How Visual Feedback of Decomposed Movements of the Center of Pressure Trajectories Affects Undisturbed Postural Control of Healthy Individuals

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Abstract—The center-of-pressure (CP) trajectory is a complex movement comprising both the vertically projected displacements of the centre-of-gravity (CG) and the CP - CG, differences whose magnitudes are proportional to the horizontal accelerations communicated to the CG. One may therefore, investigate whether the information given by these movements can be differentially used for controlling the standing posture. To this aim, a group of healthy adults was tested through four conditions including visual feedback (VFB) of their CP in real time and, with a 578 ms delay, CP, CG, and CP - CG, movements. The CG, and, thus, CP - CG, movements, were implemented from a numerical filter applied to the CP displacements. The postural behavior was assessed on the basis of basic CG, and CP - CG, movements estimated from the CP trajectories. The postural behavior observed during delayed CG, feedback was similar to the one observed with the similarly delayed CP movements feedback. On the other hand, the delayed CP - CG, feedback infers a decrease of the CP - CG, movements and concomitantly an increase of the CG, movements. This data highlight that there is enough information in the displayed CP trajectories to enable control of the CG and that providing CP - CG, information can lead the subjects to solely decrease these movements.

Index Terms—Center of gravity, center of pressure, difference between center of pressure and center of gravity, postural control, visual feedback.

I. INTRODUCTION

An easy way to study undisturbed postural control is to position a subject on a force platform and ask him/her to reduce as much as possible his/her body motions. The output signal of the platform gives rise to a resultant trajectory, the center of pressure (CP) displacements, which correspond to the point of application of the resultant reaction forces aimed at counteracting the gravity acceleration. The only objective of these CP displacements is to control the movements of the centre of gravity (CG) or center of mass of the body, since the soles of the feet constitute the only contact the subject has with his/her surroundings. Because of the inertia of the human erect posture, the body CG cannot follow with accuracy the CP movements which result from the lower limbs muscular activation. Consequently, as seen, for instance, through Fig. 1, in most of the time, there is a vertical misalignment between the CP and the vertical projection of the CG displacements (CG,). Brenière et al. [1] have underlined that the amplitudes of these differences between CP and CG, trajectories (CP - CG,) express the horizontal acceleration communicated to CG. Therefore, the body develops to counteract these inertial forces alone explaining why standing upright and still is, in fact, an impossible feat. Perturbing functions such as breathing and blood circulation further complicates this equilibrium task. In order to secure balance, or to simply minimise the body motions as much as possible, our central nervous system must, thus, detect the ongoing perturbation as soon as possible and then select the most appropriate response to return the CG to a more balanced position.

From a biomechanical point of view, it can be argued that the CP displacements include both the vertically projected CG movements (CG,) and the horizontal acceleration applied to

Manuscript received April 21, 2006; revised October 7, 2006.

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Digital Object Identifier 10.1109/TBME.2006.89159
it, i.e. the difference $C_P - C_G$. Interestingly, postural performance can be assessed by the former whereas the muscular means called into play are well deduced through the latter even though there might be transient coincidence between these two movements. This point can be experimentally demonstrated by showing that $C_P - C_G$ movements largely increase when the vertically projected CG of the body is moved away forward from the ankle axes without any concomitant change of the $C_G$ movements [2]. Because these two components do not always vary in proportion or even in the same direction, it now seems advisable to extract these two features from global CP movements. In addition, a ratio involving the $C_P - C_G$ relative to the $C_G$ movements allows to quantify the deadening capacity of the postural system to counteract the disturbing inertial forces. Precisely, these ratios, measured along each axis, take into account the neuromuscular activity, i.e. amplitudes of the $C_P - C_G$, movements, relatively to the postural performance, i.e. the amplitudes of the $C_G$ movements. From a physiological point of view, these ratios, thus, express the capacity of the central system to detect the postural perturbation and to produce the appropriate corrective response.

