Trunk extensor muscles fatigue affects undisturbed postural control in young healthy adults

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Abstract

Background. The purpose of this study was to investigate the effects of trunk extensor muscles fatigue on undisturbed postural control in young healthy adults.

Methods. Fifteen university students were asked to stand upright as immobile as possible with their eyes closed in two conditions of Fatigue and No fatigue of the trunk extensor muscles. Muscular fatigue was achieved by performing trunk repetitive extensions until maximal exhaustion. Centre of foot pressure displacements, recorded using a force platform, were used to compute the motions of the vertical projection of the centre of gravity and those of the difference between the centre of pressure and those of the difference between the centre of pressure and the vertical projection of the centre of gravity. These motions were processed through space–time and frequency domain analyses.

Findings. Larger centre of pressure minus centre of gravity and centre of gravity motions in the Fatigue than No fatigue condition are observed along both the medio-lateral and antero-posterior axes, this effect being more accentuated along the antero-posterior axis.

Interpretation. The present findings suggest that trunk extensor muscles fatigue deteriorates undisturbed stance control, yielding, along the antero-posterior axis mainly, (1) a greater neuromuscular requirements for ensuring standing control, as indicated by the increased centre of pressure minus centre of gravity motions, and (2) a deterioration of postural performance, as indicated by the increased centre of gravity motions.

Keywords: Upright stance; Muscular fatigue; Trunk extensor muscles; Centre of foot pressure; Centre of gravity; Centre of pressure minus centre of gravity

1. Introduction

In recent years, a growing number of studies have investigated the effects of muscular fatigue on the regulation of bipedal quiet upright standing. Generally, a deterioration of postural control with muscular fatigue was reported (e.g., Caron, 2003; Ledin et al., 2004; Vuillerme et al., 2002, 2006; Vuillerme and Demetz, 2007; Vuillerme and Nougier, 2003). Considering postural control as a sensorimotor process (e.g., Schmidt, 1975), it is conceivable that muscular fatigue, known to alter the peripheral proprioceptive system, the central processing of proprioception but also the force-generating capacity (e.g., Taylor et al., 2000), affects both the sensory and the motor side of the process. In most investigations cited above, the displacements of the centre of foot pressure (CoP), whose successive positions express the displacements of the point of application of the resultant reactive force, were used to characterise postural control. At certain moments, the CoP displacements controlling the centre of gravity (CoG) are minimised whereas, at other moments, when...
the CoG position is about to induce a loss of balance, the CoP displacements make it return to a position where horizontal acceleration will be reduced. From this, as proposed by Rougier and Caron (2000), it seems coherent to dissociate the CoP into two elementary components, the centre of gravity vertical projection (CoGv) and the difference between the latter and the former (CoP–CoGv), presenting specific attributes in undisturbed stance control. The former, representing the whole body motions, can be considered an index of postural performance in undisturbed upright stance control (e.g., Winter et al., 1998), whilst the latter is proportional to the horizontal acceleration communicated to the CoG and is assumed to express the neuromuscular requirements for controlling undisturbed upright stance control. Consequently, large CoP–CoGv motions indicate a greater neuromuscular demand to maintain standing balance. Interestingly, this latter point can be demonstrated by the recruitment modalities in the motor units, which, according to the size principle (Henneman et al., 1965), see the faster units called into play for increasing muscular force. Indeed, as revealed by the modelling used to estimate the CoG motions from the CoP displacements, the larger the contribution of fast motor units, the greater the velocity (or its frequency) and thus the larger the difference CoP–CoGv. Thus, decomposing the CoP trajectory into two elementary motions can indicate to which extent a modification of the global CoP motions can arise from either a single exaggerated elementary motion or both of them (e.g., Rougier, 2003; Rougier et al., 2001; Rougier and Caron, 2000). In addition, the investigations cited above referred to postural control following lower limb efforts. However, muscle proprioceptive information arising from numerous receptors distributed throughout the whole body is known to participate in the control of body posture (e.g., Massion, 1992; Roll and Roll, 1988). Interestingly, (1) since the antero-posterior positions of the centres of gravity of the portions of the body above the ankle, knee and hip are not vertically aligned (Woodhull et al., 1985), maintaining an upright standing posture necessarily requires muscular activities of sagittal plane movers of the hip and (2) it has been reported that impairments in lumbar neuromuscular functions have detrimental effects on postural control (e.g., Byl and Sinnot, 1988; Hamaoui et al., 2004; Mientjes and Frank, 1999). Therefore, the purpose of the present experiment was to investigate the effects of trunk extensor muscles fatigue on undisturbed postural control. It was hypothesised that fatigue at this level impairs postural control. Because the fatigue supposedly affect both sensory and motor components (e.g., Taylor et al., 2000), it can be hypothesised that both CoP–CoGv and CoGv motions could be enhanced. Furthermore, due to the musculature investigated, different effects according to the medio-lateral (ML) or antero-posterior (AP) axes can be expected, with a decreased postural control mostly occurring in the sagittal plane.

