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Undisturbed stance on a double seesaw: Interaction between asymmetries of the center-of-pressure patterns under each foot and weight-bearing

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ABSTRACT

Both center-of-pressure (CP) displacements under each foot and relative body-weight distribution intervene in the production of resultant CP movements. To better understand their respective involvement, a protocol was set up for young healthy individuals consisting in standing on a double seesaw, favoring pitch motions and laying on a dual-force platform. The postural control effects induced by two types of asymmetry, weight-bearing and the CP movement patterns, were investigated. These asymmetries were achieved by associating two seesaws with two different lengths for the radii of the ridges and by requiring specific body-weight distributions. The results indicate that the postural strategies, aimed at controlling anteroposterior sway, are related to the subjects' capacity to minimize the CP displacements under the less stable support, whatever load is applied. In contrast, the degree of involvement of the more stable support must be viewed as a complement used to secure the appropriate motor output, i.e., the resultant CP movements. Within this objective, both the applied load and the CP amplitudes under the more stable support are taken into account. These data provide additional insights into the compensatory mechanisms between the interactions between the two feet, which are used to produce the adequate resultant CP movements and therefore upright stance control. The specificity of the double seesaw that can induce asymmetric CP patterns and/or asymmetric body-weight distribution makes it a legitimate contender to be used as a rehabilitation device for patients with neurological and/or traumatic diseases.

1. Introduction

Postural control in upright standing is based on the subject's ability to produce muscular torques from his/her lower limbs in order to displace his/her center of gravity. Numerous biomechanical studies aimed at better understanding the organization of this control are based on kinetic data collected from force platforms. These muscular torques are expressed through the resultant center-of-pressure (CP_{Res}) displacements, i.e., the point where the resultant vertical reaction force is applied. Since humans are bipeds, it can be of interest to consider the actions intervening under each foot using a dual-force platform. Interestingly, the right and left CP (CP_{RF} and CP_{LF}, respectively) displacements, combined with body-weight distribution time series, are used to compute CP_{Res} movements, the controlling variable aimed at displacing the center-of-gravity movements, the controlled variable (Winter et al., 1996).

Recently, it was shown that the use of a double seesaw, i.e., a device composed of two rocking platforms facilitating forward–backward movements (pitch) in a side-by-side foot position, could facilitate asymmetric patterns between CP_{RF} and CP_{LF} movements (Rougier and Perennou, 2019). This postural behavior can be obtained using different radii for the circular ridges placed under the seesaws. Interestingly, in this case, the CP displacements are always larger on the side of the support providing better stability, i.e. the longer radii, and without any time lag between the two seesaws but, interestingly, without necessarily engaging any weight-bearing asymmetry.

These two kinds of asymmetry can be observed in numerous pathologies, traumatic or neurological, and are well documented. For instance, after stroke most impaired hemiparetic patients present substantial asymmetries in their body-weight distribution,

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which can reach more than 90% on average for the nonparetic lower limb, and significant differences in the CP patterns, including the amplitude and orientation of these displacements (Genthon et al., 2008; de Haart et al., 2004; Mizrahi et al., 1989). A similar observation can be made for patients after an ankle sprain (Genthon et al., 2010) or an amputation (Rougier and Bergeau, 2009), even though the levels of weight-bearing asymmetry are less pronounced than for the more impaired hemiparetics. In all cases, the postural strategy for controlling anteroposterior (AP) sway is based on a modification of the pressure distribution, the basic mechanism involved for securing balance control along that axis (Winter et al., 1996; Rougier, 2007). Since the effects of the CP movements under each foot upon CP_{Res} are proportional to the load applied on the limb, compensatory strategies are generally observed. In these strategies, a concomitant increase in the CP under the more loaded and less impaired lower limb is combined with a decrease in the opposite CP under the less loaded and less impaired limb. Their aim is to produce adequate and sufficient CP_{Res} displacements along the AP axis to ensure efficient control of the center of gravity, and therefore the body's balance.