In undisturbed stance control, the sensory inputs naturally play a major role. Among them, the pressure distribution under the soles of the feet can provide quite accurate information. However, regarding the sensitivity of these receptors [3], their precision cannot be compared to the information potentially provided by a force platform. From that, feeding back such information in a more detailed way can be particularly useful for both healthy and disabled individuals. As revealed through recent investigations, the visual feedback (VFB) technique allows to infer some specific postural behaviors depending on the scale of the display and/or the time delay through which the CP displacements are visualized [4], [5]. By modifying the scale display, it is the $C_G$ movements that are the most affected whereas selecting a delay affects only upon the $C_P - C_G$, component. What is more, these effects are totally compatible in the sense that the scale display effects are still seen whatever the time delay and vice-versa [6].

In this postural organisation, the CP is generally viewed as the controlling variable [7] in the sense that only the CP movements have the capacity to displace the body CG. However, the question of the controlled variable remains open even though some experiments conducted on posturo-kinetic co-ordinations have suggested that the CG position could be a fair candidate [8], [9]. However, recourse to a modelling such as fractional Brownian motion (fBm) has provided additional insights when applied on the $C_G$, and $C_P - C_G$, basic movements [10]. To be precise, each movement would be controlled in successive fashion: the $C_P - C_G$, movements over the shortest time intervals, and the $C_G$, over the longest ones. In addition, when one of these movements is controlled, the other one would behave as a random process. The complexity of these CP trajectories could, thus, explain the opposite effects observed during feedback protocols in young healthy individuals consisting in both a $C_P - C_G$, increase and a $C_G$, decrease [11] and the relative variability of the effects seen when training disabled patients with this technique [12], [13]. Better understanding the postural effects induced by VFB techniques for improving its effects on disabled patients is, thus, the main goal of this research. In this investigation, our aim was to focus on the nature of the information picked up by the subject when a complex CP trajectory is displayed through the screen of a monitor. Is the subject capable to simultaneously or alternatively extract information from both CG displacements and horizontal acceleration (which is proportional to the $C_P - C_G$, amplitudes), or is he constrained to privilege one of them? In other words, is he able to plainly extract from the CP signals the CG information required to control the body movements? In addition, what can be the consequences of monitoring one basic trajectory on our capacity to control it, as assessed through the fBm modelling? In particular, does the respective contribution of deterministic and stochastic processes involved in the control of the various trajectories, as assessed through the scaling regimes H computed from this fBm modelling, could be modified by the nature of the displayed information? One can hypothesise that visualizing a trajectory might improve its control and, thus, might weaken the its propensity to produce wiggling motions. The answers to these questions could be useful for providing a really efficient outcome and for increasing the appropriateness of the technique. In particular, one may hypothesise that getting information about only one basic movement (CG, or $C_P - C_G$,) could reinforce the capacity to limit its displacements. Moreover, one may hypothesise that the conditions based on CP and CG having both CG information in them would induce rather similar postural behaviors in our subjects whereas receiving CP-CG information would largely disturb their capacity to improve the control of their body movements. The biomechanical significance of the $C_P - C_G$, amplitudes in terms of neuro-muscular activity and their potential influence over the relative facility to handle the CG motions makes their hypothetic decrease an interesting objective in the perspective of rehabilitation or training programs.

Until now, the main problem from a technical point of view came from the possibility of computing these CG, and from that CP - CG, movements rapidly enough to allow the subject to use the information. However, in the past, several techniques have been proposed to estimate the CG movements, once any adopted from the data recorded, on various bases: the kinematic method relies on the knowledge of the position and mass of all body segments [7], [14]. Other avenues involving mechanical properties issued from the Newtonian mechanics are based on a double integration of the horizontal forces recorded through 3-D force platform [15]. Close to this principle is the necessary vertical alignment between CP and CG, observed when the horizontal acceleration becomes null, which has led King and Zatsiorsky [16] to propose the zero point to zero point double integration technique. Lastly, considering the CG movements as a low pass filtered movement of the CP, Benda et al. [17] have proposed an ideal filter with a single frequency cut-off. More sophisticated is the amplitude $C_G, /C_P$ relationship in the frequency domain proposed by Brenière [18] and extended to quiet stance control by Caron et al. [19]. As explained by these authors, this ratio is computed from the angular momentum equation applied to the whole body with respect to the CG using the inverse dynamic approach.

