European Archives of Oto-Rhino-Laryngology (2019) 276:41–48
https://doi.org/10.1007/s00405-018-5170-6

OTOLOGY

Normative data for static balance testing in healthy individuals using open source computerized posturography

Esther Domènech-Vadillo[1,2] · Gabriel Aguilera-Aguilera[3] · Carmen Sánchez-Blanco[3] · Ángel Batuecas-Caletrio[3] · Carlos Guajardo[4] · Nicolás Pérez[4] · Gabriel Trinidad-Ruiz[5] · Carlos Gimeno[6] · Julio Rama[7] · Marcos Rossi-Izquierdo[8] · Elena San-Roman-Rodriguez[8] · Berta Patiño-Castiñeira[8] · Juan Manuel Espinosa-Sanchez[9] · Eusebi Matiñó[10] · Rafael Barona[11] · Claudio Krstulovic[11] · Jesús Benitez-Rosario[12] · Elvira Santandreu[13] · Francisco Carlos Zuma e Maia[14] · María Guadalupe Álvarez-Morujo de Sande[15] · Ariadna Valldeperes[16] · Jorge Rey-Martínez[16,17]

Received: 24 May 2018 / Accepted: 10 October 2018 / Published online: 16 October 2018

Abstract

Purpose Computerized posturography is the gold standard for balance assessment. Because of the great cost and dimensions of commercial equipments, low-cost and portable devices have been developed and validated, such as RombergLab, a software in open source term which works connected with a low-cost force platform. The objective of this study was to obtain normative posturography data using this software.

Methods A multicentric prospective and descriptive study, with 350 healthy participants, was designed. Static postural stability (measured using the modified clinical test of sensory interaction on balance) was evaluated using the software connected to the force platform. Using the confidence ellipse area (CEA) in each condition, global equilibrium score (GES) was calculated and adjusted for significant variable factors using cluster analysis.

Results Mean (SD) GES was 0.72 (0.22). Age ($p < 0.01$), height ($p < 0.01$) and recruitment center ($p < 0.05$) were found as influence factors for GES. Cluster analysis obtained 16 groups stratified by age and height. GES decreases with age and height ($p < 0.005$). No significant interaction of age nor height was found with GES in these clusters ($p > 0.05$). After correction for height and age, GES was no longer influenced by the recruitment center ($p > 0.05$).

Conclusions With the introduction of the global equilibrium score values of the present study into the software, we consider RombergLab v1.3 a reference posturography tool for healthy individuals. Further studies are needed for validating it as a suitable instrumented test for screening between healthy and pathologic subjects and its reliability over time for the follow-up of patients.

Keywords Posturography · Low-cost posturography · Portable posturography · Open source software · Reference values

Introduction

Balance impairment may have a great negative impact with repercussion on daily activities, work and social life and brings with it the risk of falls, especially in older adults [1]. It can be due to multiple causes, including vestibular, musculoskeletal and neurological disorders, and it may be multifactorial in many cases. Early identification of balance impairment and appropriate intervention may prevent dysfunction and loss of independence [2].

For thorough assessment of balance, it is necessary to examine the sensory systems which contribute to postural control: the visual, somatosensory and the vestibular ones. With this purpose, and since the original Romberg's test [3] was described, multiple clinical tests have been developed, such as the clinical test of sensory interaction on balance (CTSIB) [4] or its modified version, the modified clinical test of sensory interaction on balance (mCTSIB) which has excellent reliability and validity in adults with vestibular disorders and can be easily administered in all clinical settings [5]. mCTSIB includes four conditions for evaluating static

✉ Esther Domènech-Vadillo
estherdova@hotmail.com

Extended author information available on the last page of the article

postural stability: eyes open on firm surface, eyes closed on firm surface, eyes open on foam surface and eyes closed on foam surface. Third and sixth conditions of the original CTSIB, in which a dome is used to provide visual conflict, are excluded since some authors found no differences in the performance between eyes-closed and visual-conflict conditions [6].

Posturography consists of the instrumented assessment of balance to quantify postural control in an upright stance. Computerized posturography is nowadays the gold standard for the instrumented balance assessment. It consists of a force platform, which measures the reaction forces against the subject on test, and a computer software. This computer software is used to calculate the center of pressure (COP) of the subject over the platform along time, which is a good indicator of the projection of the subject's center of gravity during slow movements [7].

Because of the great cost and dimensions of current commercially available posturography equipments, some low-cost and portable devices have been used and validated for clinical standing balance assessment, some of them developed for other purposes such as gaming tools [8–19]. Most of the softwares designed for control and analysis of data from these devices are under private software terms.