The possible interaction between the two types of asymmetry (CP pattern under each foot and weight-bearing), has been, to our knowledge, poorly investigated. In healthy young adults, when standing on solid ground it was shown that the greater the weight-bearing asymmetry, the greater the CP displacements under each foot (Genthon and Rougier, 2005), with nonetheless a greater increase for the unloaded side. Naturally, these two increases in turn favor larger CP_{Res} movements along both the ML and AP axes. Other interesting information is also provided by clinical follow-ups. Generally during their recovery process, hemiparetic patients progressively decrease these two kinds of asymmetry (Sackley, 1991; Bohannon and Leary, 1995; Titianova and Tarka, 1995; de Haart et al, 2004), whereas patients after an anterior cruciate ligament reconstruction recover their weight-bearing capacity more rapidly than their asymmetry of CP patterns (Rougier et al., 2012).

Combining a double seesaw device with different radii to assess CP pattern asymmetry with voluntary weight-bearing asymmetry in young healthy adults seems a good way to improve our knowledge of these interactions. In particular, the objective in this study was to determine to which extent the postural control system is able to display the most efficient motor command output (subjects were required to stand as still as possible) despite variable asymmetries. Our main hypothesis is that the subjects should take into account their body-weight distribution to adapt their CP amplitudes under each foot. More precisely, the respective contribution of each foot in the production of the CP_{Res} movements, assessed through a method previously developed for analyzing the effects of weight-bearing asymmetry (Rougier and Genthon, 2009), should provide interesting insights. Through our contribution indices, it can be hypothesized that the relative unequal contribution of the two CPs, due to the difference between the radii of the two seesaws, should vary with weight-bearing asymmetry. In particular, overloading the support offering the least stability should allow the subjects, from a given level of body-weight asymmetry, to shift the predominant foot involved in their balance control along the AP axis. This postural strategy would indicate that the central nervous system, in planning the motor output, takes into account both the body-weight distribution and the mechanical characteristics of the supports.

2. Methods

2.1. Subjects

This study was approved by the ethics committee of Savoie-Mont-Blanc University. Thirteen healthy young adults, 11 men and two women, aged from 20 to 24 years (body weight, 69.5 kg ± 7.3; height, 174.4 cm ± 8.2; mean ± standard deviation; all left-footed) with no known visual or balance pathology gave their written informed consent and were included in this study. All subjects were students in sports and physical education and, on average, did about 4–6 h of physical activity per week.

2.2. Seesaw device

The double seesaw device, made of two side-by-side individual wooden seesaws (each weighing 1.35 kg), is made of two rectangular plates (40 cm long × 20 cm wide) mounted 7 cm above two circular ridges (radius: 55 cm or 35 cm). As seen in Fig. 1 the device was laid on a dual-force platform (PF02, Equi+, Aix-les-Bains, France). The seesaw movements, achieved exclusively along the AP axis to favor pitching body motions, were assumed to have no friction with the force platform.

2.3. Protocol

Three conditions were randomly performed requiring subjects to stand on a double seesaw with different radii (35 and 55 cm for the left and right feet, respectively) with three levels of weight-bearing asymmetry (67–33; 50–50 and 33–67; i.e., the percentages of body-weight applied on the left and right feet, respectively).

For all conditions, the subjects were asked to stand as still as possible with their eyes closed, their arms at their sides, and the inner border of their feet parallel and 12 cm apart. For each condition, the feet were placed to allow horizontal positioning of the seesaw at the onset. Before each condition, a preliminary training trial was set to allow the subject to accommodate with the requested body-weight distribution, with the oral help of the investigator. This training appears sufficient to allow the subjects to find it again later during data collection. If necessary, more feedback was given, but only between the trials to avoid any possible interaction with the postural evaluation. Three trials lasting 64 s, interrupted by 32-s rest periods during which the subjects, standing upright, were allowed to open their eyes, were recorded and averaged for each condition. The signals from the load cells under the plates were amplified and converted from analog to digital form through a 14-bit acquisition card before being recorded on a personal computer with a 64-Hz sampling frequency.

