A Visual Analysis Approach to Static Postural Control Acquired by a Force Plate

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Abstract: Force plates are biomechanical equipment responsible for providing data to understand the mechanics of human movement. However, mathematical software used to process data are a barrier to researchers without much experience and prior knowledge on areas from Exact Sciences and Information Technology. This paper aims to implement a visual approach to analyze human static postural control obtained from a force plate as a means of helping researchers interpret its data. By measuring ground reaction forces and their respective torque moments, the displacements of the Center of Pressure in its medial-lateral and anterior-posterior directions are calculated to observe and evaluate the postural balance's behavior. Data processing and visualization were implemented using Python programming language. Scatter plots, heat maps, violin plots, and box plots were used as graphic representations for data collected before and after muscular intervention in older adults with sarcopenia. Applying the developed approach makes it possible to visually observe each of the Center of Pressure's oscillation values measured for data collection and how they relate. This fact differs from statistical information, which summarizes the sample's data in a quantified value. Therefore, data visualization is essential to complement the statistical data and provide another view to force plate data.

1 INTRODUCTION

Biomechanical equipment is essential to obtain data related to the mechanics of human movement and its evaluation and understanding. In addition to the quantitative analysis methods for this area of study, there is the qualitative part of the evaluation, which can be provided through data visualization for a non-numerical and visual way to display values acquired for a variable. As an example of biomechanical research, it is possible to qualitatively assess the behavior of a person's postural control in a dynamic state of movement or standing still, both actions under different vision and surface conditions.

However, one barrier to biomechanical analysis is the mathematical software used to process data. Researchers must have prior knowledge or learn how to manipulate these tools to analyze their data, which makes this step reliant on the experience and expertise presented by the researcher on other areas from Exact Sciences and Information Technology (Dunn *et al.*, 2017). As a result, several biomechanical analyses are quantitative, and only the most experienced researchers use qualitative methods to look at the data. Consequently, the use and benefits of data visualization for biomechanical analyses remain unknown to some researchers from Healthcare areas.

For those with experience in analyzing data, software such as MATLAB and Origin are employed to create visual representations for biomechanical variables. In the case of research based on data collections from force plate equipment, the behavior of a person's Center of Pressure (COP) is evaluated by visualizing one of its displacement directions by the other, which represents right-left and front-back oscillations (Duarte and Freitas, 2010). Since including programming languages, such as Python and R, in analyses, the options and possibilities for data visualization have become increasingly extensive.

This paper aims to implement graphic visualizations using data visualization libraries from Python (Seaborn, Plotly Express and Plotly Graph Objects) to improve the analysis of human static postural control acquired by a force plate to help

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evaluate, interpret, and disseminate postural analysis results to researchers with different levels of experience. The force plate used in this paper measures the components of ground reaction forces and their respective torque moments applied to its surface. From its results, the Center of Pressure in its medial-lateral (ML) and anterior-posterior (AP) directions were calculated to assess its displacement during data collection and evaluate the behavior of human postural balance. In the experiments, the analyzed data belong to static positions performed by older adults with sarcopenia before and after being subjected to a muscular intervention (Bertolini *et al.*, 2021). Both data processing and visualization were implemented using Python programming language.

In the visual analysis, scatter plots, heat maps, violin plots, and box plots corresponded to the graphical representations used to evaluate older adults' postural balance through the behavior of their COP. Thus, each oscillation in their balance can be visually identified by displaying all COP's values and the relationships between them. This way of looking at the data differs from the statistical information, which summarizes a sample's data in quantified values. Applying a visual approach to look at the results acquired from a force plate is essential to contribute to biomechanical analyses by complementing the statistical approach and providing an overall view of the data.

The second section of this paper presents related works to provide perceptions on possible applications with a force plate and how its data has been analyzed quantitatively and qualitatively. The third section describes the methodology employed for visual analysis of the data acquired from the force plate. The fourth section provides a case study for applying the developed visual approach to analyze one of the static positions performed by an older adult with sarcopenia. In the fifth and last section, conclusions and further works are presented.

2 RELATED WORKS

Borges *et al.* (2016) compared static postural balance among older adults with and without mild cognitive impairment using a three-dimensional electromagnetic sensor system. The calculated variables of interest corresponded to velocity and displacement of the Center of Pressure. Tables, line graphs, and scatter plots were implemented using the Origin software to analyze the data. Scatter plots represented each direction of the COP's displacement by the other, and line graphs were used to combine these directions at the time of data collection.