The common feature of all these above mentioned techniques is their a priori incapacity to be fed back to a subject without a long delay. This problem is approached by algorithms that give good results on large scale data [20]. In the present study, we focused on large scale data within the setting of a fBm modeling. In addition, the inclusion of the scaling parameter is to a major advantage.

A. Experimental setup

Two groups of subjects were used in age and height. The main difference was knowledge of the consequence of barefoot standing (PBS). The subjects of the PBS protocol were asked to abduct and adduct their feet to slightly decrease the CG vertical projection on the screen. The ability of the subject is to work the PBS motions to produce a motion pattern compatible to the trajectories proposed by Stéphane Barbeau and colleagues. The subjects were connected to the force platform by a fluorometer on the soles of the feet. Any additional touches from the subjects were converted into force patterns on a computer with an anterior-posterior adjustment of the foot to zero force level. The subjects were seated at the end of a chair and had to display the last 64 points on the screen. The subject undertook ten repetitions for all conditions as an average on the platform. The subjects were also asked to horizontally displace their body as much as possible.

The overall experimental protocol is made of four experimental conditions. The first two were regarded as "normal" conditions to become in comparison with these conditions.
long delay. Nevertheless, some numerical algorithms can now approach these low-pass filters and permit a rapid outcome. The algorithm chosen for this investigation, for instance, allows to give at best the information with a 578 ms delay. This value is largely acceptable for a feedback process as shown by our past study, which used time delays up to 1200 ms and emphasized the larger postural effects (reduction of the CP – CGv amplitudes without change for the CGv movements) for 600 ms [4]. By setting a protocol including various VFB including CP, CGv, and CP – CGv, movements displayed with a similar delay, one might be able to describe their respective effects upon standing control. In addition, a feedback of the CP movements without delay was included in the protocol to assess these behaviors in comparison to a more traditional and already investigated technique.

II. METHODS

A. Experimental Procedure

Twelve healthy subjects, ten males and two females, ranging in age from 19 to 24 years (body weight 65.4 kg ± 11.5 kg; height 175 cm ± 7.6; mean ± standard deviation) with no known visual or balance pathology gave their written informed consent and were included in this study. The subjects stood barefoot on a triangular force platform of 80 cm each side (PF01, Equi+, Aix les Bains, France) in a natural position (feet abducted at 30°, heels separated by 3 cm) and were asked to decrease the CP, CGv, or CP – CGv displacements on the screen as much as possible with their arms at their sides. It is worth noting that no instruction was given regarding body motions. The VFB was implemented by displaying the various trajectories through a specific software (PROG01, Equi+, Aix les Bains, France) on the screen of an additional 21-in. monitor connected to the computer and placed at eye level 80 cm in front of the subjects. Lighting inside the room was provided by a fluorescent tube in the ceiling and the subjects did not receive any additional cues from the periphery. The signals issued from the load cells, on which the plate lays, were amplified and converted from analogue to digital form before being recorded on a personal computer with a 64 Hz sampling frequency. The anterior-posterior (AP) and medio-lateral (ML) displacements of the various trajectories were depicted on the screen from top to bottom and from left to right, respectively. In order to facilitate the tracking, the data acquisition software was programmed in such a way that the spot was always positioned at the center of the screen at the onset of the trial and only the last 64 positions (i.e. 1 s) were represented. It should be also underlined that the recording started at the onset of the feedback for all conditions. The CP trajectory measured from the force platform, also called stabilogram when described through the horizontal plane by certain authors, was then processed in a number of different ways.