2.4. Signal processing

The CP_{Res} movements along both the ML and AP axes were computed using the following formula (Winter, 1995):

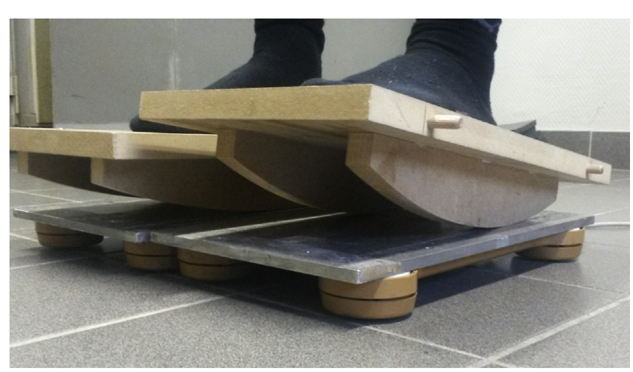

Fig. 1. Photograph of the double seesaw device lying on a double force platform. The condition displayed here is the 50–50 with the seesaws with the 35 and 55 cm radii under the left and right feet, respectively.

$$CP_{Res} = CP_{LF} \times \frac{R_{LF}}{R_{LF} + R_{RF}} + CP_{RF} \times \frac{R_{RF}}{R_{LF} + R_{RF}}$$

where R_{LF}, R_{RF}, CP_{LF} and CP_{RF} are the vertical reaction forces and center-of-pressure positions under the left and right feet, respectively. The mean percentage of body-weight (%BW) was also computed for each trial.

To assess the respective role of each foot in the dynamic process for displacing the CP_{Res} displacements, theoretical CP_{Res} displacements were recomputed (Rougier and Genthon, 2009). The principle consists in interchanging certain time series values by the mean of these series. For instance, a CP_{Res} trajectory can be split into two elementary trajectories, CP_{LF} and CP_{RF}, which were intended to correspond to the CP_{Res} displacements that would have been obtained if the subjects' left or right feet only were involved in the control, respectively. As seen in Fig. 1 from the study of Rougier and Genthon (2009), when the feet of a healthy subject are positioned side by side, the CP_{LF} and CP_{RF} displacements are orthogonal to each other. To assess their relative contribution to balance control along a given axis, $Contr_{LF}$, and $Contr_{RF}$ indices were then computed from the relative dispersions (s.d.) of CP_{LF} and CP_{RF} with respect to the sum $CP_{LF} + CP_{RF}$ (Rougier and Genthon, 2009).

$$Contr_{LF} = s.d.\ CP_{LF}/(s.d.\ CP_{LF} + s.d.\ CP_{RF})$$

$$Contr_{RF} = s.d.CP_{RF}/(s.d.CP_{LF} + s.d.CP_{RF})$$

Since by definition $Contr_{LF} + Contr_{RF} = 1$, only the highest indices expressing the most involved foot in the control along the ML and AP axes are presented. The higher the index, the greater the foot's contribution.

The ANOVA of Friedman was calculated for the %BW and the variances of CP_{Res}, CP_{LF}, CP_{RF} along both the ML and AP axes. When statistically significant results were obtained, i.e., when $p < 0.05$, Dunn post-hoc tests were used. Wilcoxon tests were performed to compare CP_{LF} and CP_{RF} movements in each condition. Nonparametric analyses were performed because the homoscedasticity assumption was not passed.

3. Results

For a representative subject, Fig. 2 displays the movements of the CPs (Res, left and right feet) for the three experimental conditions. One can see in particular the lateral shift of the CP_{Res} trajectories depending on the changes in the weight distribution and the amplitude modifications for the CP under the left and right feet.

3.1. CP_{Res} movements and body-weight distribution

The ANOVA of Friedmann indicates a lack of significant effect for the CP_{Res} movements intervening along the ML axis (χ^2 (13,2) = 1.08; $p > 0.05$). In contrast, statistically significant results were found along the AP axis (χ^2 (13,2) = 7.54, $p = 0.023$). As seen from the plots in Fig. 3A, standing on the double-seesaw with a larger load on the plate with the longer radii led to a decrease of the CP_{Res} movements along the AP axis. The post-hoc effects show differences between the 50–50 and 33–67 conditions.