2. Methods

2.1. Subjects

Fifteen university students from the Department of Sports Sciences at the University of Savoie (mean age = 21.3 (SD 1.1) years; mean body weight = 72.2 (SD 11.3) kg; mean height 178.9 (SD 6.7) cm) voluntarily participated in the experiment. They gave their informed consent to the experimental procedure as required by the Helsinki declaration (1964) and the local Ethics Committee. None of the subjects presented any history of musculoskeletal problem, neurological disease or vestibular impairment.

2.2. Apparatus

A force platform (Equi+, model PF01, Aix les Bains, France), constituted of an aluminium plate (800 mm each side) laying on three uniaxial load cells, was used to measure the displacements of the CoP. Signals from the force-platform were sampled at 64 Hz, amplified and converted from analogue to digital form through a A/D converter (14 bits).

2.3. Task and procedure

Eyes closed, the subjects stood barefoot, feet together, their arms hanging loosely by their sides and were asked to sway as little as possible. The eyes closed condition has been chosen in order to avoid that vision interfering with the induced postural behaviours. This task was performed under two experimental sessions. The No fatigue condition served as a control session; in the Fatigue condition, the measurements were performed immediately after a fatiguing procedure. The muscular fatigue was induced until maximal exhaustion with trunk repetitive extensions (mean duration = 54 s). Subjects lay prone on a bench with the upper body unsupported in the horizontal plane. The lower extremities were secured to the bench with straps at the hips, knees and ankles. During the test, arms were held crossed the chest. Subjects were instructed to raise their upper body to a horizontal position and then lowering it back down as many times as possible following the beat of a metronome (40 beats/min). Verbal encouragement was given to ensure that subjects worked maximally. The fatigue level was reached when subjects were no more able to complete the trunk extension exercise. To ensure that balance measurement in the Fatigue condition was obtained in a genuine fatigued state, the fatiguing exercise took place beside the force platform, so that there was a short time-lag between the exercise-induced fatiguing activity and the balance measurements (less than 30 s) and the fatiguing exercise was repeated prior to each trial. Three 32-s trials for each condition were performed.
2.4. Signal processing

As stated above, displacements of the CoP were split into two elementary components: the vertical projection of the CoG (CoGv) and the difference between CoP and CoGv (CoP–CoGv). Body sways being particularly reduced, one may consider that the moment of inertia of the body remains constant throughout the trials. In this case, CoGv motions can be deducted from CoP trajectories, since there exists in that case a frequency relation between these two variables (Breniere 1996; Caron et al., 1997). It is relevant hereby to consider that CoP oscillations operating over too high frequencies would not infer appreciable CoGv movements. In the present study, the determination of the CoGv motions is directly derived from the CoP trajectories on a frequency basis through an amplitude ratio between CoGv and CoP developed by Breniere (1996) for gait and adapted by Caron et al. (1997) for standing posture.

2.5. Data analysis

CoP–CoGv and CoGv motions were processed through two different analyses. (1) A space–time-domain analysis first includes the calculation of the surface covered by the trajectory with a 90% confidence interval, the mean speed and the variances of positions along the ML and AP axes of the CoGv and CoP–CoGv elementary motions. (2) A frequency-domain analysis, issued from the Fast Fourier Transform process, is based on root mean square (RMS in mm), and median frequency (MF in Hz) parameters aimed at characterising the mean spectral decompositions of the sway motions on specific bandwidths (0–0.5 Hz for CoGv and 0–3 Hz for CoP–CoGv). These bandwidths were chosen to give these indices the larger sensitivity since the modifications occurring on the frequency spectra intervene generally inside these bounds (see Farenc and Rougier, 2000).

2.6. Statistical analysis

Data obtained for the mean speed and the surface areas covered by the CoGv and CoP–CoGv motions were submitted to separate one-way analyses of variance (ANOVA) (2 Fatigues (No fatigue vs. Fatigue)). To further investigate whether the effect of the trunk extensor muscles fatigue was similar according to the ML or AP axes, 2 Fatigues (No fatigue vs. Fatigue) × 2 Axes (ML vs. AP) ANOVAs with repeated measures on both factors were applied to the variance, the RMS and the MF of the CoGv and CoP–CoGv motions. Post-hoc analyses (Newman–Keuls) were used whenever necessary. Level of significance was set at 0.05.

