}_i)$$

The (x_{norm}, y_{norm}) matrix contains the coordinates of all points of the normalized statokinesigram.

The proposed normalization does not introduce any spatial distortion in the statokinesigram and affects only its scale (see Fig. 2). This is equivalent to fitting the statokinesigram of each subject into respective circumferences of same area.

To proceed with further statistical analysis, the normalized statokinesigram must be split according to the experimental paradigm, and parameters of interest must be calculated for each phase of the experiment.

A MATLAB function called `statoknorm.m`, for *statokinesiogram normalization*, is available at the Mathworks site, in the "File exchange" session; furthermore, a code and some data exemplifying the application of the method are available at https://dl.dropboxusercontent.com/u/70636046/SNMethod_App.zip or at https://dx.doi.org/10.6084/m9.figshare.2066718.v2.

Testing the method

To test the method, it was applied to a statokinesigram data set collected in a previous study, comparing results obtained from nonnormalized and normalized statokinesigrams. In that

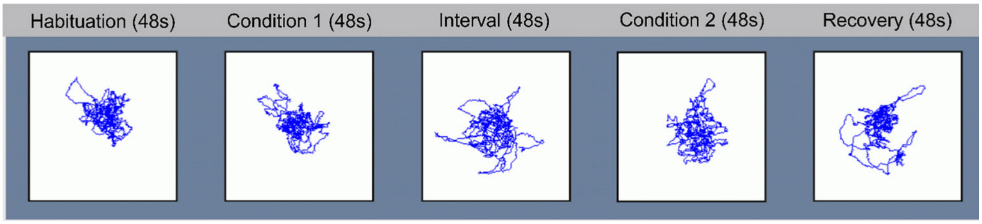

Fig. 3 Example of normalized statokinesigrams split into the five phases of experiment

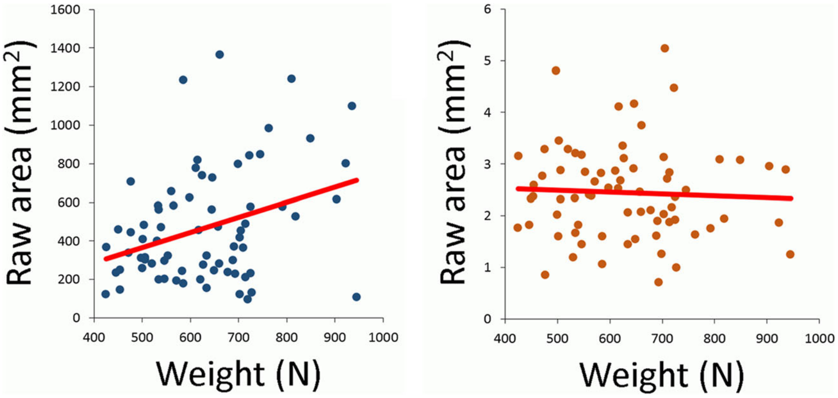

Fig. 4 Correlations of raw area versus weight (left) and normalized area versus weight (right)

study, 71 subjects (mean age: 23 ± 4 years; 36 men, 35 women) standing on a force platform underwent five different experimental phases: "Habituation," "Condition 1," "Interval," "Condition 2," and "Recovery" (see Fig. 3).

During the experimental session, part of the measuring protocol was zeroing the platform before the subject proceeded with the experiment. The first phase of the experiment ("Habituation") was used to measure the subject's weight and to calculate the area parameter from both nonnormalized and normalized statokinesigrams. The area calculated from the nonnormalized statokinesigram was called the "raw area," and the area calculated from the normalized statokinesigram was called the "normalized area." The "Raw area" and "normalized area" from the "Habituation" phase were correlated with weight and height of all subjects in order to appreciate the effect of normalization over anthropometric factors. We then tested to establish whether the effect of gender, found in the "Condition 1" area when analyzing nonnormalized data, would be maintained after normalization. Subsequently, the difference between the "Condition 1" and "Condition 2" areas was computed for both the nonnormalized and normalized data. Finally, the area behavior during the experiment was verified with the area in the "Habituation" phase being correlated with the area in the "Interval" and "Recovery" phases, to attempt to confirm the elimination of subjects' individual characteristics. All the areas cited above were computed employing the 95 % confidence ellipse (Duarte & Zatsiorsky, 2002).

Results

Effects of height and weight over area

The results showed a significant correlation (Spearman Rho = .25, p = .038) between weight and raw area. Applying the normalization method, the results showed no correlation between weight and the normalized area (Spearman Rho = –.06, p = .60) (see Fig. 4).

