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Estimation of centre of gravity movements in sitting posture: application to trunk backward tilt

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ABSTRACT

The aim of this study was to highlight, in sitting posture, the value of distinguishing between the movements of the vertical projection of the centre of gravity (CG_v) and its difference from the centre of pressure ($CP-CG_v$). A protocol for healthy, young, trained adults, consisting in tilting their trunk backward or keeping it vertical was used. A frequency analysis shows that statistically significant effects were only seen on $CP-CG_v$ movements: the RMS increased by 37% ($p=0.004$), while the MPF decreased by 5% ($p=0.016$), suggesting an increased muscular activity in these tilting postures. In contrast, no statistically significant effects on *CP* and CG_v were reported. These data highlight the advantage, in sitting posture, of splitting overall *CP* displacements into basic components (i.e. CG_v and $CP-CG_v$), each of them having a biomechanical significance.

1. Introduction

Postural tests in sitting position are commonly used to assess the trunk movements of healthy individuals (Bouisset and Duchene, 1994) or of patients with low back pain (Cholewicki et al., 2000; Radebold et al., 2001; Silfies et al., 2003; Reeves et al., 2006; Reeves et al., 2009; van Daele et al., 2009, 2010; van Dieën et al., 2010). Compared to standing posture, these tests can more precisely target the balance control of the trunk by eliminating the regulation of the lower limbs. In most cases, they consist of in measuring the displacement of the resultant *CP* on a stable or unstable platform while the subjects maintained CG_v within the support surface. This permanent postural regulation by the *CP* is imposed by the impossibility of maintaining a constant level of postural muscle contraction over time (de Luca et al., 1982). The distance between the *CG* and the rotation axis causes an inertia for the movements of the CG_v whereas the *CP*, located in the support surface, has no inertia to counteract for being displaced. These differences in the physical characteristics of the two movements infer horizontal accelerations communicated to the *CG* and therefore its displacements (Brenière et al., 1987). In addition, previous studies (e.g. Winter et al., 1998; Rougier et al., 2001) in upright standing have stressed the relation between the amplitudes of these $CP-CG_v$ movements and the level of muscular activity at the lower limb level. As a result, maintaining an upright forward tilt increases displacements from $CP-CG_v$ more than CG_v (Rougier et al., 2001). This result demonstrates the importance of taking into account separately these two basic movements during a postural task. Indeed, focusing only on the *CP* displacements (the controlling variable in the equilibrium maintenance) does not measure its effectiveness on the CG_v movements (the controlled variable according to Massion (1992)).

Three methods have been identified for estimating CG_v displacements (Lafond et al., 2004): (1) kinematic; (2) zero-point-to-zero double integration; (3) *CP* low-pass filter. The third method, easy to implement with posturographic data, was used in the current study. Although the body motions only mobilise the lowest joints, hence allowing it to be modelled as an inverted pendulum, the moment of inertia is assumed to remain constant all along the trials durations. In this case, the CG_v movements can be considered as low-pass filtered displacements of the *CP* (Benda et al., 1994).

Moreover, the additional insights provided by these $CP-CG_v$ movements can plainly be relevant for patients with low back pain and scoliosis by expressing the horizontal acceleration communicated to the *CG*, i.e. the muscular activity level of the system. Although this approach has been used in standing posture for many years (Caron et al., 1997; Corriveau et al., 2000; Rougier et al., 2001; Rougier, 2003; Masani et al., 2007), it remains unexplored to our knowledge in the sitting posture. However, in this posture the amplitude relationship between the CG_v and the *CP*, through which the CG_v movements can easily be estimated if the position of the arms and head remain fixed regarding the trunk. In the sitting posture, the value of splitting the global *CP* into two basic components, i.e. CG_v and $CP-CG_v$ displacements, could be highlighted by using a postural task in which the trunk is tilted backwards or not tilted. With this method, only a force

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Nomenclature

Ω	angular velocity ($2\pi f$ rad s^{-1})
A_i	amplitude of each class
AP	anteroposterior
CG	centre of gravity of whole body
CG_v	vertical projection of the centre of gravity
COM	centre of mass of segment
CP	centre of pressure
C_{pi}	proximal distance from CG/segment length
$CP-CG_v$	difference between CP and CG_v
d_i	distance between CG and centre of mass of the segment (m)
f	natural or eigen body frequency (Hz) as defined by Brenière (1996)
h	height of CG relative to the supporting surface (m)
i	many segments
I_G	body inertia (kg m^2)
k_i	radius of gyration (kg m^2)
M	body weight mass (kg)
m_i	mass of segment (kg)
ML	mediolateral
MPF	mean power frequency (Hz)
RMS	root mean square (mm)
S_i	centre frequency of each class
x_{di}, y_{di} and z_{di}	positions of the distal joint on x, y and z axis/segment length
x_{pi}, y_{pi} and z_{pi}	positions of the proximal joint on x, y and z axis/segment length

platform is necessary. Compared to other tools (e.g. markers) it is an inexpensive and easy way to estimate the CG_v movements. The only prerequisite is the calculation of the moment of inertia for the adopted posture. As for upright standing, our main hypothesis is that an increase in muscular activity level ($CP-CG_v$) would be expected during backward tilting whilst the other parameters (CP and CG_v) would remain unchanged.