Pinto *et al.* (2019) used four force plates and eight motion capture cameras to compare postural control among two yoga practitioners and two non-practitioners. The variables for their evaluation involved displacements of the Centers of Mass and Pressure, components of ground reaction force, and amplitudes of joint angles, such as the hip, lower back, and knee. Tables, line graphs, and scatter plots were implemented by using MATLAB software for the analysis step. Scatter plots represented the directions of the Center of Pressure's displacement by each other.

Seo *et al.* (2022) assessed the balance of older adults in different vision and surface conditions: eyes open and closed with firm and foam surfaces. A Nintendo Wii Balance Board force plate was chosen to capture the amplitude, velocity, area, and covariance of the Center of Pressure's displacements. The MATLAB software implemented tables and scatter plots, illustrating the medial-lateral direction of the COP's displacement by the anterior-posterior one.

Zychowska *et al.* (2022) used an AMTI force plate to evaluate the consequences of COVID-19 infection on postural control. Within the analyzed group of infected people, those with respiratory abnormalities and others with olfactory abnormalities were also observed as a consequence of COVID-19. MATLAB software assessed the trajectory of the Center of Pressure displacements. The analyses were quantitatively, through tables, and qualitatively, with scatter plots. The visualizations combined one direction of the Center of Pressure's displacement with the other.

Herrera *et al.* (2023) developed a framework to aid the application of Virtual Reality in the context of upper limb rehabilitation. The software can record and store kinematic data during the manipulation of objects in virtual environments. Data acquired from the developed application can be used to evaluate each patient's rehabilitation progress. In a case study to test the software's functionalities, 10 healthy individuals aged between 15 and 39 were conducted in three trials for the conditions of a real environment and an immersive virtual one to measure the number of blocks they were able to pass from one side of a box to the other within a minute. To compare the results, the mean value of the three attempts was calculated and a line graph displayed a link connecting values obtained for each environment. A three-dimensional heat map was also used as an example of visual analysis for the recorded kinematic data.

3 VISUAL ANALYSIS APPROACH AND RESULTS

To implement a visual approach to analyze biomechanical data acquired from a force plate, the data used by this paper came from research on the evaluation of static postural control during the moments before and after a muscle training intervention applied to older adults with sarcopenia, in other words, a loss of muscle mass responsible for affecting their postural balance (Bertolini *et al.*, 2021).

During the data collection, 22 older people (12 women and 10 men aged between 59 and 93) were given three attempts at the static positions of feet together, feet apart, and semi-tandem, under the condition of eyes open and closed. The first two positions were performed for 30 seconds, and the third was performed for 10 seconds. The last performed position was unipodal support with the dominant and non-dominant foot for 10 seconds. Data was collected at 100 Hz (Bertolini *et al.*, 2021).

The OR6-6 model for the force plate made by Advanced Mechanical Technology, Inc. (AMTI) was used to collect data from older people (Bertolini *et al.*, 2021). With this biomechanical equipment, the components of the ground reaction force and their respective torque moments are measured according to the person's contact with the surface of the force plate. Both forces and moments act in an orthogonal coordinate system, in which the x and y-axis are the horizontal components, and the z-axis is the vertical one. From the obtained values, it is possible to calculate, throughout the data collection's duration, the displacement of the Center of Pressure in its medial-lateral and anterior-posterior directions (in centimeters), which respectively correspond to oscillations along the x and y directions. The COP consists of a positioning variable responsible for indicating right-left (medial-lateral) and front-back (anterior-posterior) displacements (Duarte and Freitas, 2010).

For this paper, the Python programming language was used to calculate the oscillations of the Center of Pressure acquired by a force plate and then to implement the graphic visualizations. The x-axis of the graphs represents the COP's ML displacement, and its values are increasing towards the left since older adults were positioned on the force plate so that the x-axis has a positive direction to their left side. The y-axis has a positive sense towards the front of them. Therefore, the y-axis of the graphs represents the AP displacement, with its values increasing upwards.

The values in each calculated variable of the Center of Pressure were translated to make the first one collected corresponding to zero. To accomplish this, the initial value was subtracted by itself, and all the other values were subtracted from the initial one. As a result, reflected in the visualizations, the person's static postural balance is analyzed with the first acquired value as a reference while displaying it as the graph's central point (0,0).

3.1 Scatter Plots

Scatter plots combine the medial-lateral and anterior-posterior displacement variables to display the concentration and dispersion of the Center of Pressure's behavior values. It is possible to notice where the highest and lowest concentrations of data are. In addition, the graph's values can be colored according to the time they occurred during the data collection, which allows us to know which data is from the beginning and the end of the phenomenon.