For the percentages of body-weight distribution, the statistical analysis indicates significant effects (χ^2 (13,2) = 26, $p < 0.001$). This result confirms that the instructions were respected regarding the body-weight asymmetries. Indeed, the %BW reported for the left

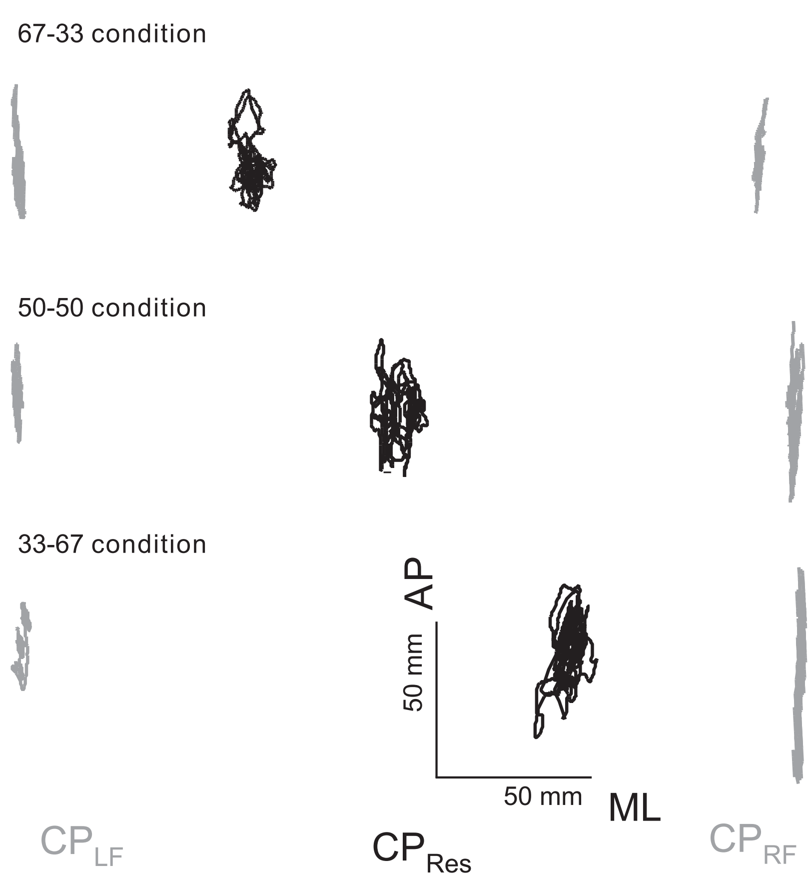

Fig. 2. Displacements of the CP_{lf}, CP_{Res} and CP_{rf} during a 64-s stance trial in a representative subject for the three experimental conditions. Note the asymmetrical patterns of the CP_{LF} and CP_{RF} movements in the 50–50 and 33–67 conditions.