Due to this lack of an easily accessible equipment for posturography, a software in open source term (RombergLab), based on a validated clinical balance test (the aforementioned mCTSIB) and to be used with a low-cost force platform, was design, developed and validated [20]. It allows for carrying out static posturography without a high neither economic nor space investment.

To standardize this posturography equipment and to introduce it for clinical and research applications, we need to define normal reference values. With this purpose, the present study was designed.

The objective of this study was designed to obtain normative posturography data for a healthy population using RombergLab software.

Materials and methods

Design

A multicentric prospective and descriptive study was designed. This study was approved by the governmental Human Research Ethics Committee (CEIC-E) with the code PI2016171 (PS). Participants were informed in detail about the study procedure and methods and all of them provided written consent prior to participation in the study. A document with a detailed protocol was given to each researcher previous to the beginning of the study.

Participants

350 subjects, recruited from 14 hospitals and clinics, were tested. Participants were healthy individuals, aged between 18 and 70 years. History was taken with special emphasis on discarding disorders which could affect equilibrium.

The following were criteria for the inclusion of patients:

1. Absence of present or previous vestibular symptoms
2. Absence of present or recent uncorrected visual impairments
3. Absence of present or recent spinal or lower extremities musculoskeletal impairments
4. Absence of present or previous neurological disorder
5. Absence of present or previous systemic illness that could cause peripheral neuropathy, such as diabetes.
6. Absence of drugs or toxics which could affect equilibrium.

And the exclusion criteria were:

1. Presence of any disorder mentioned above
2. Age under 14 or over 70
3. Pregnant women
4. Impossibility to understand the instructions to participate in the study
5. Those who refused to participate in the study.

Procedures

RombergLab open source posturography software was used. It was developed for macOS computer (Apple Inc, Cupertino, CA), connected with the Nintendo® Wii Balance Board™ (WBB) (Nintendo, Kyoto, Japan) force platform, via Bluetooth. This software was clinically validated in a previous study [20] and it is published in the software repository GitHub (GitHub, Inc). Its last version can be downloaded from https://github.com/bendermh/RombergLab.

The software works in the following way: it receives the outputs from the four pressure sensors of the platform and processes the computed forces to get the center of pressure (COP) data. The user can see the COP displacement represented on real time on a graphical user interface (GUI). There are two modes available for balance assessment: A free record mode, in which the user can set any recording time by just pressing the start/stop button, and a balance assessment mode where four timers of 40 s each define the four conditions of the mCTSIB: eyes open on firm surface (condition 1), eyes closed on firm surface (condition 2), eyes open on foam surface (condition 3) and

eyes closed on foam surface (condition 4). Main outputs in both recording modes are a *XY* position plot and a sway area calculation [expressed in square distance units (SDU), not in square centimeters] using confidence ellipse area (CEA) [20].

The static postural stability was evaluated from each subject. It was performed using the Balance Assessment Mode available in the software. One trial for each condition was carried out. The bespoke foam used 50 × 40 × 14 cm (width × length × thickness), 40 kg/m^3 density was obtained from a specialized company (https://www.espumaamedida.com, Terrassa, Spain).

Before starting the assessment, an automatic calibration procedure was employed to set to zero incorrect values that may be recorded soon after switching on the platform.

Subjects stand on the platform without shoes (socks were permitted) and feet were placed apart, separated between them with the reference of the two rectangles marked on the surface of the platform.

Before the test, the investigator explained to the participant what each trial consists of and whether he or she had to stand with eyes open or closed or had to stand on the platform or on the foam. The subject was instructed to keep his or her arms attached to the trunk and to remain as still as possible during each trial. The explorer watched the subject carefully to prevent falls.

We considered a fall any movement of feet from their original position.

All these items were specified in the protocol documentation which was given to each researcher previous to the beginning of the study.

Data collection

We collected the following personal data of each participant: age, sex, height and recruitment center. The outcome measure used was CEA provided by the software for each condition: eyes open on firm surface (CEA_1), eyes closed on firm surface (CEA_2), eyes open on foam surface (CEA_3) and eyes closed on foam surface (CEA_4). Anonymized data were collected by each researcher using an Excel (Microsoft®, Redmon, WA, USA) worksheet, which was sent via e-mail to the principal investigator (J.R.) who grouped them together in a single Excel worksheet.

Equilibrium scores development

From raw data, we developed scores to obtain more comprehensible posturography parameters.