Figure 1 illustrates a scatter plot for the semi-tandem position with eyes closed during the first pre-intervention execution attempt. The light colors indicate the data collected at the beginning of the acquisition, while the dark colors indicate the final moments of it. Histograms can be added on the side of the visualizations to help locate the regions with concentration values.

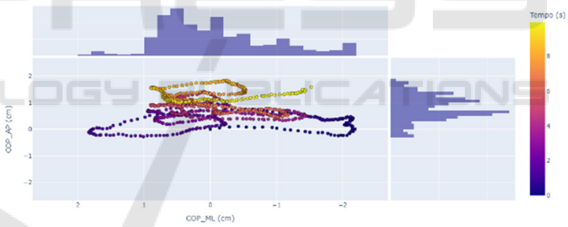

Figure 1: Scatter plot colored by time (Tempo) and combining the COP's displacement in medial-lateral (COP_ML) direction by its anterior-posterior (COP_AP) direction.

Scatter plots can also be used to individually display the COP's displacement directions by the time for data collection. Similarly, it is possible to color the values according to the time they were

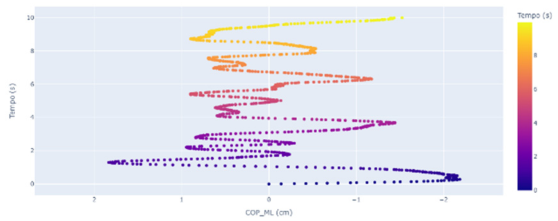

Figure 2: Scatter plot colored by time (Tempo) and combining the COP's displacement in medial-lateral (COP_ML) direction by the time for data collection.

collected. Figure 2 shows the visualization for the ML direction by time, and Figure 3 displays this combination for the AP direction. The represented static position is the same as in Figure 1.

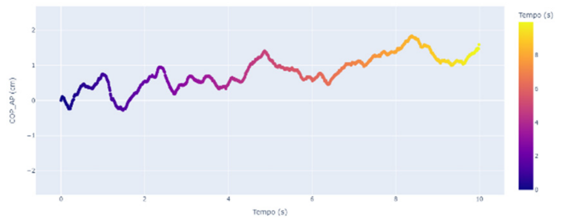

Figure 3: Scatter plot colored by time (Tempo) and combining the COP's displacement in anterior-posterior (COP_AP) direction by the time for data collection.

3.2 Heat Maps

Heat maps also combine the Center of Pressure's directions of displacement. However, this data visualization style displays the regions with a concentration of values in a topographical way.

Figure 4 illustrates a heat map for the same static position as Figure 1. Warm colors indicate the highest concentrations of data, and cool colors show where there are fewer values present. Line graphs on the sides of the visualization can also be added to help indicate the regions with the highest density of values.

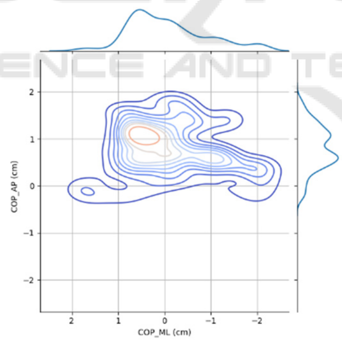

Figure 4: Heat map combining the COP's displacement in medial-lateral (COP_ML) direction by its anterior-posterior (COP_AP) direction.

3.3 Violin Plots and Box Plots

Box plots display the distribution behavior of the variables' values. With this visualization style, the displacements of the COP in the ML and AP directions can be analyzed individually. In addition, they provide visual information on the maximum, minimum, median, and quartiles of a sample's data. Thus, it is possible to be aware of the amplitude and symmetry present in the data. A box plot can be included within a violin plot, whose purpose is to display the density of the data as well, but in a mirrored way. In this visualization, the stretch of the violin's extremities along the graph's axis indicates how far apart the values are, and its peaks indicate how concentrated they are.

For the same static position in Figure 1, Figure 5 provides a violin plot with a box plot to observe the values acquired in the ML direction. Based on the same visual style, Figure 6 shows the performance of the Center of Pressure's AP direction. Both figures have each of the data displayed next to the graph as support for the visualization.