The same procedure was performed with height. The results showed a significant correlation (Spearman Rho = .26, p = .026) between height and raw area. This was expected since weight and height had a strong correlation in this sample (Spearman Rho = .80, p < .001). After applying the normalization method, the results showed no correlation between height and normalized area (Spearman Rho = .007, p = .95; see Fig. 5).

Effect of gender

When analyzing nonnormalized data, a Mann–Whitney U test was employed to investigate any gender difference. The results

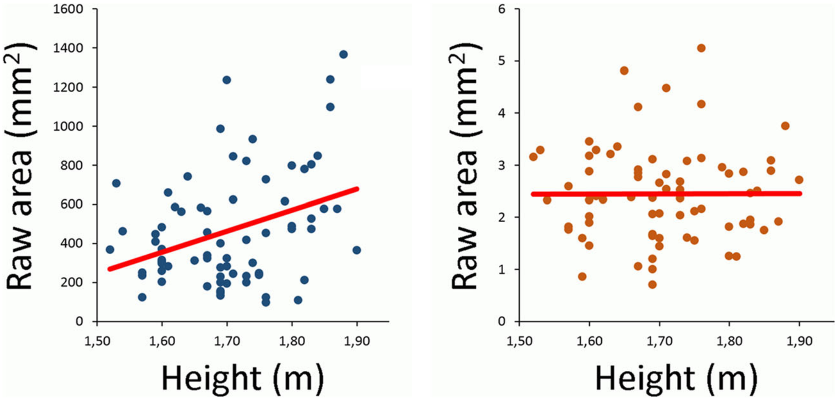

Fig. 5 Correlations of raw area versus height (left) and normalized area versus height (right)

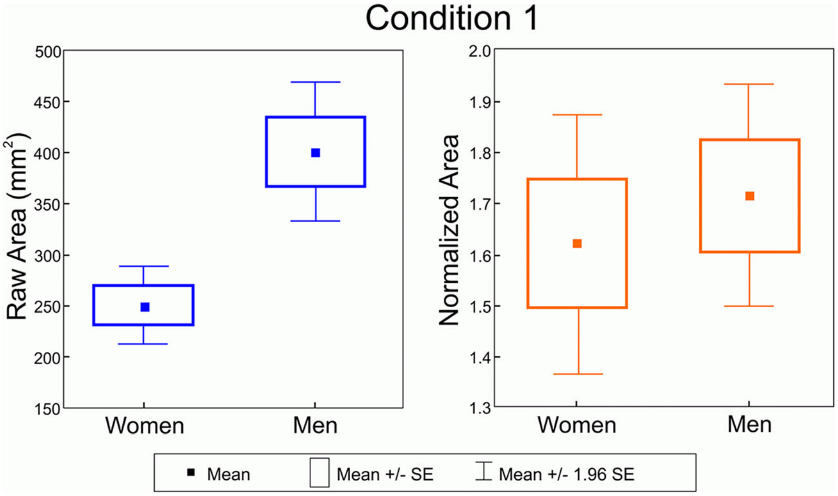

Fig. 6 The effect of gender found in raw data (left) disappeared in normalized data (right)

showed that the area in "Condition 1" was larger for men [*Z*(71) = –2.20, *p* = .027]. However, performing the same analysis with normalized data, the areas of women and men did not differ [*Z*(71) = –1.21, *p* = .23]. See Fig. 6.

The difference between men and women in terms of their heights and weights was also computed. Men were taller and heavier than women (see Table 1).

Testing differences between "Condition 1" and "Condition 2" areas

A Wilcoxon matched pair test was applied to check differences between "Condition 1" and "Condition 2." The area in "Condition 1" was found to be smaller than the area in "Condition 2" for nonnormalized data [*Z*(71) = 2.85, *p* = .004]. Similar results were obtained for normalized data [*Z*(71) = 3.23, *p* = .001]. See Fig. 7.

Correlations between areas in different phases of the experiment

For raw data, a high correlation was found between areas in the "Habituation" phase and the "Interval" phase (Spearman Rho = .74, *p* < .001), and the "Habituation" phase and the "Recovery" phase (Spearman Rho = .72, *p* < .001). No correlations were found using normalized data ("Habituation" vs. "Interval," Spearman Rho = .07, *p* = .58; "Habituation" vs. "Recovery," Spearman Rho = .003, *p* = .98; see Fig. 8).