The experimental protocol, for the whole sample, included four experimental conditions involving the VFB technique and performed in a random order. For each condition, the subjects were required to perform one unrecorded prior trial in order to become accustomed to the feedback task specificity. One of these conditions corresponds to a VFB of the CP displacements in real time (CP0). The common feature of the three remaining conditions was the use of a delayed (578 ms) feedback of CP displacements (CP578), estimated CGv (CG578) or estimated CP – CGv (CP – CG578). The estimation at a time i of the CGv and, thus, the CP – CGv, movements, was assessed from the CP movements through a numerical filter as follows:

\[ \text{CGv}(i) = B_0 \cdot \text{CP}(i) + B_1 \cdot \text{CP}(i - 1) + B_2 \cdot \text{CP}(i - 2) + A_1 \cdot \text{CGv}(i - 1) + A_2 \cdot \text{CGv}(i - 2) \]

where \( B_0, B_1, A_1, A_2 \), and \( A_3 \) were chosen in order to fit the 64 Hz sampling as close as possible to the CGv/CP ratio used to estimate a posteriori the CG movements from the global trajectories of the CP (see below). As already mentioned, one of the main features of such a filter, because of both sampling rate and algorithm, is to infer the estimated CG movements with a constant time delay of 578 ms, hence, justifying the CP578, CG578, and CP – CG578 conditions. One can see, through Fig. 2, the various estimated CGv movements.

The gain or display scale corresponds to the ratio expressing the amplitudes of the displacements and the corresponding movements on the screen. For instance, a gain of two signifies a 2 cm displacement of the spot on the monitor. Our objective being that subjects might visualise the various movements in quite a similar size, three different gains were applied depending on the movements (gains 4, 5, and 10 for the CP, CGv, and CP – CGv, respectively). Each condition was composed of five trials lasting 64 s, a rest period of a similar duration being allowed between each trial. The rest time period between each condition lasted at least 10 min.

B. CGv and CP – CGv Movements Estimation

CGv and CP – CGv movements were estimated from the CP trajectories measured through the force platform. To be more precise, because of the constancy of the body moment of inertia throughout the various conditions, an amplitude ratio of the vertically projected movements of the CG (CGv) and CP movements (CGv/CP) and sway frequencies can be used to determine CGv, and consequently CP – CGv movements. From this
CG, /CP ratio, displayed graphically in Fig. 3 and initially proposed by Brenière [18], it can be logically deduced that CP displacements operating over too high frequencies would not incur appreciable CG movements. This ratio appears maximal for the lower frequencies (CG, and CP are characterized by similar positions at 0 Hz) and tends towards zero above 3 Hz. The CGv estimation consists in multiplying the data, transformed in the frequency domain through a fast Fourier transform (FFT), by the above-mentioned low-pass filter and recovering to the time domain through an inverse FFT. All of this data processing was automatically performed through the Equi+-PROGO1 software. The article by Caron et al. [19] provides the details of this procedure.

C. Signal Processing

The signal processing used in this study has been described in detail in previous studies [6], [10]. Two approaches were adopted to study the CP – CGv and CGv basic movements through the following.

1) a classical method based on the computation along both ML and AP axes of the variance of the successive positions of these two movements and their deadening ratios RML and RAP (variance of CP – CGv movements divided by variance of the CGv movements). To be more explicit, the larger the ratio, the more deadening the postural strategy. For instance, an increased ratio means that, despite increased horizontal accelerations (as expressed through increased amplitudes of CP – CGv movements), the CGv movements do not increase in comparable proportions or, even, decrease.