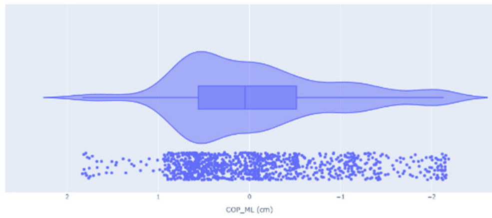

Figure 5: Violin plot with a box plot within it for the behavior of the COP's displacement in the medial-lateral (COP_ML) direction.

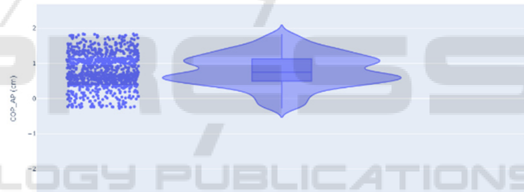

Figure 6: Violin plot with a box plot within it for the behavior of the COP's displacement in the anterior-posterior (COP_AP) direction.

4 DISCUSSIONS

As a demonstration for applying the visual approach developed in this paper, the results for the static semi-tandem position with eyes closed during pre- and post-intervention are evaluated and compared based on the graphic visualizations implemented with Python language.

From the scatter plots and heat maps combining one direction of the Center of Pressure's displacement by the other, it is possible to notice large dispersions in the values from the first and third attempts of pre-intervention and the first one of post-intervention. These results indicate the older adult had more difficulty in finding their balance point control throughout the data collection, which caused their COP to oscillate at practically every moment. On the second attempt for each moment of intervention, dispersions also occurred, but on a smaller scale. On the second one, for pre-intervention, older adults started the data collection with more minor variations in their balance. On the second attempt in post-intervention, they finished it with the values of the COP's displacements, concentrating on a single region.

Additionally, an improvement can be noticed in the post-intervention results, culminating in its third attempt to present values much closer to and around

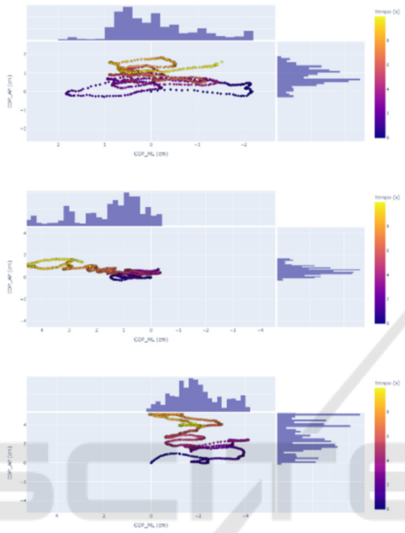

Figure 7: Scatter plots for the pre-intervention moment with the first, second and third (from top to bottom respectively) attempts at the semi-tandem position with eyes closed.

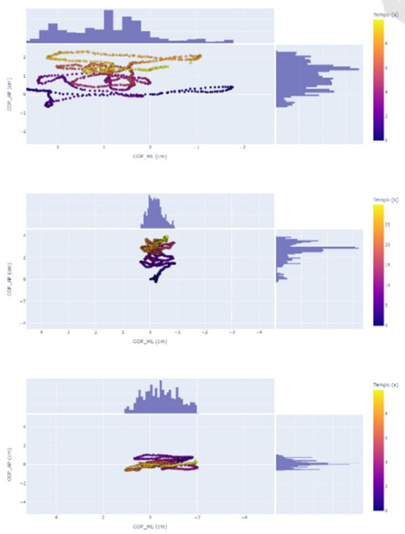

Figure 8: Scatter plots for the post-intervention moment with the first, second and third (from top to bottom respectively) attempts at the semi-tandem position with eyes closed.

the graph's central point (0,0). Such behavior from the results indicates an improvement in the older person's ability to maintain their balance throughout the data collection by displacing their Center of Pressure much less than in previous collections. Figures 7 and 8 illustrate the pre-and post-intervention results with scatter plots. Likewise, Figures 9 and 10 display the data with heat maps.

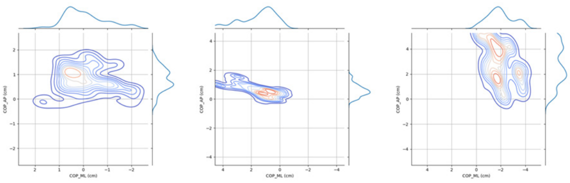

Figure 9: Heat maps for the pre-intervention moment with the first, second and third (from top to bottom respectively) attempts at the semi-tandem position with eyes closed.