Using the values of CEA of each subject in each condition (CEA_x), we calculated a mathematical normalized equilibrium score for each condition (ES_x), using our population CEA 5th and 95th percentiles (P_5CEA_x and $P_{95}CEA_x$), in the following way:

$$\mathrm{ESX} = \frac{P_{95}CEA_x - (CEA_x - P_5CEA_x)}{P_{95}CEA_x}$$

When CEA_x is lower than P_5CEA_x (what means that the area of movement of the subject in that condition is smaller than that of 5 out of those 100 individuals of the sample), ES_x is greater than 1. When CEA_x is higher than $P_{95}CEA_x$ (what means that the area of movement of the subject in that condition is larger than that of 95 out of those 100 individuals of the sample), ES is lower. This means: the better the equilibrium, the higher the ES—and vice versa.

As an overall measure of balance, we created a global equilibrium score (GES) from the ES in each condition, as follows:

$$\mathrm{GES} = \frac{\mathrm{ES1} + \mathrm{ES2} + \mathrm{ES3} + \mathrm{ES4}}{4}$$

The interpretation of the GES is the same as for the ES, i.e., higher GES values indicate better global equilibrium of the subject—and vice versa.

Statistical analysis

Statistical analysis was performed using R 3.4.2 Statistical computing language (R Core Team, 2017. R: A language and environment for statistical computing. R Foundation for Statistical Computing, Vienna, Austria; URL https://www.R-project.org/). Statistical differences between the main collected variables and the normal distribution were evaluated with the Kolmogorov–Smirnov test. Descriptive statistics were obtained for all variables. Normal values were defined by the mean and SD. Outliers of main variables were identified by the boxplot graphical method, determined by the 1.5 interquartile range method [21].

Generalized linear model (GLM) test was performed to assess statistical significance between the variable factors sex, age, height and recruitment center as predictors of GES. *K*-means cluster analysis was used to get stratification groups of the significant variable factors from the GLM test. Cluster variables were analysed with a multiple analysis of variance MANOVA test to measure statistical significance of the association between stratified factors and GES.

Tables of standardized values were obtained with the mean and SD of GES according to GLM results. All the statistical tests were computed using R standard packages. Statistical significance level for this study was 0.05.

Results

For this study, 350 subjects were evaluated. There were 152 men (43%) and 198 women (57%). The mean age was 37.38 years (SD ± 13.35). The average height was 168.83 cm (SD ± 9.11).

The mean CEA in each condition was 14.44 SDU (SD ± 11.99) for condition 1, 15.42 SDU (SD ± 12.35) for condition 2, 69.16 SDU (SD ± 53.34) for condition 3 and 236.40 SDU (SD ± 229.96) for condition 4.

Two individuals that fell in condition 4 were excluded for calculation of mean CEA in this condition, and so for further calculation of scores.

Mean ES were 0.71 (SD ± 0.33) for condition 1 (ES1), 0.71 (SD ± 0.31) for condition 2 (ES2), 0.72 (SD ± 0.30) for condition 3 (ES3) and 0.74 (SD ± 0.31) for condition 4 (ES4). Mean GES was 0.72 (SD ± 0.22).

Means of personal data and GES analysed per recruitment center are shown in Table 1.

Statistical analysis of GES

For the analysis of GES, outliers were removed from the database for statistical analysis.

When we analysed recruitment center groups based on GES, all of them showed a normal distribution except one (center 2), which was removed for further statistical analysis.

The GLM found age ($p < 0.01$), height ($p < 0.01$) and recruitment center ($p < 0.05$ for eight centers) as influence factors for GES but not sex ($p > 0.05$).

Taking into consideration the two quantitative variables influencing GES (age and height), the cluster analysis defined four groups for the age and four groups for the height, the combination of which results in 16 groups. These clusters are shown in Fig. 1.

MANOVA test showed differences of age and height ($p < 0.005$) between clusters (GES decreases with age and with height) but did not show significant interaction of age, height or recruitment center with GES in these clusters ($p > 0.05$). This means that after correction for height and age, GES was no longer influenced by the recruitment center.

The mean and SD and boxplots of GES per clustered groups are shown in Table 2 and Fig. 1, respectively.

