Postural control in healthy young adults using a double seesaw device

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A B S T R A C T

Postural control on single and double seesaws was investigated in young healthy adults required to stand as still as possible on two side-by-side seesaws favoring pitch motion and lying on two separate force platforms. The device offers the possibility to get associated or dissociated seesaws and, if dissociated, to induce asymmetric patterns for the centers-of-pressure (CP) under both left and right feet by using different radii for the two seesaws. Substituting a parallelepiped volume to one seesaw offering a firm contact to one foot is also possible. The results indicated that dissociating the two seesaws led to increased resultant CP (CP_{Res}) and vertically projected center-of-gravity movements (CG_v) only along the mediolateral axis, whereas a slight decreasing tendency characterized these movements along the antero-posterior axis. When standing on two independent seesaws with different radii, significantly larger CP displacements were seen along the antero-posterior axis under the foot lying on the more stable support, i.e., the seesaw with the longer radius or the parallelepiped volume. In these two asymmetrical conditions, the CP_{Res} output results from a compensatory mechanism, i.e. larger movements under one foot to compensate for the decreased movements occurring under the opposite foot. This postural control strategy is aimed at allowing sufficient CP_{Res} displacements in order to appropriately secure balance. Because of the complex sensorimotor coordination induced, involving differentially in certain cases both legs, the double seesaw device can be viewed as a possible tool for challenging postural control by inducing asymmetrical patterns between left and right feet CP movements.

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1. Introduction

Upright quiet stance is a sensorimotor task that requires the contribution, when available, of various sensory cues (vision, touch, proprioception and vestibular). Since the latter is insufficiently solicited in many people (Birren, 1945; Walsh, 1973), this has led some investigators to enhance self-initiated body sways by using destabilizing devices (Mauritz et al., 1980; Dietz and Berger, 1982, 1984; Dault et al., 2001). One of the most common devices, easy to set up, is the seesaw, made of a rigid plate lying on two circular ridges, on which subjects stand. Depending on the orientation of the ridges regarding the feet positioning and the body, roll or pitch motions can be favored. In all cases, the biomechanical principle consists in an amplified displacement of the resultant center-of-pressure (CP_{Res}), due to the combined translation and rotation of the apparatus (Ivanenko et al., 1997). These CP_{Res} movements, which are computed with dual force

platform from the two trajectories of the centers of pressure (CP) of each platform and the body-weight distribution time series, are considered as the controlling variable (Winter et al., 1996) and are aimed to control those of the vertically projected center-of-gravity (CG_v). However, because of the large inertia of the standing body, if the CP_{Res} amplitudes are increased with sufficient velocity, the CG_v displacements are less influenced by seesaw movements. As a result, the difference between these two movements ($CP-CG_v$), whose amplitudes appear proportional to the horizontal acceleration communicated to the CG_v (Brenière et al., 1987) and are fairly correlated with the neuro-muscular activity (Rougier et al., 2001), is necessarily increased and therefore creates a more difficult postural control and decreased stability. Moreover, Ivanenko et al. (1999) have shown that modifying the level of postural stability, with the use of shorter radii, lessens the role of proprioceptive information (and therefore increases the contribution of vestibular inputs) in the postural response. Responding to this modified sensorimotor coordination requires a learning process, as highlighted by the decreased CP_{Res} movements, which can be observed in young healthy adults within a few tens of minutes (Rougier, 2012).

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A single seesaw, in which both feet are joined together by nature, constrains an upright subject to perform in-phase feet movements and favors symmetry between the CP under the left and right feet (CP_{lf} and CP_{rf}, respectively). The appropriateness of such seesaws to the features of neurological patients appears rather limited, principally considering their double asymmetry to control their upright stance. Indeed, a weight-bearing asymmetry (Shumway-Cook et al., 1988) is generally joined by an action asymmetry, i.e. CP_{lf} and CP_{rf} of different amplitudes (De Haart et al., 2004; Genthon et al., 2008). Considering these aspects, the use of two separate seesaws, one under each leg, by allowing independent movements, would be less constraining to perform asymmetrical controls. In addition, the compensatory nature of the actions intervening under both legs could be preserved. In asymmetrical patients, the limited CP displacements under the disabled leg are indeed compensated by those under the sound (or less disabled) leg (De Haart et al., 2004; Genthon et al., 2008, 2010; Rougier and Bergeau, 2009). These strategies are aimed to allow the patient to sufficiently displace his/her CP_{Res} to efficiently control his/her CG_v movements and therefore his/her balance.