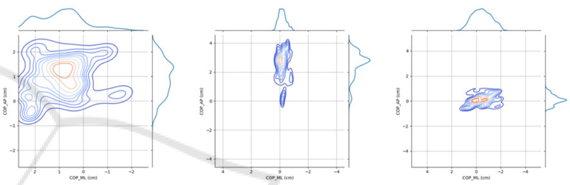

Figure 10: Heat maps for the post-intervention moment with the first, second and third (from top to bottom respectively) attempts at the semi-tandem position with eyes closed.

From the scatter plots combining the medial-lateral direction of the COP's displacement by the duration of data collection, a more prominent oscillation in the values was noticed during most pre-intervention attempts. In contrast, most post-intervention data was closer to zero, with the second attempt showing the tiniest variations.

Applying the same visualization style for the anterior-posterior direction over time makes it possible to notice a similarity in most of the values' behavior for both moments of intervention. The second attempt in pre-intervention and the third one in post-intervention show the closest data to zero. Figure 11 displays the results for the ML direction in pre- and post-intervention. Similarly, Figure 12 illustrates the results for the AP direction.

Instead of displaying the temporal information alongside the Center of Pressure's displacement values, violin graphs with box plots within them enable the density of a single sample's data to be observed in a more detailed way. For the ML direction visualization, it is possible to notice most of the pre-intervention attempts, and the first one in post-intervention displays the most prominent

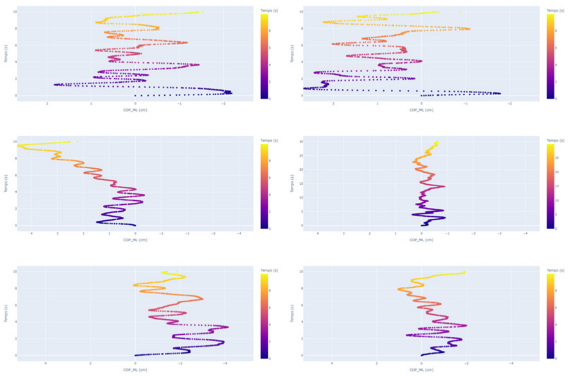

Figure 11: Scatter plots for the medial-lateral direction during pre- (left) and post-intervention (right) with the first, second and third (from top to bottom respectively) attempts at the semi-tandem position with eyes closed.

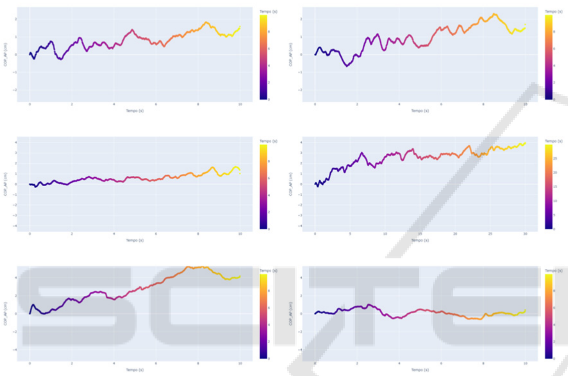

Figure 12: Scatter plots for the anterior-posterior direction during pre- (left) and post-intervention (right) with the first, second and third (from top to bottom respectively) attempts at the semi-tandem position with eyes closed.

oscillations in the older adult's postural balance. On these attempts, the violin stretches throughout the graph, indicating a dispersion in the values. However, post-intervention results indicate an improvement in minimizing the COP's displacement in its ML direction and maintaining a more concentrated posture control at each sample taken. Values in these attempts are closer to zero, especially in the second one, and the graph's violin is not stretched as much.

Finally, for AP direction, attempts to present the smallest dispersions correspond to the second data collection in pre-intervention and the last two in post-intervention. These results indicate a more considerable concentration of data approaching the zero value. In the post-intervention moment, it is possible to observe the values becoming increasingly concentrated with each attempt taken. Figure 13 illustrates the ML direction obtained in pre- and post-intervention. Likewise, Figure 14 displays the results for AP direction.

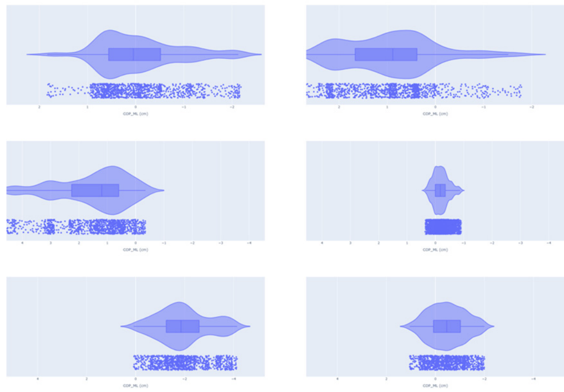

Figure 13: Violin plot with a box plot within it for the medial-lateral direction in pre- (left) and post-intervention (right) with first, second and third (from top to bottom respectively) attempts at semi-tandem position with eyes closed.

