How Performing a Repetitive One-Legged Stance Modifies Two-Legged Postural Control

Cyril Burdet, Nicolas Vuillerme, and Patrice R. Rougier
Laboratory of Exercise Physiology, University of Savoie, Le Bourget du Lac, France

ABSTRACT

Burdet, C, Vuillerme, N, and Rougier, PR. How performing a repetitive one-legged stance modifies two-legged postural control. J Strength Cond Res 25(10): 2911–2918, 2011—The proprioceptive cues in the control of movement is recognized as playing a major role in postural control. However, little is known about its possible increased contribution to postural control consecutive to repetitive muscular activations. To test this, the short-term effects induced by a 1-legged exercise on 2-legged postural control with the eyes closed were assessed in healthy subjects. The center-of-pressure (CP) displacements obtained using a force platform were split into 2 elementary movements: center-of-gravity vertical projection (CGv) and the difference (CP – CGv). These movements assessed the net postural performance and the level of neuromuscular activity, respectively, and were processed afterward (a) through variances, mean velocity, and the average surface covered by the trajectories and (b) a fractional Brownian motion (fBm) modeling. The latter provides further information about how much the subject controls the movements and the spatiotemporal relation between the successive control mechanisms. No difference was found using the classical parameters. In contrast, fBm parameters showed statistically significant changes in postural control after 1-legged exercises: The spatial and temporal coordinates of the transition points for the CG movements along the anteroposterior axis are decreased. Because the body movement control does not rely on visual or vestibular cues, this ability to trigger the corrective process of the CG movements more quickly in the postexercise condition and once a more reduced distance has been covered emphasizes how prior muscular activation improves body movement detection. As a general rule, these data show that the motor systems control body motions better after repetitive stimulation of the sensory cues. These insights should be of interest in physical activities based on a precise muscular length control.

KEY WORDS postural control, unipedal, bipedal, center of pressure, center of gravity

INTRODUCTION

Contrary to its apparent simplicity, keeping a balanced posture is a continual challenge for the central nervous system. Indeed, as long as a subject stands in a vertical position, perfect balance, that is, immobilizing the body segments, cannot be obtained. Several phenomena such as heartbeat, breathing, and motor unit synchronization cause these destabilizations.

However, the main source of postural movements stems from the muscular activity required to produce the shear forces applied at the various joints aimed at maintaining the segments from each other because of the nonvertical alignment of the segments’ centers of mass. One property of the muscles is their incapacity to develop a constant tension (11); it therefore follows that postural control consists in an inexorable regulation of the center of gravity (CG) by center-of-pressure (CP) displacements. As proposed initially (33), the CP and CG are thought to be the controlling and controlled variables, respectively. Interestingly, the gap between the CP and the vertical projection of the CG (CGv) expresses the horizontal acceleration communicated to the CG (4) and from that the muscular activity (24). Therefore, it also appears to be relevant to dissociate the complex CP displacements into 2 different elementary movements: the CGv and its difference from the CP (CP – CGv). These 2 movements have been demonstrated as being independent (24). They can be easily estimated through a biomechanical simulation developed by Brenière et al. (3) and validated for upright standing by Caron et al. (7).

The CP paths can be explained by 2 independent factors involving different muscle groups around the ankle and hip joints: the pressure variations and the load–unload mechanisms (23,34). These 2 mechanisms are predominantly involved in controlling the CP displacements along the anteroposterior (AP) and mediolateral (ML) axes, respectively. As a result, improving somatosensory cues from the ankle joints is expected to improve the control of the pressure distribution, at least along the AP axis of the feet, and
Postural Control during 1- and 2-Legged Stance

The purpose of this study was to investigate the immediate effects produced by an increased and prolonged muscular activation on the postural performance consisting in standing alternately on each leg. Standing on 1 foot, as compared to bipedal stance, infers an increased loading of the foot and the involvement of the same muscles in controlling the movements along the AP axis (5). Because of an increased solicitation of the muscular receptors, because of the larger loading, it can be hypothesized that repeatedly performing a 1-legged stance could positively affect the control mechanisms aimed at securing a 2-legged stance. In particular, it can be expected that the postural corrective processes could be initiated after a shorter distance has been covered.