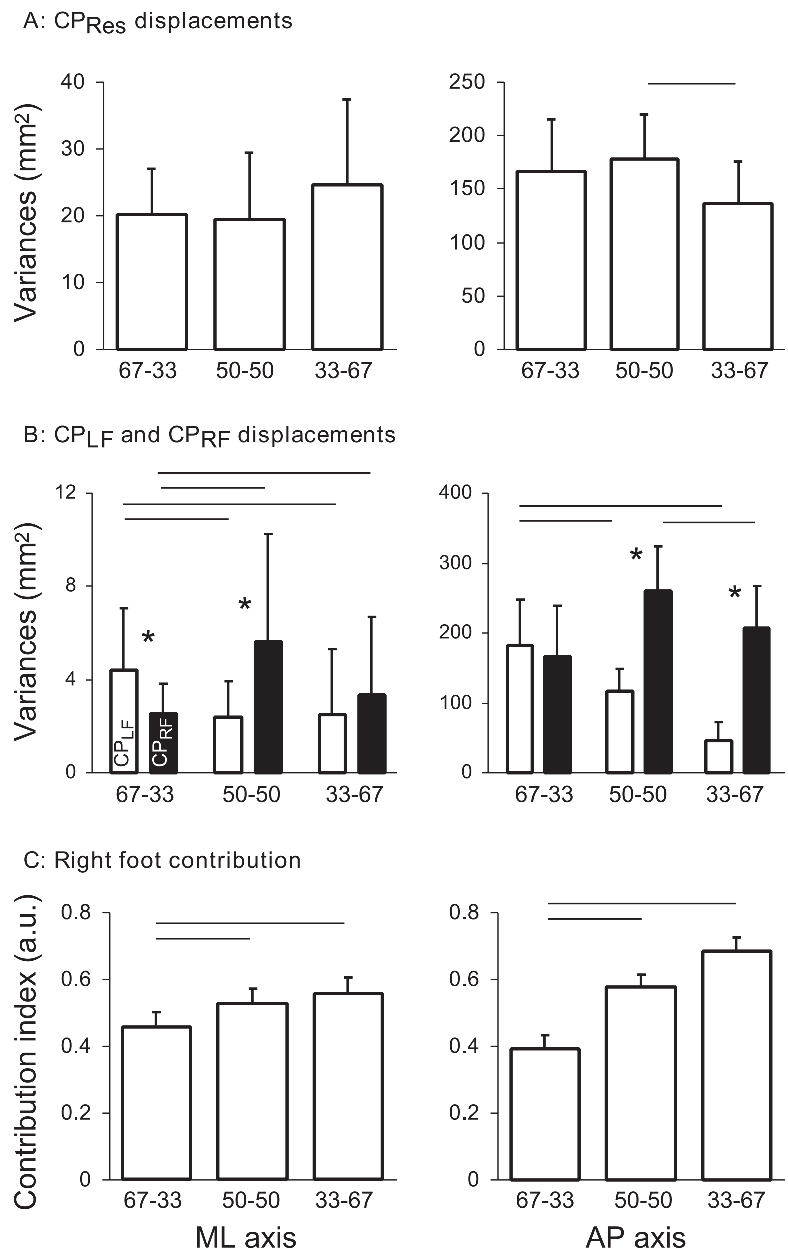

Fig. 3. Bar charts of the variances (mean + s.d.) measured along the ML and AP axes for CP_{Res} (A), CP_{LF} and CP_{RF} displacements (B) and the right foot contribution indices (C) for the three experimental conditions. The simple effects are displayed above the charts by horizontal bars. Note the progressive contribution of the right foot in the production of the CP_{Res} movements from 67–33 to 33–67 conditions.

foot were, 0.67 + 0.02, 0.51 + 0.01 and 0.32 + 0.02 for the 67–33, 50–50 and 33–67 conditions, respectively.

3.2. Variances of CP_{LF} and CP_{RF} movements

The ANOVA of Friedman for the two movements along both ML and AP axes displays significant results. This applies for the left (ML: χ^2 (13,2) = 12.15, p = 0.002; AP: χ^2 (13,2) = 24.15, p = 0.001) and the right foot (ML: χ^2 (13,2) = 9.38, p = 0.009; AP: χ^2 (13,2) = 10.31, p = 0.006).

The post-hoc effects, displayed in Fig. 3B, show that the variances of the CP_{RF} and CP_{LF} displacements are the greatest for the 50–50 and 67–33 conditions along both the ML and AP axes, respectively. Concerning the differences of variances between the two feet, tested through Wilcoxon tests, some effects were found for the 67–33 and 50–50 conditions along the ML axis and for the 50–50 and 33–67 conditions along the AP axis. In other words, the variances are greatest for the CP_{RF} in the 50–50 condition and for the CP_{LF} in the 67–33 condition along both the ML and AP axes.

3.3. Contribution indices

As seen for the bar charts in Fig. 3.C, the main feature of these foot contributions is their progressive variation. In the present case, the $Contr_{RF}$ are computed because this support is more involved in most conditions. This is true for the 33–67 condition and, to a lesser degree, the 50–50 condition. It is worth noting that the left foot contribution predominates for the 67–33 condition.

From a statistical point of view, the ANOVA of Friedman values indicate significant effects along both the ML (χ^2 (13,2) = 15.85, p = 0.001) and AP axes (χ^2 (13,2) = 24.15, p = 0.001). Post-hoc effects are displayed through horizontal bars above the charts (Fig. 3C).

4. Discussion

Three important findings are worth noting from this study. Firstly, the differences between the variances of the CP movement along the AP axis occurring under each foot depend on both the level of stability provided by the supports and the body-weight distribution. Secondly, the respective contribution of each foot in the production of the CP_{Res} movements varies as a function of weight-bearing asymmetry. Lastly, the amplitudes of the CP_{Res} movements along the AP axis result from the interaction between the two types of asymmetry. Applying more load on the support providing more stability tends to decrease these CP_{Res} movements.