Table 1 Gender characteristics of the sample

	Men	Women	Statistics
Mean weight	691.00 N	549.80 N	*t*(69) = –5.62, *p* < .001
Mean height	1.76 m	1.63 m	*t*(69) = –7.66, *p* < .001

Discussion

The results showed significant correlations between weight and raw area, and height and raw area, confirming the influence of these factors on the statokinesigram's area (Alonso et al., 2012; Hue et al., 2007). The correlation between "Height" and "Weight" with "area" parameter was eliminated when the normalization method was applied to the sample.

The effect of gender found in the raw data analysis disappeared after normalization, suggesting that the gender effect could be due to anthropometric factors. Men were taller and heavier than women, somen showed greater area values than women.

For the experimental conditions, however, the difference found when analyzing the raw data was similar to the difference found when analyzing the normalized data: the area in "Condition 1" was smaller than the area in "Condition 2" but in the normalized data, the significance level of the statistical test applied was higher.

A correlation between the "Habituation," "Interval," and "Recovery" areas supported the evidence that factors related to the subjects' individual characteristics were eliminated from the sample by the normalization process. In these phases, subjects had simply to remain motionless on the platform looking ahead at a gray screen. The high level of correlations found in the raw data suggests that the characteristics of the sample, due to anthropometry and other factors, which were present in the first phase, remained during all the experimental phases. The absence of any correlation in the normalized data suggests that those factors were eliminated from the sample. The proposed method removes individual differences and highlights the effects of the experimental conditions.

Among the possible factor which can interfere in the CoP signal, fatigue and learning effects tend to remain after normalization, so they should be avoided through good experimental design. Another important aspect that needs to be

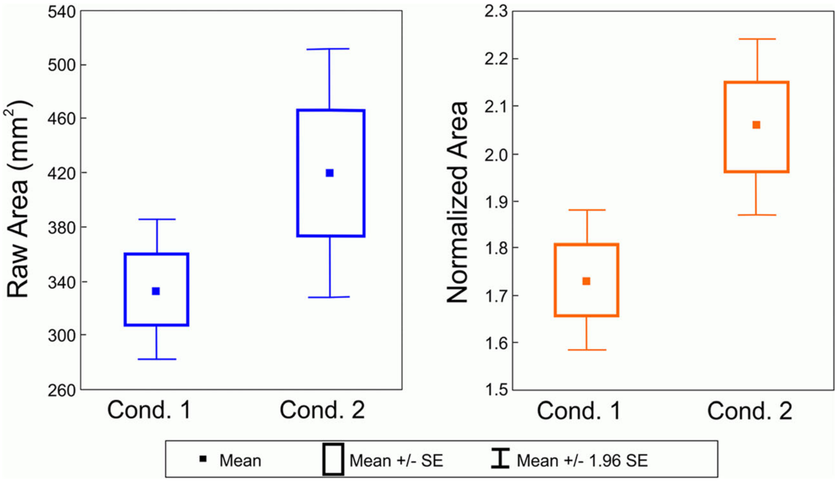

Fig. 7 Difference between the “Condition 1” and “Condition 2” areas, for raw (left) and normalized (right) area

standardized in experimental design is foot placement, since subjects with different foot positions will show different CoP displacement patterns (McIlroy & Maki, 1997). All the subjects must assume an identical foot position on the platform in order to decrease both inter- and intrasubject variability.

The proposed method reduces the variability of the CoP signal by confining the statokinesigram of each subject in circumferences with the same area, or equal to π, or equal to the average area of the sample, or proportionally to any value that you multiplied $\mathrm{Mod}_{\mathrm{norm}_i}$ by. The advantage of performing