METHODS

Experimental Approach to the Problem

The repetitive muscular activations being sought to infer an improved proprioception at the lower leg level, upright quiet stance seems appropriate to assess their effects on a sensorimotor task. This proprioception improvement is expected to modify the capacity of the central nervous system to detect and then correct the body sway, hence legitimating to analyze the CP trajectories the fBm approach which highlight, through the shape of the variograms and their slope inflection, the onset of the corrective process. Lastly, because repetitive upright stance sessions could infer by themselves some modifications in the postural control organization, a control group was also involved in this study and required to perform 2-legged standing when the experimental group perform 1-legged stance maintenances.

Subjects

Two groups of 11 healthy subjects were included in this study. A first group of 3 women and 8 men (age, 27 ± 6.6 years; weight, 69.8 ± 8.8 kg; height, 177.8 ± 6.5 cm) participated in the bipedal–unipedal–bipedal (BUB) protocol. As explained below, a control group was also included, which followed the same protocol but only in bipedal stance (BBB). This group was composed of 11 healthy adults not involved in the main protocol (5 women and 6 men; 25 ± 4.5 years; weight, 65.1 ± 6.9 kg; and height, 173.1 ± 5.6 cm). As shown by the Mann and Whitney tests, none of these values presented any statistically significant differences. For both groups, no particular musculoskeletal impairments such as ankle sprain or ankle instability or neurological disorders that might have affected their sense of balance was detected. All subjects were students in sports and physical activity and were therefore regularly physically active. They had not been involved in any physical activity the day they were tested. All subjects were informed of the aims of the study, and they gave their consent in accordance with the Declaration of Helsinki (1964).

Material

A triangular force platform (Equi+-PF01, Aix-les-Bains, France) was used to record the CP trajectories. Each recording sequence lasted 64 seconds and was sampled at 64 Hz. The CP trajectories were then processed in different ways using a specific software program (Equi+-Prog01).

Procedure

A reference (PRE) and a postexercise (POST) condition were recorded before and after a series of upright postural
maintenance trials. In both conditions, the subjects were asked to stand as still as possible in a natural position (feet abducted at 30°, heels 3 cm apart), with their eyes closed to eliminate visual input. Each condition consisted of performing 5 64-second trials with a rest of similar duration. In the BUB protocol, between PRE and POST conditions, the subjects were asked to perform 10 successive trials lasting 64 seconds consisting of standing on 1 foot. This exercise was performed with their eyes closed to make the task more difficult and therefore to induce greater muscular activity. In addition, the proprioceptive cues were hypothesized to play a major role in the integrative process. At the end of each trial, the support leg was changed so that the subjects alternately stood on their left or right foot.

Parallel to these measures, a control (BBB) protocol was set up including another group of subjects who performed the PRE and POST conditions similarly but instead of standing still on 1 foot performed 2-legged stance tasks with their eyes closed during the same periods as unipedal stance training (10 64-second trials). This control protocol was thought to assess whether the possible postural control changes could be caused by a learning effect resulting from the repetition of the trials.

Estimation of Center-of-Gravity Vertical Projection and CP – CGv Movements
As stated above, CGv and CP – CGv movements were determined from the CP trajectories. A relationship in the frequency domain between the amplitude ratio of the vertical projection of the center of gravity (CGv) and CP trajectories (CGv/CP) was used to estimate the CGv and consequently the CP–CGv movements. The different steps leading to the estimation of the CGv and consequently to CP–CGv movements, are detailed in the text and illustrated in Figure 1.