The goal of the present study is to assess balance control strategies, in terms of CP_{Res}, CP_{lf}, CP_{rf} and CG_v movements, induced by a double seesaw device. Choosing healthy young adults avoids sensori-motor deficiencies interfering with the observed postural control strategies. Our protocol comprises several experimental conditions including connected or disconnected seesaws and, for the former case, symmetrical and asymmetrical features by using different radii values for the two seesaws. Our main hypothesis was that the independence of the two seesaws should lead to increased and reduced movements to control the upright posture along the mediolateral (ML) and anteroposterior (AP) axes, respectively. It is indeed speculated that such condition renders the postural control more precarious, leading the subjects to prepare step initiation through hip loading-unloading movements. In case of asymmetrical features (two different radii for the two circular ridges under each plate), compensatory mechanisms were hypothesized to operate by involving, in greater proportions, the leg offering the best stability, as individuals suffering from an ankle sprain and able to use their sound leg do for instance (Genthon et al., 2010). Because of its reduced stability, it is indeed preferable to limit as much as possible the CP displacements under the opposite leg.

2. Methods

2.1. Subjects

This study was approved by the ethics committee of the Savoie-Mont-Blanc University. Fourteen healthy young adults, 11 males and three females, aged from 22 to 26 years (body weight, 72.5 kg ± 8.9; height, 176.4 cm ± 9.6; 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, practice 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), which can be connected to obtain a single seesaw supporting both feet, are constituted of two rectangular plates (40 cm long × 20 cm wide) mounted 7 cm above two circular ridges (radius: 55 cm or 35 cm). A parallelepiped wooden volume, of similar height was also used in one condition to provide a stable support under one foot. As seen from

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

Five conditions were randomly performed: (1) standing with both feet on the force platform without any seesaw (REF), (2) standing on a single seesaw (all radii equal to 35 cm) whose plates were mechanically attached (single seesaw SS-A), (3) standing on a double seesaw whose plates were independent, all radii being equal to 35 cm (DS-I), (4) standing the left foot on the parallelepiped volume and the right foot on a single seesaw with a 35-cm radius (SS-R) (5) standing on a double seesaw with different radii (55 and 35 cm for the left and right feet, respectively; DS-DR).

For all conditions, the subjects were asked to stand as still as possible with their eyes closed, their arms at their sides, and their inner border of the feet parallel and 12 cm apart. For each condition, the feet were placed to allow horizontal positioning of the seesaw at the onset. Three trials lasting 32 s, interrupted by 16-s rest periods during which upright subjects 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):

$$CP_{Res} = CP_{lf} \times \frac{R_{lf}}{R_{lf} + R_{rf}} + CP_{rf} \times \frac{R_{rf}}{R_{lf} + R_{rf}}$$

where R_{lf}, R_{rf}, are the vertical reaction forces under the left and right feet, respectively.