4.1. The movements under each foot take into account both the level of stability provided by the seesaw and the body-weight distribution.

In our previous study (Rougier and Perennou, 2019), it was shown that standing on a double seesaw with different radii for the circular ridges led the subjects to use the seesaw providing better stability (longer radius) more of the time. This principle, again observed in the current study, applies for the CP movements along both the ML and AP axes. As can be seen in Fig. 2 with various CP trajectories for a representative subject across the three conditions, the patterns of the CP displacements under each foot remain longitudinal, i.e., along the main axes of the feet. This feature explains why most of the effects, depicted through the AP axis, are not also found along the ML axis. In this foot position, since the pressure distribution mechanisms, which determine the CP patterns, are mainly involved in securing AP sway (Winter et al., 1996; Rougier 2007), we were bound to focus solely on the postural control strategies observed along the AP axis.

Interestingly, adopting an asymmetric body-weight distribution produces different changes for the amplitudes of the CP patterns under each foot. Indeed, in one case (33–67 condition), the two variances were lower in quite similar proportions, whereas, in the other case (67–33 condition), the changes in the variances went in opposite directions. To be more precise, loading the less stable support (left foot), as in the 67–33 condition, leads to increased CP movements, whereas the large movements under the more stable support (right foot), decrease concomitantly (Fig. 3B). These postural behaviors can be highlighted through various scientific approaches.

From a biomechanical point of view, it can be argued that the large CP movements for the right foot, as they are observed for the 50–50 condition, appear now, in this 67–33 condition, unnecessary for eliciting significant CP_{Res} movements, i.e., large enough to appropriately control the center-of-gravity movements. This feature, due to the increased loading of the left foot, is highlighted by the formula used to compute the CP_{Res} movements, which consists in the addition of two products involving the CP displacements and the relative foot loadings (see Methods). To be more specific, the load increase allows the subject to reduce his/her CP displacements under the more stable right foot. Nonetheless, the application of this principle seems limited to the transition from 50–50 and 33–67 conditions. In the 67–33 condition, instead of increasing the CP under the more stable support (right foot), the subjects adopted the opposite strategy consisting in increasing the CP under the less stable support. In fact, continuing with the same strategy would have led the subjects to significantly increase the movements under the more stable support. Unfortunately, unless drastically decreasing the movements under the loaded and less stable left foot, this strategy would lead to large CP_{Res} movements. Moreover, loading a rocking platform while attempting to improve its stability is highly unrealistic. This is explained by both the sensitivity of the CP displacements to muscular force variations and the mechanical specificity of the device. Indeed, for quasi-isometric conditions, one can hypothesize that the greater the muscular activity, the larger the number of motor units recruited as well as the torque variations and therefore the CP displacements. This phenomenon is here augmented by the longer radii of the ridges under this seesaw. As a result, applying more weight on this support further amplifies the CP displacements. One can therefore consider that loading this less stable support is in no way the easiest solution to obtain precise control of the CP_{Res} movements.

From a neurophysiological point of view, searching to decrease the CP amplitudes under the two feet as much as possible, as for the 67–33 condition (Fig. 3B), might be viewed as a way to facilitate a common tonic drive of the two ankle plantar flexors (Gibbs et al., 1995; Mochizuki et al., 2005). This possible feature would likely explain the progressively increased correlation between the two CP trajectories observed when subjects limit weight-bearing asymmetry (Mansfield et al., 2011). However, going further in that direction would require taking into account the degrees of amplification of the CP displacements by each seesaw. Indeed, the CPs recorded through our force platform only constitute an amplification of the real CP, i.e., the one occurring under the subject's foot, resulting from the combined rotation–translation motions of the seesaws (Ivanenko et al., 1997).

Taking these opposite behaviors together, it appears that the postural control strategies would first rely on the subject's ability to limit his/her CP displacements under the less stable support as much as possible. As shown by the bar charts in Fig. 3B, a progressive decrease of these movements with the applied load contrasts with the irregular behavior characterizing the more stable right foot. Along these lines, one could propose that the requisite CP_{Res} output could result from two not necessarily discordant constraints, on one hand to limit the displacements under the less stable support to the lowest level possible even though a significant load, resulting from the body-weight distribution, is applied and, on the other hand, to use predominantly and complementarily the more stable support. This strategy stems from the incapacity of the seesaw to be entirely stabilized since CP movements under the feet necessarily occur. These limited movements result from the nonisometric muscular contractions of the lower limbs (de Luca et al., 1982).