Signal Processing
Two different approaches were used to study the various movements: (a) a classical analysis including mean positions and variances along the ML and AP axes, surface (27), and mean velocity and (b) a mathematical model called fractional Brownian motion initially proposed by Mandelbrot and van Ness (18) and first applied to postural control analysis by Collins and de Luca (10). The mean positions of the CP trajectories were calculated with regard to a reference defined by the intersection of the line passing behind the heels and the sagittal median line between both feet. Positive values indicate that the position is situated in a forward direction (positive AP axis) and to the right (positive ML axis) with respect to these lines. From a general point of view, fBm modeling provides a quantitative measurement of wiggle in a trajectory in a single direction. Through this feature, the noninteger dimension of a trajectory can be characterized. For instance, in the present case, a trajectory expressed as a function of time can be quantified by a dimension ranging from 0 to 1 because the trajectory fills more space than a simple point but less than a line. In turn, H can be deduced from the relation:

$$\langle \Delta x^2 \rangle = \Delta t^{2H},$$

where \(\langle \Delta x^2 \rangle\), in mm², is the mean square distance covered by a given point and \(\Delta t\), in seconds, represents the increasing time intervals. It should be noted that the squared distances are only used to prevent a null mean squared displacement. Graphically, \(H\), the Hurst exponent, corresponds to the half-slope of a variogram, depicted bilogarithmically, that is, the relation between \(\langle \Delta x^2 \rangle\), and increasing \(\Delta t\). Knowing the \(H\) value makes it possible to assess the relative contribution of stochastic (randomly controlled) and deterministic trends in the overall control process. A median value of 0.5 for \(H\) indicates that past and
future increments are not correlated and suggests that a pure stochastic (or random-walk) process is operating. On the other hand, that is, if $H$ differs from 0.5, a positive ($0.5 < H$) or a negative ($H < 0.5$) correlation can be inferred, assuming that persistent and antipersistent processes are operating, respectively. Persistent and antipersistent scaling regimes indicate that there is a greater probability for a material point to either continue along or to return along a given axis, respectively. Scaling regimes $H$ moving away from the 0.5 median value indicate an increased contribution of deterministic processes. On the other hand, the closer the regime is to 0.5, the lesser is the determinism and the greater the stochastic activity.

Because quite a flat line preceding or succeeding a steeper line generally characterizes variograms relative to undisturbed upright stance maintenance, a final step consists in determining the transition point for both axes, that is, the point corresponding to the slope inflection. Because CP and CG, displacements are, by definition, in phase, the temporal coordinate of the transition points of the CP trajectories will also be the temporal coordinate of the CGv and CP – CGv movements. The method used for this purpose is based on how the distance between the CP variogram and a completely stochastic process evolves, as a function of increasing $\Delta t$, which is characterized by a slope of 1. The principle retained, contrasting with the less objective method initially used (10), is that the $\Delta t$ for which this distance is maximal is the $\Delta t$ of the transition point (22). 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. The filter effect actually leads to curvilinear functions moving progressively away from or closer to the slope of 1 mentioned above (because $2 \times [H = 0.5] = 1$). Specifically, the temporal order of the increments from CP trajectories was randomly shuffled and then recombined to generate stochastic trajectories, which were then processed like the experimental CP trajectories to obtain CGv and CP – CGv movements. Scaling regimes relative to average stochastic variograms over the same $\Delta t$ must, therefore, be taken as a reference such that

$$H_{\text{cal}} = (H_{\text{exp}} - H_{\text{sto}}) + 0.5,$$

where $H_{\text{cal}}$, $H_{\text{exp}}$ and $H_{\text{sto}}$ represent the calculated, experimental, and stochastic scaling regimes, respectively. Thus, for each of the 2 CGv and CP – CGv movements investigated and each ML and AP axis, 2 scaling exponents (indexed as short and long latencies: $H_s$ and $H_l$) and the coordinates of the transition point were extracted. Figure 2 illustrates this procedure with CP, CGv, and CP – CGv trajectories. As reported by Collins and de Luca (10), the intraclass correlation coefficients for the parameters issued from the fBm modeling are highly reliable. Our method to determine the transition point coordinates objectively should further increase these levels of reliability.

### Statistical Analyses

The PRE and POST conditions tested through the 2 BUB and BBB protocols were compared using nonparametric Wilcoxon tests based on the ranks. The 2 groups that participated in the BUB and BBB protocols were compared in the PRE condition using nonparametric Mann and Whitney tests. Indeed, as shown by the Kolmogorov–Smirnov tests, the normal distribution cannot be assessed for any of the parameters computed from both conditions or for both groups, thus justifying the use in each case of nonparametric tests. For all statistical analyses, a $p$ value of 0.05 (alpha) was accepted as the level of significance. If a difference was not statistically significant at the chosen level, the beta risk of an erroneous conclusion of equivalence was chosen as a $p$ value $\leq 0.2$.