CG_v and $CP_{Res} - CG_v$ movements were estimated from the CP_{Res} displacements from a CG_v/CP_{Res} ratio (Brenière, 1996; Caron, Faure and Brenière, 1997). The ratios, for the conditions involving the use of seesaws, were adapted to take into account the seesaws' and subjects' characteristics (height and mass), as indicated previously (Rougier et al., 2011). The various steps of analysis to calculate CG_v and $CP_{Res} - CG_v$ movements are displayed in Fig. 2. This CG_v/CP_{Res} ratio, at a maximum level, i.e. close to 1, for the lower frequencies

Fig. 1. Photograph of the double seesaw device lying on a double force platform. The condition displayed here is the DS-DR.
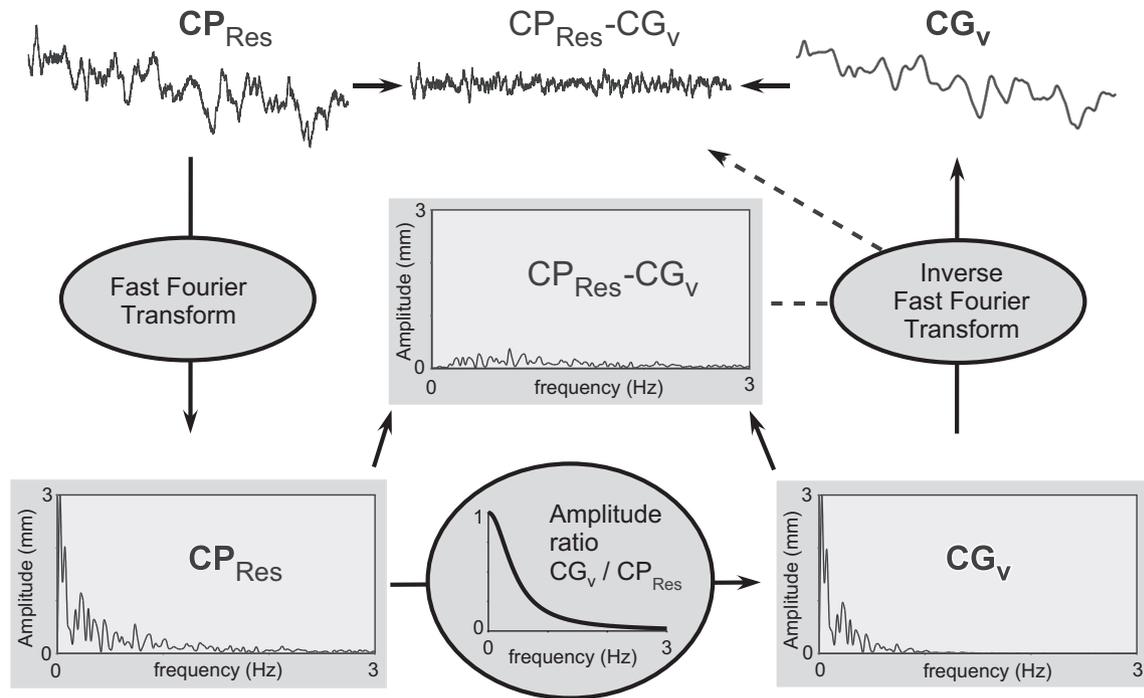
Fig. 2. To obtain the CG_v, for instance along the AP axis, and consequently the $CP_{Res} - CG_v$ difference, a mathematical low-pass filter expressing an amplitude ratio between CG_v and CP_{Res} as a function of the movement frequency can be used. In this case, the CP_{Res} displacements are processed through a fast Fourier transform (FFT) to obtain the amplitude distribution as a function of the frequency. Once this CP_{Res} spectrum is obtained, multiplying with the aforementioned filter will give the CG_v spectrum and subtracting will give the $CP_{Res} - CG_v$ spectrum. Through an inverse FFT (iFFT), it is possible to return to the temporal domain and obtain CG_v and consequently $CP_{Res} - CG_v$ displacements. Note that $CP_{Res} - CG_v$ movements can be obtained either by directly subtract CP from CG_v temporal series (solid arrows) or indirectly by processing an iFFT from the $CP_{Res} - CG_v$ spectrum (dashed arrows).