Discussion

Posturography is a widespread test for the assessment of balance. The high price and dimensions of current commercially available posturography equipments have motivated the development of low-cost options for posturography during previous years. WBB has been demonstrated to provide COP data, the gold standard measure of balance [22], that is both valid and reliable [23]. A recent systematic review [24] found the reliability of WBB consistently reported as moderate to excellent and similar to the results of prior studies using force platforms for static standing computerized posturography. The majority of studies suggested that WBB provides valid data. In particular, the highest ranked articles

Table 1 Means of personal data and global equilibrium score (GES) analyzed per recruitment center

Center	*N*	Age (years) [mean (SD)]	Height (cm) [mean (SD)]	GES [mean (SD)]
1	25	29.48 (11.62)	166.44 (5.25)	0.92 (0.06)
2	27	34.70 (13.55)	168.93 (8.11)	0.70 (0.26)
3	24	27.92 (10.54)	169.25 (7.02)	0.81 (0.16)
4	27	41.78 (13.48)	169.22 (9.96)	0.68 (0.20)
5	25	46.08 (11.90)	167.16 (10.59)	0.63 (0.26)
6	25	35.24 (15.30)	172.24 (9.62)	0.67 (0.23)
7	31	33.32 (9.66)	171.96 (10.27)	0.68 (0.20)
8	20	40.85 (13.25)	169.00 (9.71)	0.47 (0.20)
9	27	34.70 (11.44)	166.59 (7.14)	0.83 (0.11)
10	24	44.08 (13.80)	167.04 (9.55)	0.70 (0.20)
11	25	35.40 (10.34)	169.16 (7.77)	0.68 (0.23)
12	19	44.00 (12.10)	166.68 (8.79)	0.83 (0.14)
13	25	45.28 (10.71)	169.56 (10.33)	0.73 (0.22)
14	26	33.85 (13.70)	169.15 (11.02)	0.70 (0.16)
Total	350	37.38 (13.35)	168.83 (9.11)	0.72 (0.22)

Recruitment centers (Center) are randomly numbered from 1 to 14. *N* referes to the number of subjects recruited in each center. Age, height and GES are defined by the mean and the standard desviation (SD)