2) a mathematical model termed fBm [20]. This modelling allows to specify the degree to which a trajectory is controlled and its use was validated for the CP trajectories [21]. Its general principle is that the aspect of a trajectory, expressed as a function of time, may be quantified by a fractional, i.e. a non finite integer space dimension. The latter, thus, provides a quantitative measurement of evenness in the trajectory in a single direction. This fractional dimension D, along a single axis, is in fact linked to the Hurst scaling exponent H since D = 1 - H for the present case. This scaling regime H graphically corresponds to the half slope of the line portions constituting a variogram depicted bi-logarithmically. The variogram in fact expresses the mean square displacements \( \langle \Delta x^2 \rangle \) as a function of increasing time intervals (1/64 s < \( \Delta t < 10 \) s) and is given by

\[
\langle \Delta x^2 \rangle = \Delta t^{2H}.
\]

Note that the squared distances are simply used to prevent a null mean displacement. A major feature to extract from the variogram analysis is the knowledge of the scaling regimes \( H \) which indicate the level of correlation between past and future increments and from that, the degree of control of the trajectory over these time intervals. A median value of 0.5 for \( H \) indicates a lack of correlation at this level, hence, suggesting that the trajectory is totally uncontrolled. On the other hand, i.e. if \( H \) differs from 0.5, positive (0.5 < \( H \)) or negative (\( H < 0.5 \)) correlation can be inferred, which is indicative of a given part of determinism in the control. Depending on how \( H \) is positioned with respect to the median value 0.5, it can be inferred that the trajectory is more or less controlled, i.e. endowed with more or less stochastic processes: the closer the regimes are to 0.5, the larger the contribution of stochastic processes. In addition, depending on whether \( H \) is superior or inferior to the 0.5 threshold, persistent (the point is drifting away) or anti-persistent behaviors (the point retraces its steps) can be revealed, respectively.

Since two straight line portions generally characterise varigrams relative to undisturbed upright stance maintenance (a quite flat line preceding or succeeding a steeper one), a final step consists in the determination of the transition point for both axes, i.e. the point corresponding to the slope inflection. CP and CGv, displacements being by definition in phase, the temporal coordinate of the transition points on the varigrams characterizing the CP trajectories will also be that of the CGv and CP – CGv movements. The method used for this purpose is based on the evolution, as a function of increasing \( \Delta t \), of the distance between the CP variogram and a completely stochastic process. This stochastic process is characterized by a 1 slope (inferring, in that case, a 0.5 value for \( H \)). The retained principle is that the \( \Delta t \) for which this distance is maximal is the \( \Delta t \) of the transition point [22] and is in contrast with the less objective method initially used by the pioneering work of Collins and De Luca [23]. However, it should be pointed out that the stochastic behavior, taken as a reference, is itself modified by the low or high-pass filter used for the computation of CGv, and CP – CGv movements. As seen in the upper part of Fig. 4, the filter effect leads in fact to curvilinear functions moving progressively away from or closer to the slope mentioned above (since \( 2 \times (H = 0.5) = 1 \)). Scaling regimes relative to “average stochastic varigrams” over the same \( \Delta t \) must, therefore, be taken as a reference in a way that

\[
H_{\text{calc}} = \left( H_{\text{exp}} - H_{\text{sto}} \right) + 0.5
\]

where \( H_{\text{calc}}, H_{\text{exp}}, \) and \( H_{\text{sto}} \) represent the calculated, experimental and stochastic scaling regimes, respectively. Thus, for each of the two movements investigated and each ML and AP
component, two scaling exponents (indexed as short and long latencies: $H_1$ and $H_2$) as well as the spatio-temporal coordinates of the transition point were extracted.

To evaluate the effects of the various VFB conditions, all parameters were analysed through a non parametric one-way analysis of variance (ANOVA) of Friedman with repeated measures, the post hoc subsequent analysis consisting in Dunn tests. In all cases, the first level of significance was set at $p < .05$.

### III. RESULTS

Before presenting the results of both basic movements, it is relevant to emphasise that modifying the VFB conditions does not affect the mean positions in both ML and AP axes. Consequently, the various effects observed through this investigation cannot be explained by a modification of the position of the body with respect to the base of support.