(CG_v and CP_{Res} are characterized by similar positions at 0 Hz), tends toward zero above 3 Hz. The CG_v estimation consists in multiplying each amplitude of the CP_{Res} spectra along both the ML and AP axes, transformed in the frequency domain through a fast Fourier transform (FFT), by the CG_v/CP_{Res} ratio and recovering to the time domain with an inverse FFT. Once estimated, CG_v and $CP_{Res} - CG_v$ displacements were analyzed through their variances along each ML and AP axis. The body-weight distribution (%BW) time series over the two legs was also computed.

In order to assess the degree of linear correlation and the possible time-lag between the two CP_{lf} and CP_{rf} movements along the AP axis, a cross-correlation function was computed. Two parameters were extracted: the maximal value of the function (r_{max}) and the absolute values of the corresponding time-interval (tr_{max}).

ANOVAs of Friedman were performed for the variances of CP_{Res}, CG_v, $CP_{Res} - CG_v$ along both ML and AP axes, r_{max}, tr_{max}, %BW. 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. Non-parametric analyses were performed because homocedasticity assumption was not passed.

3. Results

An example of the CP_{lf}, CP_{rf} and CP_{Res} displacements measured for the whole protocol can be seen in Fig. 3 through representative trials collected from one subject.

3.1. Variances of CP_{Res}, CG_v and $CP_{Res} - CG_v$ movements

The ANOVA of Friedman revealed statistically significant effects for all these variances. Effects were reported along the ML and AP axes respectively, for CP_{Res} displacements: χ^2 (14,4) = 45.03 ($p < 0.001$) and χ^2 (14,4) = 47.09 ($p < 0.001$), for CG_v movements:

χ^2 (14,4) = 36.72 ($p < 0.001$) and χ^2 (14,4) = 44.74 ($p < 0.001$) and lastly, for the $CP_{Res} - CG_v$ movements: χ^2 (14,4) = 47.77 ($p < 0.001$) and χ^2 (14,4) = 45.49 ($p < 0.001$).

As can be seen from the post-hoc effects in Fig. 4, it is the condition with the two independent seesaws (DS-I) which inferred the larger CP_{Res}, CG_v and $CP_{Res} - CG_v$ movements along the ML axis. In contrast, along the AP axis, conditions with the shorter radii (SS-A and DS-I) determined the larger movements. Although disconnecting the two seesaws did not seem to affect postural stability (CG_v movements) and the neuro-muscular activity ($CP_{Res} - CG_v$) along this AP axis, setting longer radii for one seesaw leads to a CG_v movements decrease ($p < 0.05$). Lastly, placing a stable support under one foot (SS-R) allows the subjects to get a further improved stability, close to what is observed for the REF condition.

3.2. Body-weight distribution

The ANOVA of Friedman indicated a lack of statistical effects for this variable (χ^2 (14,4) = 6.54; $p > 0.05$). One can therefore consider that subjects equally distributed their body weight on their two legs throughout this protocol.

3.3. Cross-correlation between CP_{lf} and CP_{rf} movements

The ANOVA of Friedman showed a statistically significant effect for the r_{max} values χ^2 (14,4) = 47.54 ($p < 0.001$). As seen from the post-hoc analysis and Fig. 5, the r_{max} is equal to 1 for the SS-A condition whereas its values are slightly (but non-statistically significant) lower in DS-I and DS-DR and even lower for REF and SS-R conditions (with significant differences). Additionally, there was no time-lag differences (tr_{max}) across the conditions (χ^2 (14,4) = 6.33; $p > 0.05$) between the two CP_{lf} and CP_{rf} displacements. The absolute values of tr_{max} were ranged between 0.07 s ±0.17 and 0.01 s ±0.01 for the REF and seesaw conditions, respectively.