2. Methods

2.1. General method

The CG_v/CP amplitude relationship in the frequency domain was proposed by Brenière (1996) and extended to quiet stance control by Caron et al. (1997)

$$\frac{CG_v}{CP} = \frac{\Omega_o^2}{\Omega_o^2+\Omega^2} \quad (1)$$

and then

$$CG_v = CP\frac{\Omega_o^2}{\Omega_o^2+\Omega^2}$$

with

$$\Omega_o = \sqrt{\frac{Mgh}{I_G+Mh^2}} \quad (2)$$

and Ω=angular velocity ($2\pi f$ rad s^{-1}).

The amplitudes of the CG_v (left part) correspond to the amplitudes of the CP multiplied by a filter characterizing the inertial oscillation of the system around its axis of rotation (right part). This ratio, which appears to depend on the frequency of the CP displacements, is computed from the angular momentum equation applied to the whole body with respect to the CG_v using the inverse dynamic approach. Once the CG_v has been estimated, it is possible to breakdown the CP trajectories into two basic components: the CG_v displacements, which can be used to quantify the body motions and therefore the postural performance; and the difference between CP and CG_v ($CP-CG_v$), whose amplitude is proportional to the horizontal acceleration communicated to the CG (Brenière et al., 1987). The same approach can be adapted for the sitting position to assess the postural control of the trunk. The only variable of the filter (Eq. (1)) with respect to standing is the natural frequency of oscillation of the body (Ω_o) which depends on the inertia I_G (Eq. (2)). As the locations of different segments in a sitting position is not the same as in the standing position (Fig. 1), a new calculation of inertia applied to the CG_v for a sitting subject is required.

2.2. Calculation of inertia

Sixteen segments (i) were considered: head and neck; upper, middle and lower part of the trunk; arms; forearms; hands; thighs; legs; feet. The joint coordinates (x_{pi}, y_{pi} and z_{pi}) relative to the height of the subjects were estimated, from data reported by Drills and Contini (1966), for a sitting upright position and a sitting tilting position with crossed arms. The limbs' centres of mass relative to the segment length were calculated from proximal coefficient (C_{pi}) (Dempster, 1955)

$$\overrightarrow{OG}_i = \begin{pmatrix} x_{pi}+c_{pi}(x_{di}-x_{pi}) \\ y_{pi}+c_{pi}(y_{di}-y_{pi}) \\ z_{pi}+c_{pi}(z_{di}-z_{pi}) \end{pmatrix}$$

The position of the CG relative to the height of the subject was calculated using the following general formula:

$$\overrightarrow{OG} = \frac{\sum_{i=1}^{n} m_i \overrightarrow{OG}_i}{\sum_{i=1}^{n} m_i}$$

Fig. 1 shows the limbs' COM and CG locations for both sitting positions. A difference between the locations of CG for both conditions has to be underlined.

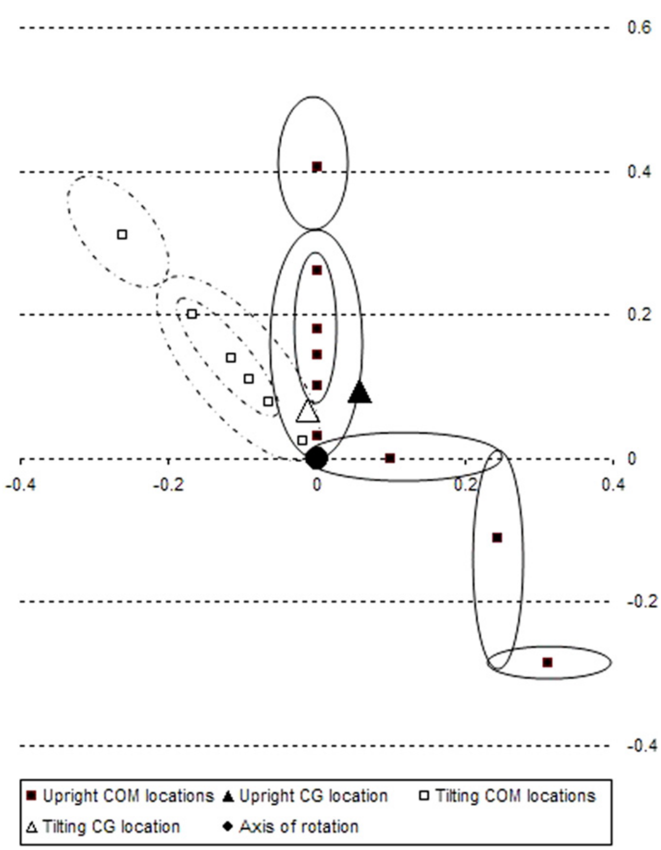

Fig. 1. Axis of rotation location, the limbs' COM locations and the CG of the whole body locations for each condition.