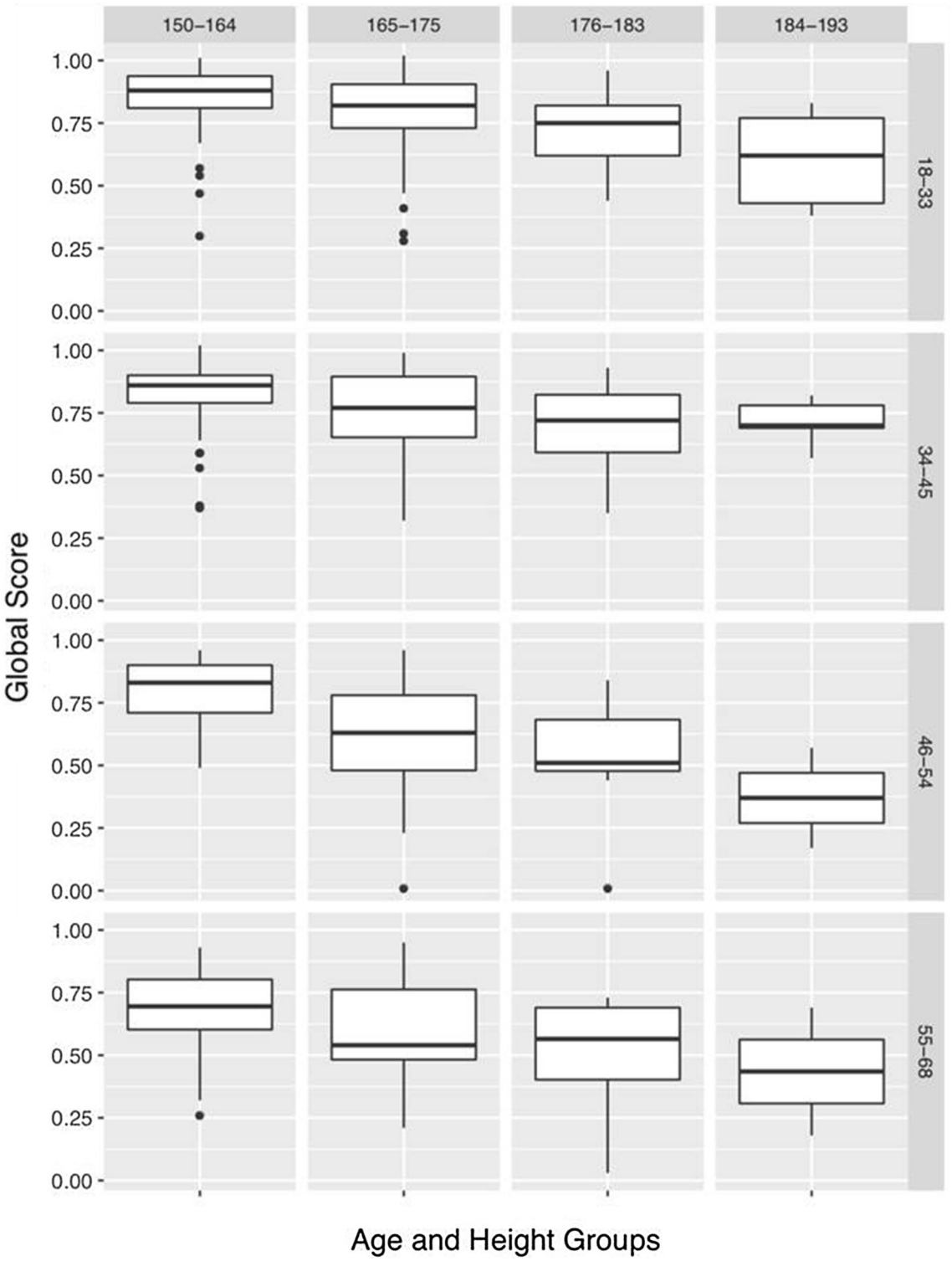

Fig. 1 Boxplots of global equilibrium score (GES) per clustered groups based on age and height. Height clusters are placed on the *x* axis and age clusters on the *y* axis. The bands of the boxplots represent the first, second and third quartiles; the ends of the whiskers are the 95th and 5th percentile; the dots represent the outliers

Table 2 Mean (SD) of global equilibrium score (GES) per clustered groups

GES [mean (SD)]	18–33 years	34–45 years	46–54 years	55–68 years
150–164 cm	0.83 (0.16)	0.81 (0.17)	0.79 (0.14)	0.68 (0.18)
165–175 cm	0.80 (0.16)	0.73 (0.22)	0.62 (0.28)	0.59 (0.22)
176–183 cm	0.70 (0.14)	0.69 (0.17)	0.50 (0.22)	0.50 (0.27)
184–193 cm	0.60 (0.18)	0.71 (0.10)	0.37 (0.28)	0.34 (0.22)

showed excellent validity (ICC from 0.74 to 0.99) when it was compared with commercial force platforms. Concerning repeatability across different WBB devices, Leach [12] found a low inter-device variability, while Bartlett [11] suggested that repeatability of a single measurement within a board was better than measurement across devices.

The current study has evaluated equilibrium in healthy individuals using RombergLab, an open source posturography software that works connected with the force plate Nintendo® Balance Board™. This software was validated in a previous study, using a clinically approved software and force platform [20].

In this study, we have created equilibrium scores to describe balance in a healthy sample. Raw data obtained from posturography may be difficult to interpret, so the creation of scores helps to make them more comprehensible. The use of a global equilibrium score (GES), such as the composite score of the sensory organization test (SOT) from one of the most widespread posturography equipments [25], gives an overall idea of the balance of a subject.

Our main results show a mean GES of 0.72 (SD ± 0.22) in healthy individuals. GES was found to be influenced by age, height and recruitment center, so a cluster analysis was done to obtain normal values depending on height and age. When clusters were analysed, there were significant differences between the clusters and we could observe that GES decreases with age and with height, which means that the global equilibrium is worse as older and taller the individual is. One important fact is that when GES was stratified by these two variables, the recruitment center was no longer an influential factor. The explanation to this may be due to differences of age and height between centers.