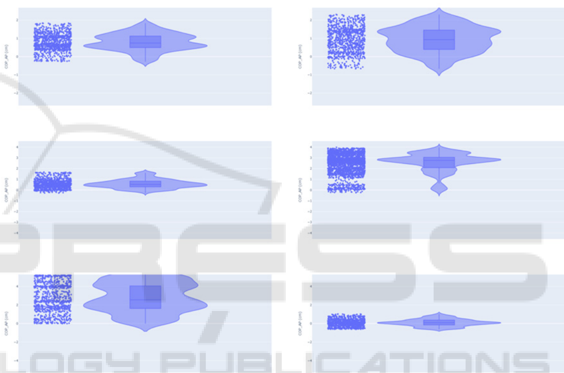

Figure 14: Violin plot with a box plot within it for the anterior-posterior direction in pre- (left) and post-intervention (right) with first, second and third (from top to bottom respectively) attempts at semi-tandem position with eyes closed.

5 CONCLUSIONS AND FURTHER WORKS

The mechanics of human movement are measured and evaluated through a variety of biomechanical equipment. However, its data analyses consist primarily of quantitative steps, and not all researchers are aware of the qualitative methods for looking at their data. To develop a visual approach to analyze data acquired from a force plate, this paper aims to apply data visualization to the evaluation of static postural control in older adults with sarcopenia submitted to a muscular intervention to demonstrate visualizations' contributions to biomechanical research.

The Center of Pressure was calculated in its medial-lateral and anterior-posterior directions to observe the postural balance's behavior. Data processing and visualization were implemented using Python programming language. Scatter plots, heat maps, violin plots, and box plot visualizations were modeled to provide qualitative information about the values acquired for each of the COP's displacement directions, individually combined by the data collections' duration and the combinations of one of the oscillation directions by the other.

When the graphic visualizations were applied to compare the static semi-tandem position with eyes closed performed for an older adult during the data collections at pre- and post-intervention, it was possible to identify the behavior of their postural balance throughout every attempt of positioning. The concentrations, dispersions, and variations in the COP's oscillation values were displayed in the graphs to be interpreted. After visually comparing the results, it was possible to determine an improvement after the muscular intervention in the older adult's postural control for the analyzed static position.

Applying a visual approach to biomechanical analyses with data acquired from a force plate enables each value present in a sample to be visualized graphically. This way, it is possible to know all the collected data's behavior and how they relate. This overall view of the results differs from statistical information by not presenting a numerical value to characterize the phenomenon analyzed. For static postural control analyses, there is a visual perception of how the person's Center of Pressure behaves throughout the data collection, not a summarization of such action into a numerical quantification. The addition of temporal information in the visualizations is also relevant to the exact awareness of postural balance's performance at the beginning, middle, and end of a static positioning execution.

In addition, the variety of graphic visualization styles opens up a wide range of possibilities for representing a sample's data. Each visual style has characteristics that can enhance the others, and more than one visualization can complement one another in the same graph.

Therefore, graphic visualizations are essential to support and contribute to force plate users during the analyses of their results and provide different ways of looking at their data. Visual information is also necessary to increase and complement the quantitative side of biomechanical research.

For this paper, no dynamic postural control data was used, and no other variables related to the Center of Pressure were calculated. With a force plate, it is possible to capture performances regarding dynamic actions (e.g., gait, jump), and to calculate additional COP-related variables (e.g., velocity, frequency, area).

As further works, developing a non-paid, intuitive, and user-friendly computational interface for enabling researchers with different experiences in data analysis to create graphic visualizations and use them to contribute to their biomechanical evaluation of postural control acquired from a force plate is proposed, disseminating the use of visualization in analyses from force plate data. Furthermore, the tool can provide the calculation and visualization for other COP-related variables and add statistical information provided in tables to complement the qualitative data. Additional functionalities can correspond to enable users to change the variable chosen to color values in scatter plots. Parameters that differ according to the research with the force plate (e.g., frequency of data acquisition) can also be altered by users. The type of force plate from which the data will be collected must be previously decided, as force plates can generate different data and file formats, saving them. Finally, the recommendations and suggestions provided by the participations of force plate users are essential to validate the tool's usability and functionalities, as well as the visualizations used for postural control analyses.

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