REF condition

AP

50 mm

50 mm ML

SS-A Condition

DS-I Condition

SS-R Condition

DS-DR Condition
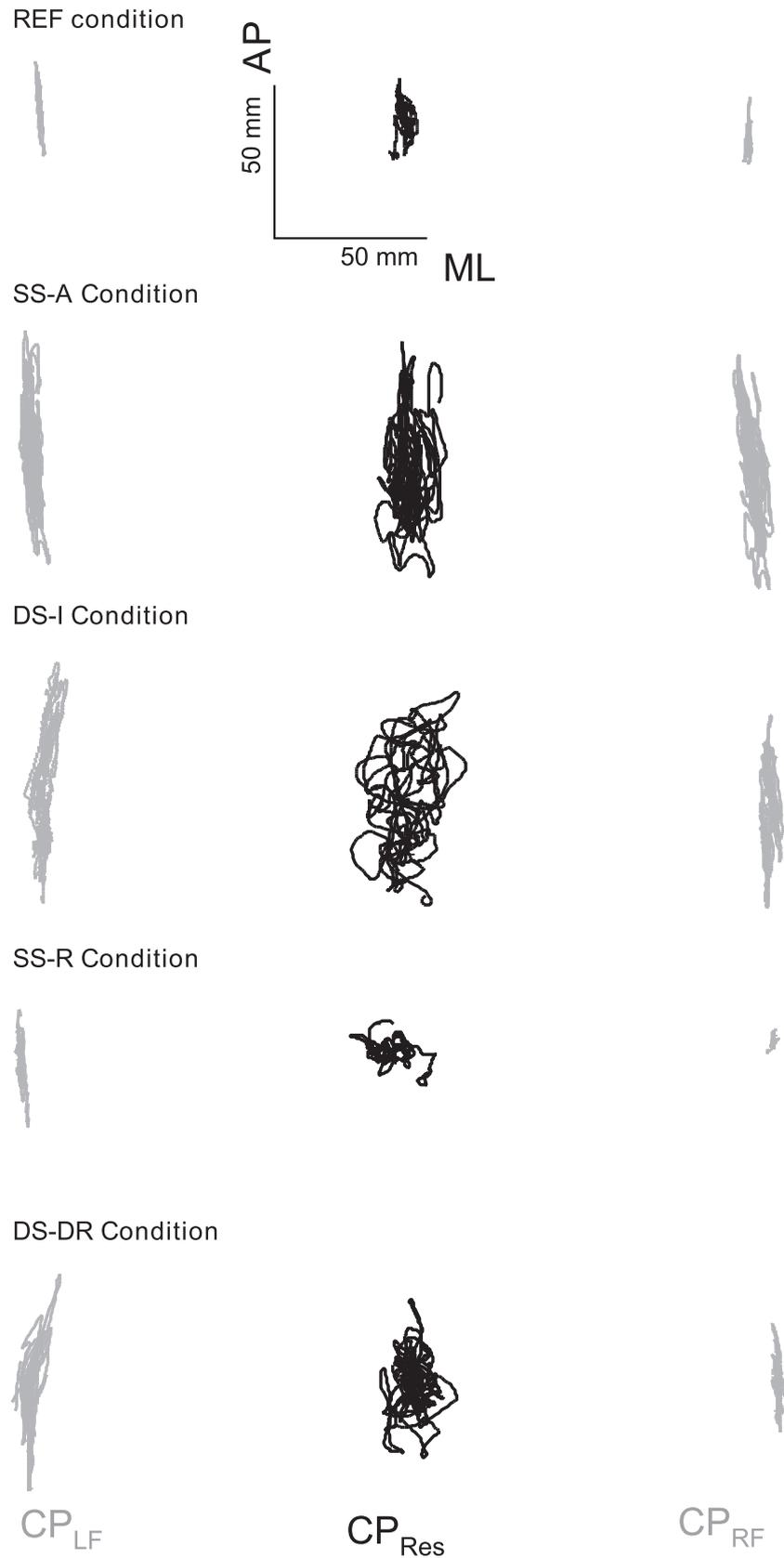
CP_{LF} CP_{Res} CP_{RF}