#### A. Classical Parameters

As revealed by the ANOVA of Friedman, a statistically significant effect was found for the variances of the successive positions of both CP – CGv (ML: $\chi^2(12,3) = 16.109, p < .0011$; AP: $\chi^2(12,3) = 12.59, p < .0059$) and CGv movements (ML: $\chi^2(12,3) = 12.5, p < .0059$; AP: $\chi^2(12,3) = 9.66, p < .0227$). The post-hoc Dunn tests indicate that there were some differences between the CP – CGv and the three remaining conditions along the ML axis for both CP – CGv and CGv movements (Fig. 5). As compared to the remaining conditions, the amplitudes of CP – CGv appear to be decreased and those of CGv increased for the CP – CGv condition. The same is true along the AP axis except that no statistical trend was found between CP57s and CP – CGv conditions.

With the amplitudes of the CP – CGv movements being reduced but those of the CGv increased, as illustrated by the bar charts of Fig. 5, the ratios $R_{ML}$ and $R_{AP}$ computed for each axis are expected to present a statistically significant effect. This is confirmed by the ANOVA of Friedman (ML: $\chi^2(12,3) = 18.5, p < .0003$; AP: $\chi^2(12,3) = 15.0, p < .0018$). The simple effects indicate that the ratios present some statistically significant diminution for the CP – CGv condition as compared to the three other VFB conditions along both ML and AP axes. In addition, some differences are worth noting with the ratios computed for the CP57s and CGv conditions which are larger than those of the CP0 condition. In both cases, these diminished ratios indicate a lower deadening capacity.
(due to data storage limitations) on the onset of control of the CP movements. The principal axes of the CP movements (Fig. 4) were computed and the post-hoc analysis was performed on the percent changes of the corresponding CP movements with respect to the reference condition. On the AP axis, the percent change of both the CP and CP movements were increased compared to the reference condition (Fig. 5).

**IV. Discussion**

This investigation was aimed at highlighting the postural effects induced by feeding back to healthy individuals various components of the CP trajectories involved in undisturbed upright stance control. By emphasizing that the provision of partial information about either the CP or CP movements influences contrasting effects, this data contributes to the assessment of the specific roles played by these movements in this equilibrium task. The comparison between the CP and CP movements with the CP condition indicates that when a given basic movement is fed back, its amplitudes tend to be decreased whilst the other is less constrained. This is true with both the CP and CP movements conditions, which display higher values, when compared to the three remaining VFB conditions. This trend indicates a lower degree of control of the CP movements over the longest $\Delta t$. 

**B. Parameters Issued From the fBm Modelling**

This modelling provides further explanations for the above mentioned results. For the CP movements, the main statistical effects come from the spatial coordinates of the transition point ($\Delta x^2$), i.e. the mean square distance covered by this movement at the time the corrective process takes over (ML: $\chi^2(12.3) = 17.7, p < .0005$; AP: $\chi^2(12.3) = 15.7, p < .0003$). As for the classical parameters, the post-hoc analysis indicates an involvement of the CP movements where smaller values were observed, when compared to the three remaining VFB conditions (Fig. 6).

The fBm parameter serving to highlight statistically significant trends for the CP movements is the long latency scaling exponent $H_l$, through which the degree of control (or the level of stochastic vs deterministic activity) of the movement can be assessed. However, this effect is solely observed along the ML axis ($\chi^2(12.3) = 15.655, p < .0013$). Here again, as shown by Fig. 6, the post-hoc analysis indicates a statistical effect for the CP movements which display higher values, when compared to the three remaining VFB conditions. This trend indicates a lower degree of control of the CP movements over the longest $\Delta t$. 