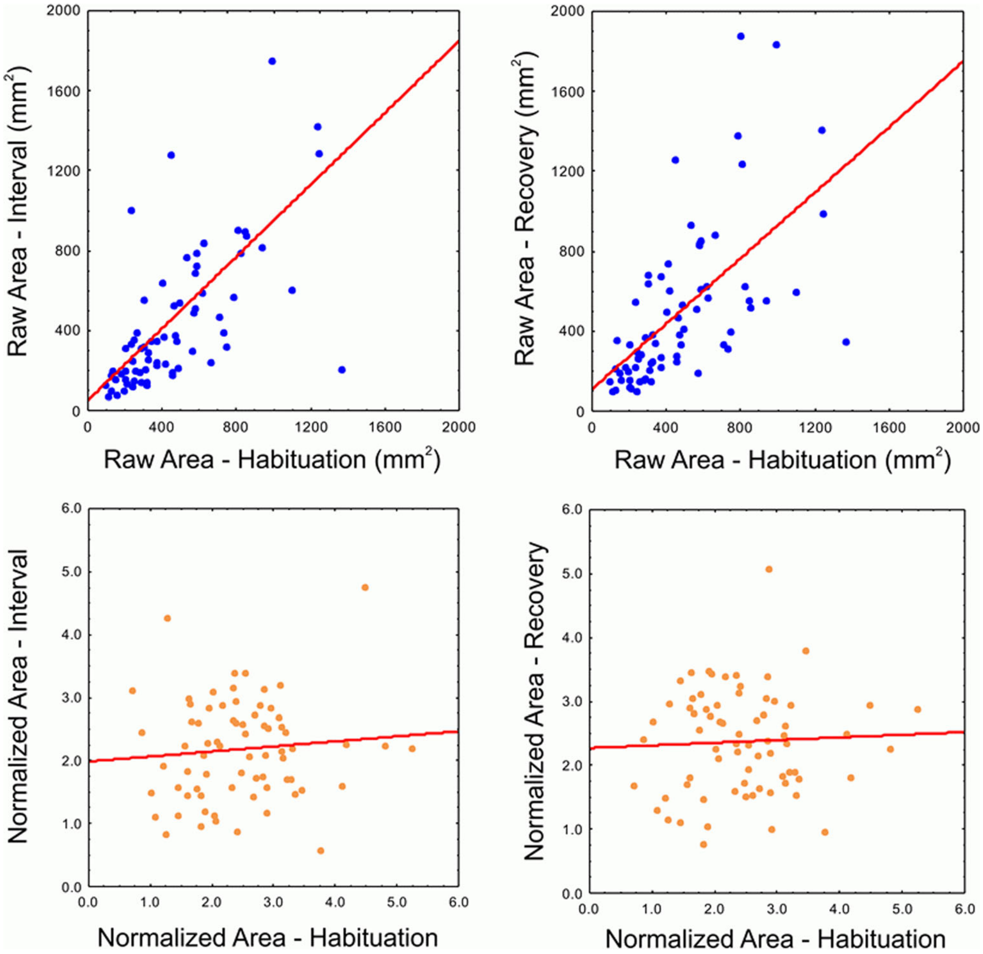

Fig. 8 Correlations between areas of the “Habituation” phase and areas of same-condition phases along the experiment, for raw and normalized data

the average area computation before normalizing the data is to maintain the measurement unit. The disadvantage is more programming and processing time. At the end of the statistical analyses, all cases will show the same result.

The sway area is a widely used parameter for the analysis of body balance. It is considered the most important among a great variety of parameters (Schubert & Kirchner, 2014); however, all other parameters can be calculated from the normalized statokinesigram and used for statistical tests. After normalization, the comparative analysis of any stabilometric parameter can be made with more confidence, as the normalized signal allows the experimental conditions' effects to be shown without interference from other factors. The application of a normalization method does not affect the "Mean Power Frequency" parameter, which maintains the same value after normalization; since the method does not spatially distort the signal, the shape of its stabilogram frequency spectrum is not changed.

The variability of the CoP signal is a limiting factor of posturography using a force platform. This variability generates difficulty in interpreting results obtained from prospective studies, designed to distinguish the postural control of different populations (Yamamoto et al., 2015); however, the application of the proposed normalization method permits the balance control of specific groups to be compared more faithfully, without worrying about matching groups with similar characteristics.

Regarding experimental paradigm that allows the application of this new method, it is important that participants experience several phases on the platform, which must be tested separately. Normalization must be applied to each subject's statokinesigram containing data of all phases of the experiment; then the normalized statokinesigram must be split, according to the experimental paradigm to calculate the parameters of each phase and perform the statistical analysis. Once the normalized signal is almost free of any interference, the methodology presented in this work may allow more reliable investigation of other questions in stabilometry studies, such as balance visual dependence, fatigue effect, learning effect, and aging.

This method does not work with data collected from experiments employing single-condition paradigms. This is the main limitation of the method. The subjects must stay on the platform while experiencing at least two conditions.

Conclusion

The application of the proposed normalization method eliminates the height and weight effects on the posturographic "area" parameter. In carefully designed stabilometric studies, the application of this method can eliminate all confounding variables from the sample, leaving only the effects of the experimental conditions. The method proposed in this article adds reliability to the classical sway area parameter and allows the comparison of normalized values across different datasets.

Author note I thank Aline Furtado Bastos, Maria Fernanda Santos, and Luis Aureliano Imbiriba for their support and encouragement in the preparation of this article. I also thank Pedro Luis Magalhães de Oliveira for his suggestions given for writing the article, and for the constant support and consideration.

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