Fig. 3. Displacements of the CP_{lf}, CP_{Res} and CP_{rf} during a 32 s stance trial in a representative subject for the five experimental conditions. Note the increase of the CP_{Res} displacements along the ML axis in the DS-I as compared to the SS-A condition and the asymmetrical patterns of the CP_{lf} and CP_{rf} movements in DS-DR and SS-R conditions.
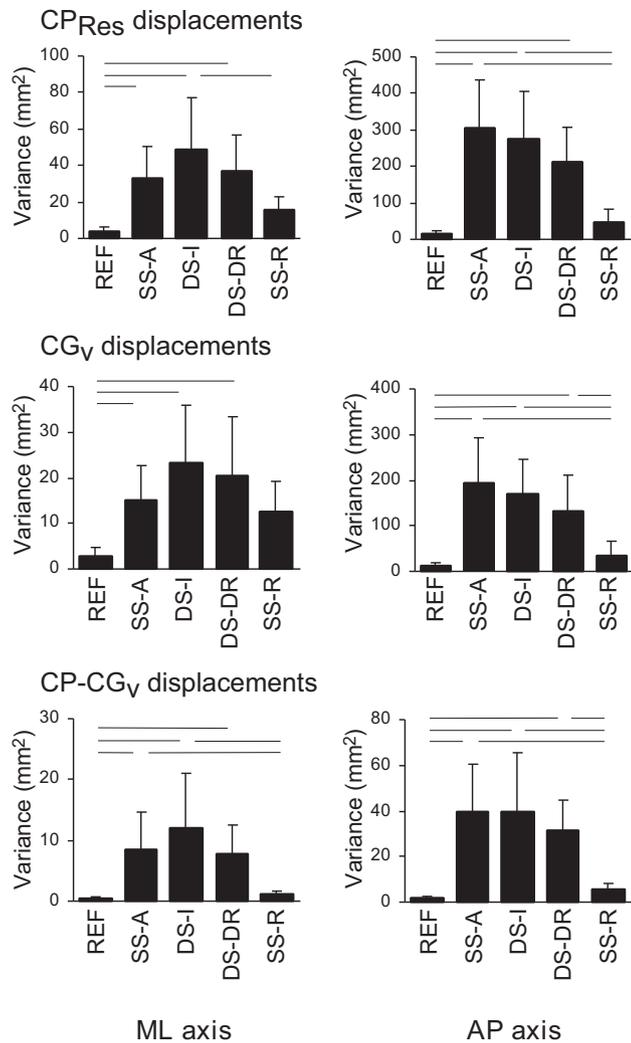
Fig. 4. Bar charts of the variances (mean + s.d.) measured along the ML and AP axes for CP_{Res}, CG_v and $CP_{Res} - CG_v$ displacements and the five experimental conditions (REF, SS-A, DS-I, DS-DR and SS-R). The simple effects are displayed above the charts by horizontal bars.

Fig. 5. Upper panel: Bar charts of the maximal values of the coefficient of correlation (r_{max}; mean + s.d.) computed from the cross-correlation functions for the five experimental conditions (REF, SS-A, DS-I, DS-DR and SS-R). Middle and lower panels: Bar charts of the variances (mean + s.d.) of the CP_{lf} and CP_{rf} movements measured along both ML and AP axes. For both panels, the simple effects are displayed above the charts by horizontal bars.

3.4. CP_{lf} and CP_{rf} movements

The Wilcoxon tests, which compare the variances of CP_{lf} and CP_{rf}, showed statistically significant effects for DS-DR conditions along both ML and AP axes (ML: $p < 0.05$; AP: $p < 0.001$) and SS-R (ML: $p < 0.001$; AP: $p < 0.001$). As shown in Fig. 5, standing on a single seesaw (SS-A) induced the largest CP_{lf} and CP_{rf} movements. Along the AP axis, variances also highlighted larger movements with associated or independent seesaws with the shorter radii. Overall, these results show that an asymmetric pattern between CP_{lf} and CP_{rf} movements occurs when the physical characteristics of the seesaws (radii) differ. To be more precise, a greater variance was always observed under the foot lying on the more stable support.