![Fig. 6. Left part: average relative variograms for the various experimental conditions and for both CP and CP movements. Note the differences in the slopes of the variograms characterizing the CP movements over the longest $\Delta t$. Right part: Bar charts representing mean (+ s.d.) for the parameters issued from the fBm modelling computed along each ML and AP axes for both CP and CP movements. The results of the ANOVA of Friedman and the post-hoc analysis are presented below and above the bar charts, respectively ($*: p < .05; **: p < .01; ***: p < .001$).](image-url)
(due for the most part to an increased distance covered at the onset of the corrective process \((\Delta x^2)\)), and the \(CP - CG_{7/8}\) condition, which sees an increase of the \(CG\) movements, principally along the ML axis (due for the most part to their decreased control as deduced from the scaling regimes \(H_2\)). In addition, the positive effects are always observed for the time intervals \(\Delta t\) when the so-called movement is controlled, the uncontrolled movement being insensitive to these VFB effects. On the whole, these opposite trends, thus, legitimate the necessity for investigating undisturbed postural control to study separately each basic movements issued from the complex CP movements. Moreover, these results underline that the control intervening over the shortest time-intervals mostly involves the CG movements and that the control operates at this level through an anti-persistent mechanisms (or closed loop control), hence confirming the theory developed initially by Collins and De Luca [23]. However, the control mechanisms operating over the shortest \(\Delta t\) remains open to discussion.

Some of the present results have to be discussed in the light of past investigations conducted on close experimental conditions. In particular, the \(CP_{11}\) and \(CP_{7/8}\) condition were presently implemented in order to be used to disentangle the effects due to the delayed information to those due to the nature CG movement itself (displacement or acceleration). By inducing contrasting postural behaviors depending on which basic movement is involved in the feedback process, one can see that providing a subject with feedback based on a delayed display of his \(CP - CG\) movements constitutes an impressive means to drastically decrease the deadening capacity of the postural system. One should bear in mind at this stage that the smaller the \(CP - CG\) movements, the smaller the horizontal acceleration communicated to the CG, the easier the control of the body movements and the better the postural performance as expressed from the CG positions dispersion. In complement, it should be emphasized that some larger CG movements usually in turn infer, all things being equal, some increased neuro-muscular demand and then, increased \(CP - CG\), movements. In other words, it is likely that some CG movements, similarly reduced as they are in the other VFB conditions, would have inferred much more reduced \(CP - CG\), movements in the \(CP - CG_{7/8}\) condition.

These data also reinforce the idea that the overall neuromuscular activity occurring in the lower limbs is well expressed by the \(CP - CG\), movements [2]. In the \(CP - CG_{7/8}\) condition, the only way the subjects can succeed for limiting the spot displacements on the screen is to relax as much as possible their lower limbs. Delaying the display of the spot indeed constrains the subjects to reduce as much as possible the CG accelerations in order to avoid unreasonable body movements that would necessitate large CP displacements and, thus, an increased energy expenditure. Suppressing the CG positions further lead the subjects to focus on minimizing these \(CP - CG\), movements. To this aim, the best solution in this case is clearly to reduce as much as possible the neuro-muscular activity. As a result, it seems that suppressing the CG movements and setting up a certain delay induce rather similar consequences which, added together, allows this particular VFB effect to be optimized. Consequently, this VFB technique, based on \(CP - CG\), movements, could be a part of the training protocol for various disabled individuals characterized by a relative inability to relax their postural muscles, such as the elderly having a history of falls [24].