Comparing our reference values with other equipments or authors is a difficult issue because of the different measurement methods used. Concerning the method to measure balance, equipments which use a dynamometric platform calculate the COP, which is a good indicator of the projection of the subject's center of gravity during slow movements [7], but there is no consensus about which calculation method of COP (area, velocity, total distance or frequency) should be used to quantitatively assess balance [26]. Our software calculates and uses CEA, while SOT uses sway angle [25], Freeman [27] uses the amplitude in AP direction, Carmona [28] also uses sway area, but without specification about which with method it is calculated or if it is raw data, and Marchetti [10] uses the normalized path length, but registered by an accelerometer instead of a force plate. There are also differences related to the formulas used to calculate the equilibrium scores. For creating these scores, we have used, as references values to normalize, the 5th and 95th percentiles of the mean of CEA of our sample in each condition; SOT uses the value of 12.5°, which is assumed to be the limit of stability for a normal individual; and Marchetti uses media and SD of young subjects. To calculate GES (or composite score for some authors), results in different conditions are used depending on which test is performed. In SOT, the six conditions of CTSIB [4] are carried out; in our study, as well as in the studies of Freeman and Carmona, the mCTSIB is used, which is composed of four conditions [the two conditions with sway-referenced visual surround are not included (conditions 3 and 6 of SOT)]; Marchetti uses the mCTSIB adding two more conditions, in which the subject is on tandem standing. Another difference for calculating GES is the weight given to each condition: we give the same weight to all conditions, as well as Carmona and Marchetti, while in SOT and Freeman, more weight is given to the difficult ones. Another difference is the sway-referenced support; while in SOT a mobile platform is used, we use a foam as well as Marchetti, Freeman and Carmona. Finally, we have to take in consideration the foam used, since it has been demonstrated that its properties may influence postural sway [29–31]. We used a foam of 50 × 40 × 14 cm (width × length × thickness) and 40 kg/m^3 (density). The foam properties differ between studies, and most of them do not specify these properties, so this makes it difficult to compare the results.

We consider that this study has some limitations. The first one is that during the test, only one trial for each condition was performed, instead of three as widely used in the literature and described for the mCTSIB [5]. It was decided like this to minimize the learning effect across trials, as has been shown to happen in previous studies [32, 33]. But we are conscious that this decision may have decreased reproducibility of the measures. The second limitation is that individuals who fell in any condition were excluded for calculating sway areas and so for calculation of scores. There were only two fallers (0.6% of the total sample), so we consider it an irrelevant limitation. The third one is the exclusion of outliers for generating normal values of the scores. This is because we cannot consider these individuals as normal subjects because they are too different from the rest of sample, maybe they had any equilibrium disorder not known before or maybe there was a technical unknown failure. The fourth aspect, which could seem a limitation, is that when we analysed GES we found the recruitment center

as an influence factor. As we explained before, when clusters by age and height were done, the recruitment center was no longer an influential factor. So, we want to remark that this is not a real limitation of the study, but it is the result of age and height heterogeneity of samples taken by each center, which is inherent in a multicentric study.

Results obtained in this study, adjusted for depending variables, have been included in the last version of the software, RombergLab v1.3 (https://github.com/bendermh/RombergLab), to keep on its validation with subjects with balance disorders as well as to allow researchers to use them in future studies.

Conclusions

RombergLab, validated open source posturography software, connected with the force plate Nintendo® Balance Board™, has been developed as a low-cost posturography equipment. With the introduction of the global equilibrium score values of the present study into the software, we consider RombergLab v1.3 a reference posturography tool for healthy individuals. Further studies are needed for validating it as a suitable instrumented test for screening between healthy and pathologic subjects and its reliability over time for the follow-up of patients.

Funding This research did not receive any specific grant from funding agencies in the public, commercial, or not-for-profit sectors.

Compliance with ethical standards

Conflict of interest None of the authors had conflict of interest in relation with the study.

Ethical standards All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional research committee and with the 1964 Helsinki declaration and its later amendments or comparable ethical standards. This article does not contain any studies with animals performed by any of the authors.

Informed consent Informed consent was obtained from all individual participants included in the study.