3. Results

3.1. Space–time domain analysis

Analysis of the CoP–CoGv motions shows larger surface area (F(1,14) = 29.32, P < 0.001; Fig. 1a) and mean speed (F(1,14) = 66.17, P < 0.001; Fig. 1b) in the Fatigue than No fatigue condition. Analysis of the variances shows a significant interaction of Fatigue × Axis (F(1,14) = 7.98, P < 0.05; Fig. 1c). The decomposition of this interaction into its simple main effects shows that the Fatigue condition yields larger variances relative to the No fatigue condition along both axes, but this effect is greater along the AP axis (P < 0.001). The ANOVAs also confirm main effects of Fatigue (F(1,14) = 29.66, P < 0.001) and Axis (F(1,14) = 14.35, P < 0.01).

Similar results are observed for the CoGv motions, the Fatigue condition yielding increased surface area (F(1,14) = 18.15, P < 0.001; Fig. 1d) and mean speed (F(1,14) = 24.69, P < 0.001; Fig. 1e) relative to the No fatigue condition. Analysis of the variances shows a significant interaction of Fatigue × Axis (F(1,14) = 15.73, P < 0.01; Fig. 1f). The Fatigue condition yields larger variances relative to the No fatigue condition along both axes, but this effect is greater along the AP axis (P < 0.001). The ANOVAs also confirm main effects of Fatigue (F(1,14) = 14.91, P < 0.01) and Axis (F(1,14) = 12.56, P < 0.01).
3.2. Frequency domain analysis

Analysis of the CoP–CoGv motions shows a significant interaction of Fatigue × Axis for the RMS ($F(1,14) = 5.49, P < 0.05$; Fig. 2a). The decomposition of this interaction into its simple main effects shows that the Fatigue condition yields larger RMS relative to the No fatigue condition along both axes, but this effect is greater along the AP axis ($P < 0.001$). The ANOVAs also confirm main effects of Fatigue ($F(1,14) = 26.87, P < 0.001$) and Axis ($F(1,14) = 17.41, P < 0.01$). In addition, analysis of the MF shows a main effect of Fatigue ($F(1,14) = 10.52, P < 0.01$), yielding higher MF in the Fatigue than No fatigue condition and a main effect of Axis ($F(1,14) = 13.13, P < 0.01$), yielding higher MF along the AP than ML axis (Fig. 2b).

Analysis of the CoGv motions shows a significant interaction of Fatigue × Axis for the RMS ($F(1,14) = 9.88, P < 0.01$; Fig. 2c). The Fatigue condition yields larger RMS relative to the No fatigue condition along both axes, but this effect is greater along the AP axis ($P < 0.001$). The ANOVAs also confirm main effects of Fatigue ($F(1,14) = 18.21, P < 0.001$) and Axis ($F(1,14) = 11.89, P < 0.01$). Finally, no significant changes are observed for the MF (Fig. 2d).

4. Discussion

The purpose of the present experiment was to investigate whether trunk extensor muscles affects undisturbed upright stance control. To this aim, fifteen young healthy adults were asked to stand as immobile as possible with their eyes closed in two conditions of Fatigue and No fatigue of the trunk extensor muscles. CoP displacements, recorded using a force platform, were used to compute the motions of the vertical projections of the CoGv and those of the difference CoP–CoGv.

The Fatigue condition yields larger CoP–CoGv amplitudes, as indicated by the surface area (Fig. 1a), mean speed (Fig. 1b), variances (Fig. 1c), RMS (Fig. 2a), and median frequencies (Fig. 2b). Results further evidenced that this effect of fatigue on amplitudes to be more accentuated along the AP axis (Figs. 1c and 2a). This suggests increased neuromuscular requirements for controlling posture following the fatiguing exercise (e.g., Caron et al., 2000; Rougier et al., 2001; Winter et al., 1998). In addition, although recent studies, involving various subjects and experimental conditions, have evidenced the relative independence of CoP–CoGv and CoGv motions in undisturbed upright stance in the sense that a modification of the amplitudes of one motion does not necessarily induce a similar effect on the other (e.g., Caron, 2003; Rougier, 2003; Rougier et al., 2001), it is important to mention that, from a biomechanical point of view, increasing CoP–CoGv motions amplitudes, seen as an expression of the initial horizontal acceleration communicated to the CoGv (Bre´niere et al., 1987), negatively affects the relative facility for the subjects to handle CoGv motions in the Fatigue condition due to the higher forces they would have to counteract. However, through a modulation of the control mechanisms aimed at handling these CoG motions, the central nervous system can largely attenuate the effects induced by some larger horizontal accelerations. In other words, it can be thus suggested that a large part of the increased CoGv motions is due to the increased neuro-muscular activity, as deduced from the amplitudes of the CoP–CoGv motions.