The particularity for these delayed VFB to be associated without any appreciable change for the CG movements resulted in a deterioration of the deadening capacity of the postural system since the ratios \(R_{11 ML}\) and/or \(R_{11 CP}\) became reduced. The lack of significant trends between the \(CP_{11}\) and \(CP_{7/8}\) conditions in the present study could stem from our deliberate will to involve only naive individuals in the sense they had no previous experience of the VFB technique. In addition, modifying the gain entails an inverse effect upon these ratios since a decrease is solely observable for the CG movements [5]. In the present study, the choice was made to use various gains depending on the nature of the movement given as VFB. By doing so, our objective was that the potential differences could not be simply explained by the differences of the movements amplitudes. In most cases, the \(CP - CG\), amplitudes indeed do not exceed one tenth of the \(CG\), ones. Even though some specific effects could emerge by manipulating such gain parameters, a recent study emphasized the compatibility of the effects induced by both scaling display and temporal delay [6]. This signifies that the effects induced by modifying one of these two variables are observed whatever the value of the other. Consequently, one can speculate that the effects observed throughout the present study are irrespective of the gain modifications between movements.

Even though, our attempt at the onset was to include only feedback conditions in the protocol, one should bear in mind however that all conditions present the particularity to lead the subjects to perform two distinct tasks, i.e. standing and looking at the display. The results must, thus, be also discussed with the literature reporting the functional linkage between postural control and “supra-postural” tasks. Stoiberigen et al. [26] reported that postural control can be tuned, at least in part, to facilitate the performance of the so-called supra-postural task. As a consequence, one may wonder if the postural control can be influenced by the visual display, independently of their attempts to control the display content. In accordance with this line of thoughts, Wulf et al. [27] have suggested that postural activity can be influenced by subtle variations in the instructions given to the subjects about the supra-postural task. In particular, they hypothesized that focusing attention on the movement effect may allow automatic processes to control the movements required to achieve the effect. On the contrary, focusing on the body movements may bring the subjects to intervene in these control processes. These effects are not found again here, even though our CP and CG conditions were thought to let the subjects visualise either the movement performed (CP) or the movement effect (CG), respectively. Another interesting result is the lack of statistically significant effects for the \(CG_{7/8}\) condition, when compared to the \(CP_{7/8}\) and \(CP_{11}\) ones. Despite a slight tendency appearing on the spatial coordinates of the transition points which become shortened, one could hypothesise a better quality in the control of the CG over the longest time intervals \(\Delta t\) to make it return towards a more balanced position. This hypothesis comes also from the fact that, according to the results of the FBM modeling [10], the CG movements would be only controlled over these periods. However, at this stage, one may highlight the gen-
eral principles observed through past studies (for instance, when closing the eyes [25]) on this topic which sees an improved control (i.e., the scaling regimes $H_B$ being farther away from the uncontrolled stochastic behavior taken as a reference) intervening when the mean squared distance of the transition point is enhanced. Consequently, the relative constancy of the control intervening over the longest $\Delta t_1$ should, thus, be viewed as expressing a reinforced control. This lack of difference between CG,78$ and CP,78$ conditions also indicates that the individuals in fact used predominantly in the CP VFB the low frequency range of the displayed movements. In other words, if one considers that CG information should be provided for controlling CG movements, one can presume that there is enough CG information in the CP trajectories displayed through the screen to elicit an improved control of the body movements, as compared to conditions without feedback technique. This also means that the information relative to the CG, movements is left out because of its difficulty to be handled due to their small amplitudes and higher frequencies and because the instruction given is generally to constrain the spot to the narrowest possible area. This logical postural behavior can be also largely explained by the respective amplitudes of the basic CP - CG, movements, as mentioned above. To conclude, this study highlighted the complexity of the CP trajectory since giving back one of the basic components induces opposite postural behaviors. Feedback based on a display of the CG, movements induces no particular effects in our subjects, when compared to a more traditional technique involving the CP trajectories, hence emphasizing that both trajectories furnish similar information about CG movements. On the opposite, providing information about the CG acceleration (i.e. CP - CG, movements) allows the subject to focus on this particular component. Further experiments are naturally needed to assess whether these effects could last consecutively to a training protocol and if disabled subjects could increase their postural abilities through these techniques.

ACKNOWLEDGMENT

The author is would like to acknowledge D. Goodhue for the correction of the English text and the constructive comments of the reviewers.

REFERENCES


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