References

1. Sudarsky L (2001) Gait disorders: prevalence, morbidity, and etiology. Adv Neurol 87:111–117
2. Salzman B (2010) Gait and balance disorders in older adults. Am Fam Phys 82:61–69
3. Romberg MH (1846) Lehrbuch der Nervenkrankheiten des Menschen. Hirschwald, Berlin
4. Shumway-Cook A, Horak FB (1986) Assessing the influence of sensory interaction of balance. Suggestion from the field. Phys Ther 66:1548–1550
5. Horn LB, Scherer MR (2015) Measurement characteristics and clinical utility of the clinical test of sensory interaction on balance (CTSIB) and modified CTSIB in individuals with vestibular dysfunction. Arch Phys Med Rehabil 96:47–48. https://doi.org/10.1016/j.apmr.2015.04.003
6. Cohen H, Blatchly CA, Gombash L (1993) A study of the clinical test of sensory interaction and balance. Phys Ther 73:346–351
7. Baloh RW, Angeles L, Furman JMR (1989) Modern vestibular function testing. West J Med 150:58–67
8. Clark RA, Bryant AL, Pua Y et al (2010) Validity and reliability of the Nintendo Wii Balance Board for assessment of standing balance. Gait Posture. https://doi.org/10.1016/j.gaitpost.2009.11.012
9. Hubbard B, Pothier D, Hughes C, Rutka J (2012) A portable, low-cost system for posturography: a platform for longitudinal balance telemetry. J Otolaryngol Head Neck Surg 41:S31–S35. https://doi.org/10.2310/7070.2011.110082
10. Marchetti GF, Bellanca J, Whitney SL et al (2013) The development of an accelerometer-based measure of human upright static anterior-posterior postural sway under various sensory conditions: test–retest reliability, scoring and preliminary validity of the balance accelerometry measure (BAM). J Vestib Res Equilib Orientat 23:227–235. https://doi.org/10.3233/VES-130490
11. Bartlett HL, Ting LH, Bingham JT (2014) Accuracy of force and center of pressure measures of the Wii Balance Board. Gait Posture 39:224–228. https://doi.org/10.1016/j.gaitpost.2013.07.010
12. Leach JM, Mancini M, Peterka RJ et al (2014) Validating and calibrating the Nintendo Wii Balance Board to derive reliable center of pressure measures. Sensors (Switzerland) 14:18244–18267. https://doi.org/10.3390/s141018244
13. Park D-S, Lee G (2014) Validity and reliability of balance assessment software using the Nintendo Wii Balance Board: usability and validation. J Neuroeng Rehabil 11:2–8. https://doi.org/10.1186/1743-0003-11-99
14. Scaglioni-Solano P, Aragón-Vargas LF (2014) Validity and reliability of the Nintendo Wii Balance Board to assess standing balance and sensory integration in highly functional older adults. Int J Rehabil Res 37:138–143. https://doi.org/10.1097/MRR.0000000000000046
15. Pavan P, Cardaioli M, Ferri I et al (2014) A contribution to the validation of the Wii Balance Board for the assessment of standing balance. Eur J Sport Sci 15:600–605. https://doi.org/10.1080/17461391.2014.956801
16. Llorens R, Latorre J, Noé E, Keshner EA (2016) Posturography using the Wii Balance Board™. A feasibility study with healthy adults and adults post-stroke. Gait Posture 43:228–232. https://doi.org/10.1016/j.gaitpost.2015.10.002
17. Levy SS, Thralls KJ, Kviatkovsky SA (2016) Validity and reliability of a portable balance tracking system, BTrackS, in older adults. J Geriatr Phys Ther. https://doi.org/10.1519/JPT.0000000000000111
18. Weaver TB, Ma C, Laing AC (2017) Use of the Nintendo Wii Balance Board for studying standing static balance control: Technical considerations, force-plate congruency, and the effect of battery life. J Appl Biomech 33:48–55. https://doi.org/10.1123/jab.2015-0295
19. Zhu Y (2017) Design and validation of a low-cost portable device to quantify postural stability. Sensors (Switzerland) 17:1–12. https://doi.org/10.3390/s17030619
20. Rey-Martinez J, Pérez-Fernández N (2016) Open source posturography. Acta Otolaryngol 136:1225–1229. https://doi.org/10.1080/00016489.2016.1204665
21. Turkey John W (1977) Exploratory data analysis. Addison Wesley, Reading, Massachusetts
22. Scoppa F, Capra R, Gallamini M, Shiffer R (2013) Clinical stabilometry standardization. Basic definitions—acquisition