4. Discussion

To our mind, two important findings should be highlighted from this study. Firstly, when comparing DS-I and SS-A conditions, standing on two independent seesaws diminishes the postural stability along the ML axis, whereas it remains wholly unchanged along the AP axis (altho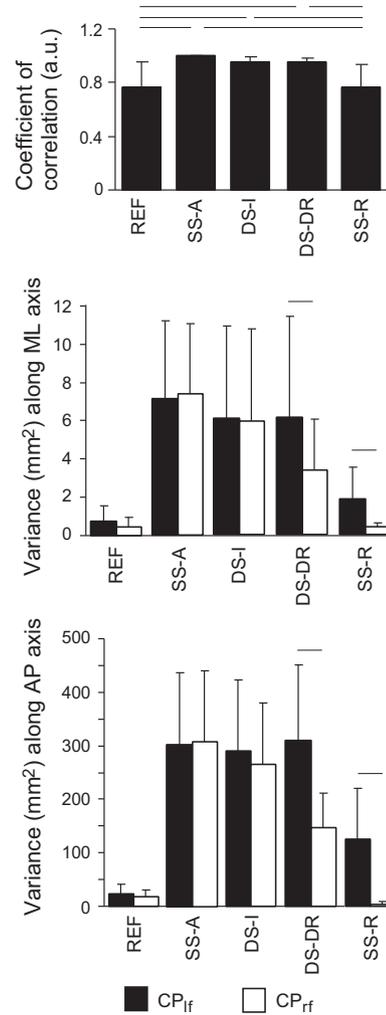ugh a slight tendency to decay can be observed). Secondly, when standing on two seesaws characterized by different radii, asymmetric patterns of CP displacements under the two feet are observed. Precisely, larger CP movements are seen on the side of the more stable support, the left foot in our protocol for the DS-DR and SS-R conditions.

4.1. Two independent seesaws modify postural control mainly along the mediolateral axis

As shown by these results, the comparison of SS-A and DS-I conditions brings out larger overall CP_{Res} displacements along the ML axis, whereas nothing statistically significant was found along the AP axis. It is worth noting that stability, expressed through CG_v displacements, is affected by the seesaw dissociation. In contrast, the effect reported for the $CP_{Res} - CG_v$ movements, which express the neuromuscular activity called into play (Rougier et al., 2001), seems uninfluenced. It should be recalled that CP_{Res} along the ML axis, when the feet are positioned side by side, are mainly the result of loading-unloading mechanisms (Winter et al., 1996; Rougier 2007; Bonnet et al., 2014). Thus, controlling the two feet movements separately, mainly through the ankle joints, would have repercussions predominantly on balance control mechanisms

involving principally the hips. These increased movements can be viewed as the result of a deliberate strategy, observed in numerous disabled (Shumway-Cook et al., 1988; Genthon et al., 2008) or elderly populations (McClenagham et al., 1996; Berger et al., 2005), aimed at favoring step initiation. Indeed, when upright stance control becomes risky with large horizontal CG movements, an effective and easy solution can be to produce, by a step, a large CP displacement aimed at counteracting the on-going CG sway. The fact that the effect also intervenes on the $CP_{Res} - CG_v$ movements might be related to a stiffening strategy. This was previously described when subjects encounter postural threat as they were for instance standing at different surface heights above ground level, for instance (Carpenter et al., 2001). To go further in this direction, it can be interesting to consider an easier condition such as DS-DR. In this case, the presence of a more stable seesaw (with a 55 cm radius) under the left foot leads to an increased body stability along the AP axis, as it could be expected, but also, interestingly, along the ML axis. The increase of the ML movements in the DS-I condition would therefore be mostly related to the perceived difficulty of the postural control as a whole and not a specific difficulty occurring along the sole ML axis.

As shown from our data from the cross-correlation analysis, the slight decay observed along the AP axis with the seesaw disconnection (principally the DS-I condition) cannot be explained by a desynchronization between CP_{lf} and CP_{rf} movements since tr_{max} values stay close to zero. Since stance control, along the AP axis, mostly rely on pressure variation mechanism for this foot positioning (Rougier, 2007), this would explain why this tendency for the CP_{Res} to decrease is found again in the variances of CP_{lf} and CP_{rf} displacements.