Results of the CoGv motions are indeed in line with this assumption, the Fatigue condition yielding larger displacements of the CoGv, as indicated by the surface area (Fig. 1d), mean speed (Fig. 1e), variances (Fig. 1f) and RMS (Fig. 2c) relative to the No fatigue condition. These features could also stem from an alteration of the functionality of the sensory proprioceptive and motor systems caused by the fatiguing exercise. This suggestion is supported by larger destabilising effects observed along the AP than ML axis, when considering what the fatiguing exercise involved in terms of joints and tendons receptors stimulation and muscles recruitment (i.e., trunk extensor muscles). Indeed, trunk muscles fatigue was shown to impair the ability to sense a change in lumbar position (Taimela et al., 1999), to delay the reaction time of the muscles in response to a sudden load (Wilder et al., 1996) and to reduce the force generating capacity (e.g., Ng et al., 2003; Potvin and O’Brien, 2002; Sparto and Parnianpour, 1998) and to increase its variability (e.g., Ng et al., 2003; Potvin and O’Brien, 2002). In addition, the increased...
CoG, displacements observed along the ML axis following the symmetric trunk extensor muscle fatiguing exercise could stem from the assumption that ML and AP body motions are not completely independent and that motion in one plane can somehow be reflected in the other plane, but in a attenuated form (Day et al., 1993). One possible explanation could be that a number of muscles control movements in both planes and provide a means by which movement can overflow from one plane to the other (Day et al., 1993). More largely, with regard to an impairment of trunk muscles function induced by the fatiguing exercise, our results are in accordance with previous studies evidencing a deterioration of postural control in individuals suffering from low back pain (e.g., Byl and Sinnot, 1988; Hamaoui et al., 2004; Mientjes and Frank, 1999) or idiopathic scoliosis (Gauchard et al., 2001; Nault et al., 2002; Simoneau et al., 2006). Interestingly, decreased balance control performances observed in low back pain patients in undisturbed upright stance and unstable sitting were recently suggested to be linked to an increased muscular active tension (Hamaoui et al., 2004) and to delayed trunk muscles response time (Radebold et al., 2001). Together, these results are in line with the increased CoP–CoG, and CoG, motions observed with fatigue in the present experiment, respectively.

Furthermore, although it is well established that impairment of performance resulting from muscle fatigue differs according to the exercise duration/intensity, the type of contraction involved, but also the muscular groups tested, we would like to emphasise the magnitude of the increase in CoG, motions observed in the Fatigue condition. At this point, considering that muscles acting on the trunk have larger cross-sectional areas than those surrounding the ankle, it is possible that fatigue in proximal muscles groups, such as trunk extensor muscles induces greater postural impairment compared with fatigue to distal muscles groups, such as ankle musculature. These increased CoG, motions should be also seen as a direct consequence of the inverted pendulum functioning. Since the compensation can occur only at the ankle joints, the impaired control of the trunk motions (which includes in fact all the upper segments which insert on the trunk) have necessarily huge repercussions at this level.

Finally, although the exact mechanism inducing postural impairment following the fatiguing exercise is rather difficult to answer and was not within the scope of our study, we would like to mention that, as observed in studies involving individuals suffering from low back pain, some subjects reported sensation of back pain at the end of the fatiguing exercise. Indeed, pain often develops following fatiguing muscle contractions. This sensation probably arises from firing of the groups III and IV afferents, that are sensitive to metabolites and inflammatory substances (e.g., potassium, lactic acid, bradykinin and arachidonic acid) accumulated within the muscle during activity to fatigue (e.g., Taylor et al., 2000). It is thus possible that postural control, apart from being dependent on trunk extensor muscles fatigue, could be dependent on back pain-related input. Although experimentally elicited pain was shown to affect postural activation of the trunk muscles (e.g., Hodges et al., 2003; Moseley et al., 2004; Zedka et al., 1999), such a proposal is yet speculative and warrant additional investigations that are included in our immediate plans.

In conclusion, the present findings evidence that trunk extensor muscles fatigue deteriorates undisturbed stance control in young healthy adults, yielding, along the AP axis mainly, (1) a greater neuromuscular requirements for ensuring standing control, as suggested by the increased CoP–CoG, motions, and (2) a deterioration of postural performance, as indicated by the increased CoG, motions. While the present study was focused on young healthy adults, it would be interesting to investigate whether trunk extensor muscles fatigue affects balance in individuals that suffered lumbar disorders or subjects showing less accurate postural capacities (e.g., elderly persons). More largely, these results stress the importance of intact lumbar muscle function on the regulation of bipedal quiet upright standing. Whether this function is critical to other postural control mechanisms, such as anticipatory adjustments for voluntary movements or automatic postural reactions to external perturbations, is currently being investigated.

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