4.2. The respective contributions of each foot to the production of CP_{Res} movement changes according to body-weight distribution

If, as seen above, the postural control strategies cannot be advantageously explained through the CP displacements occurring under each foot, the results reported herein tend to show that the contribution indices could provide interesting and additional insights. A progressive contribution of the right foot (more stable support) was noted as long as body-weight distribution increases. Conversely, this means that the contribution of the contralateral foot (less stable support) decreases with body-weight distribution. If this feature applies for both the ML and AP axes, the pitch motions induced by the seesaw configuration likely explain the larger effects along the AP axis.

As for the variance of the CP under each foot, the ranges of the contribution indices suggest that each foot should contribute equally in both the 67–33 and 50–50 conditions. The fact that equal contributions are not found for the 50–50 condition is naturally due to the asymmetric physical characteristics (radii) of the two seesaws.

The progressive nature of the increase (or decrease for the contralateral foot) expresses an adjustable involvement of the two legs in the upright stance control process, independently of the physical characteristics of the supports. One may therefore hypothesize that setting different support conditions for the two feet would not notably change the progressive involvement of each foot during weight-bearing shifting. Simply, a critical point, corresponding to an equal contribution of both feet in standing control, would itself also be shifted.

4.3. The weight-bearing asymmetry solely modifies the CP_{Res} movements along the AP axis

These results have shown that the amplitudes (variances) of the CP_{Res} movements were significantly modified since smaller and larger movements were seen for the 33–67 and 50–50 conditions, respectively (Fig. 3A). In contrast, no real effect was observed along the ML axis. These results confirm the predominant role played by the pressure distribution mechanism for controlling the AP sway when the feet are positioned side by side, as in this protocol. The lack of results along the ML axis contrasts with the data previously reported in healthy individuals standing with more or less weight-bearing asymmetry on solid ground (Genthon and Rougier, 2005). Indeed, in this study, the weight-bearing asymmetry determined increased CP movements under both loaded and unloaded feet. This dual increase necessarily leads to increased movements of the CP_{Res} movements, particularly along the ML axis. The lack of effects along this ML axis is therefore rather singular. The main explanation for this lack of increase might be related to the specificity of the double-seesaw devices and the sensation of instability they create (Rougier and Perennou, 2019). One can therefore hypothesize that the subjects are ready to initiate a step in similar ways in all conditions.

The smaller CP_{Res} displacements observed in the 33–67 condition are explained by the differences in the seesaws relative stability and therefore the opposite load effects on CP amplitudes. Due to the longer radii, increasing the load on the left less stable seasaw would tend to increase the CP movements whereas loading the contralateral right more stable seesaw would produce an opposite effect, i.e. decreased CP movements. Thus adopting a precise weight-bearing asymmetry while standing on an asymmetric double seesaw is the only way to limit CP_{Res} movements and therefore postural stability along the AP axis.

In conclusion, this study has highlighted the respective role of the two kinds of postural asymmetry, one expressing the body-weight distribution over the two lower limbs and the other concerning the CP patterns under each foot. If the subjects tend to principally use the more stable support to control their upright stance along the AP axis, the data herein show that the relative involvement of the two feet is in fact determined by the minimal contribution of the contralateral support. Despite possible counteracting phenomena between these two asymmetries, the general output of the postural control system, namely the CP_{Res} displacements, can vary slightly across conditions. This consistency of CP_{Res} movements underlines the capacity of the CNS to take into account both the weight-bearing asymmetry and the levels of CP amplifications resulting from the seesaws' pitch motions. The capacity of the double seesaw to induce asymmetric CP patterns and/or asymmetric body-weight distribution in healthy individuals should be viewed as a specificity of this device. This feature alone makes it a legitimate contender to be used as a rehabilitation device for patients with neurological and/or traumatic diseases. In addition, the possibility of proposing a quasi-infinite number of seesaw associations, combining various differences in both heights and radii values, is expected to provide the patient with a targeted involvement of both lower limbs in controlling upright stance.

Declaration of Competing Interest

None.

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