4.2. Two seesaws with different radii determine asymmetrical CP patterns under the two feet

Positioning the two seesaws with two radii of different lengths induces different ranges of motion for the CP_{lf} and CP_{rf} because of the two distinct degrees of amplification produced by the seesaws. Along these lines, one should consider the stable support used in the SS-R condition as a seesaw with a radius of infinite length. Since the body-weight distribution remained unchanged throughout the conditions, the amplitudes of the CP_{Res} displacements along the AP axis are determined in equal proportion by those of CP_{lf} and CP_{rf}. This feature explains why a decrease of CP_{Res} displacements was observed for the DS-DR, as compared to the DS-I (Fig. 4) with the substitution, for the right foot, of the 35-cm radius by a 55-cm one. Similarly, as compared to the REF condition, the CP_{Res} is increased in the SS-R condition by the substitution, under the right foot, of the rigid support by a seesaw with a 35-cm length.

In DS-DR and SS-R conditions, compensatory mechanisms are observed, consisting in a predominant use of the foot positioned on the support offering the best relative stability to produce CP_{Res} displacements along the AP axis (Fig. 5). This postural strategy is akin to those observed in patients suffering leg amputation (Rougier and Bergeau, 2009) or sprained ankle (Genthon et al., 2010), i.e., traumatic situations for which a complete sound leg can be used to compensate, partially or totally, for the injured or missing leg. Even though it is less clear, due to the muscular weakness of both legs, this mechanism also applies for hemiparetic patients (Genthon et al., 2008). Overall, these results highlight the capacity of the postural control system to use asymmetrical patterns for CP_{lf} and CP_{rf} movements to secure appropriate CP_{Res} and CG displacements, and therefore acceptable postural stability. Because of this asymmetry, the price to pay would be a relatively more complex motor command for the tonic activity of the two ankle extensors for both legs.

4.3. Rehabilitation perspectives

Modifying the sensorimotor coordination, i.e., the relation between CP_{Res} displacements and their effects on CG movements, can be useful when training disabled individuals. As highlighted by Solopova et al. (2003), it appears that the upper sensorimotor structures of the brain can be mobilized in larger proportions when one stands on a seesaw. This adaptation can also be shown, for instance, in healthy subjects walking along a curved trajectory (Courtine and Schieppati, 2003) or on a treadmill made of two separate belts allowing independent speed control of each leg, therefore mimicking a limp (Jayaram et al., 2011). According to these authors, learning a new coordination may induce reduction of the normal inhibitory tone the cerebellum exerts over the primary motor cortex. Based on this assumption one can therefore propose that standing on two seesaws with different characteristics, by generating the learning of new coordinations, may favor brain plasticity mechanisms, as previously described in patients without cerebellar damage (Morton and Bastian, 2006).

To conclude, despite a reduced sample and the possibility to obtain type I or II errors, this study has highlighted the specific nature of postural control adaptations when using two side-by-side seesaws under the feet of young healthy subjects. On the whole, our two main hypotheses regarding the influence of the independency of the seesaws on the ML control of postural movements on one hand and the preferential use, in a configuration where different radii are used, of the more stable support for controlling balance on the other hand, have been verified. Further experiments should be conducted to assess the utility of such experimental conditions in both healthy and disabled patients. For the former, the role played by the amount of practice of physical activity, the weight-bearing asymmetry and/or the determination of the structures of the CNS involved in this particular postural control could be better understood. For the latter, their capacity to handle such devices and the precise nature of the combination of seesaw parameters (height and radii) has to be determined, especially to help neurological patients with a weight bearing asymmetry to improve their balance control. Finally, one should keep in mind that the characteristics (degree and speed of learning) of the learning processes this device is supposed to favor, to date, remain largely unknown.

Conflict of interest

None.

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