interval—sampling frequency. Gait Posture 37:290–292. https://doi.org/10.1016/j.gaitpost.2012.07.009
23. Goble DJ, Cone BL, Fling BW (2014) Using the Wii Fit as a tool for balance assessment and neurorehabilitation: the first half decade of "Wii-search". J Neuroeng Rehabil 11:1–9. https://doi.org/10.1186/1743-0003-11-12
24. Clark RA, Mentiplay BF, Pua YH, Bower KJ (2018) Reliability and validity of the Wii Balance Board for assessment of standing balance: a systematic review. Gait Posture 61:40–54. https://doi.org/10.1016/j.gaitpost.2017.12.022
25. NeuroCom Balance Manager (2016) Sensory Organitation Test. Natus Medical Incorporated. http://balanceandmobility.com/wp-content/uploads/018528A_NCM_SOT_brochure_EN-US_lo-res.pdf. Accessed 13 Sept 2017
26. Chaudhry H, Bukiet B, Ji Z, Findley T (2011) Measurement of balance in computer posturography: comparison of methods—a brief review. J Bodyw Mov Ther 15:82–91. https://doi.org/10.1016/j.jbmt.2008.03.003
27. Freeman L, Gera G, Horak FB et al (2016) Instrumented test of sensory integration for balance. J Geriatr Phys Ther 23:1–8. https://doi.org/10.1519/JPT.0000000000000110
28. Carmona S, Zalazar G, D'albora R, Bordabehere G (2017) Portable posturography: validation of variables in people without posture and balance disorders. a pilot study. EC Neurol 6:3:132–136
29. Patel M, Fransson PA, Lush D, Gomez S (2008) The effect of foam surface properties on postural stability assessment while standing. Gait Posture 28:649–656. https://doi.org/10.1016/j.gaitpost.2008.04.018
30. Chaikeeree N, Saengsirisuwan V, Chinsongkram B, Boonsinsukh R (2015) Interaction of age and foam types used in clinical test for sensory interaction and balance (CTSIB). Gait Posture 41:313–315. https://doi.org/10.1016/j.gaitpost.2014.09.011
31. Liu B, Leng Y, Zhou R et al (2017) Foam pad of appropriate thickness can improve diagnostic value of foam posturography in detecting postural instability. Acta Otolaryngol 0:1–6. https://doi.org/10.1080/00016489.2017.1393842
32. Wrisley DM, Stephens MJ, Mosley S et al (2007) Learning effects of repetitive administrations of the sensory organization test in healthy young adults. Arch Phys Med Rehabil 88:1049–1054. https://doi.org/10.1016/j.apmr.2007.05.003
33. Rosengren KS, Rajendran K, Contakos J et al (2007) Changing control strategies during standard assessment using computerized dynamic posturography with older women. Gait Posture 25:215–221. https://doi.org/10.1016/j.gaitpost.2006.03.009

Affiliations

Esther Domènech-Vadillo[1,2] · Gabriel Aguilera-Aguilera[3] · Carmen Sánchez-Blanco[3] · Ángel Batuecas-Caletrio[3] · Carlos Guajardo[4] · Nicolás Pérez[4] · Gabriel Trinidad-Ruiz[5] · Carlos Gimeno[6] · Julio Rama[7] · Marcos Rossi-Izquierdo[8] · Elena San-Roman-Rodriguez[8] · Berta Patiño-Castiñeira[8] · Juan Manuel Espinosa-Sanchez[9] · Eusebi Matiñó[10] · Rafael Barona[11] · Claudio Krstulovic[11] · Jesús Benitez-Rosario[12] · Elvira Santandreu[13] · Francisco Carlos Zuma e Maia[14] · María Guadalupe Álvarez-Morujo de Sande[15] · Ariadna Valldeperes[16] · Jorge Rey-Martínez[16,17]

1 Servei d'Otorrinolaringologia, Hospital Universitari Joan XXIII de Tarragona, c/Dr. Mallafré Guasch, 4, 43005 Tarragona, Spain

2 Institut d'Investigació Sanitària Pere Virgili, Reus, Spain

3 Servicio de ORL y CCC, Hospital Universitario de Salamanca, IBSAL, Salamanca, Spain

4 Unidad de Otorrinolaringología, Clínica Universidad de Navarra, Pamplona, Spain

5 Unidad de Otorrinolaringología, Complejo Hospitalario Universitario de Badajoz, Badajoz, Spain

6 Unidad de Otorrinolaringología, Clínica Rotger, Palma de Mallorca, Spain

7 Unidad de Otorrinolaringología, Hospital Universitari Son Espases, Palma de Mallorca, Spain

8 Unidad de Otorrinolaringología, Hospital Universitario Lucus Augusti, Lugo, Spain

9 Unidad de Otorrinolaringología, Hospital Universitario Virgen de las Nieves, Granada, Spain

10 Unidad de Otorrinolaringología, Hospital General de Catalunya, San Cugat del Vallés, Barcelona, Spain

11 Unidad de Otorrinolaringología, Hospital Casa de la Salud, Valencia, Spain

12 Unidad de Otorrinolaringología, Hospital Universitario de Gran Canaria Dr. Negrín, Las Palmas de Gran Canaria, Spain

13 Unidad de Rehabilitación, Complejo Hospitario Universitario Insular-Materno Infantil, Las Palmas de Gran Canaria, Spain

14 Clinica Maia, Canoas, Brazil

15 Unidad de Otorrinolaringología, Hospital Universitario Puerta del Mar, Cádiz, Spain

16 Unidad de Otorrinolaringología, Hospital Universitario Donostia, San Sebastián, Spain

17 Unidad de Otorrinolaringología, Clínica Quirón Donostia, San Sebastián, Spain