### Results

Before presenting the results, it is necessary to point out that no statistically significant effect was observed during the control experiment (BBB protocol), which consisted of subjects standing upright when those participating in the protocol were required to stand on 1 foot. As seen from Table 1, no effect was found for the whole set of parameters. In addition, no statistically significant difference was found when comparing the 2 samples in each BUB and BBB protocol through the parameters measured during the PRE condition.
### Table 1. Mean ± SD for the 2 BUB and BBB protocols from CP – CGv and CGv movements.*†

<table>
<thead>
<tr>
<th>CGv movements</th>
<th>Surface (mm²)</th>
<th>Mean ML (mm)</th>
<th>Mean AP (mm)</th>
<th>Var ML (mm²)</th>
<th>Var AP (mm²)</th>
<th>Velocity (mm·s⁻¹)</th>
<th>Δt ML (s)</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUB PRE</td>
<td>238.81 ± 147.93</td>
<td>0.53 ± 3.91</td>
<td>189.76 ± 10.73</td>
<td>17.14 ± 14.59</td>
<td>18.69 ± 10.83</td>
<td>3.83 ± 0.79</td>
<td>0.72 ± 0.27</td>
</tr>
<tr>
<td>POST</td>
<td>203.50 ± 105.18</td>
<td>-0.95 ± 3.73</td>
<td>187.57 ± 9.38</td>
<td>10.34 ± 4.96</td>
<td>20.95 ± 14.34</td>
<td>3.67 ± 0.93</td>
<td>0.73 ± 0.21</td>
</tr>
<tr>
<td>T = 11 (p &gt; 0.05)</td>
<td>T = 19 (p &gt; 0.05)</td>
<td>T = 25 (p &gt; 0.05)</td>
<td>T = 15 (p &gt; 0.05)</td>
<td>T = 21 (p &gt; 0.05)</td>
<td>T = 16 (p &gt; 0.05)</td>
<td>T = 22 (p &gt; 0.05)</td>
<td></td>
</tr>
<tr>
<td>BBB PRE</td>
<td>213.02 ± 98.36</td>
<td>0.19 ± 2.77</td>
<td>163.15 ± 17.23</td>
<td>11.20 ± 5.10</td>
<td>19.73 ± 12.41</td>
<td>3.92 ± 0.86</td>
<td>0.74 ± 0.29</td>
</tr>
<tr>
<td>POST</td>
<td>206.15 ± 85.41</td>
<td>2.32 ± 3.59</td>
<td>160.11 ± 14.99</td>
<td>11.72 ± 5.77</td>
<td>19.56 ± 12.01</td>
<td>4.27 ± 0.84</td>
<td>0.79 ± 0.35</td>
</tr>
<tr>
<td>T = 24 (p &gt; 0.05)</td>
<td>T = 13 (p &gt; 0.05)</td>
<td>T = 20 (p &gt; 0.05)</td>
<td>T = 26 (p &gt; 0.05)</td>
<td>T = 26 (p &gt; 0.05)</td>
<td>T = 12 (p &gt; 0.05)</td>
<td>T = 27 (p &gt; 0.05)</td>
<td></td>
</tr>
<tr>
<td>CP – CGv movements</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BUB PRE</td>
<td>18.61 ± 7.73</td>
<td></td>
<td>1.07 ± 0.63</td>
<td>1.64 ± 0.57</td>
<td>9.76 ± 1.53</td>
<td></td>
<td></td>
</tr>
<tr>
<td>POST</td>
<td>17.82 ± 7.96</td>
<td></td>
<td>1.03 ± 0.56</td>
<td>1.58 ± 0.65</td>
<td>9.43 ± 1.38</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T = 22 (p &gt; 0.05)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BBB PRE</td>
<td>18.57 ± 7.89</td>
<td></td>
<td>1.08 ± 0.64</td>
<td>1.63 ± 0.60</td>
<td>9.48 ± 1.25</td>
<td></td>
<td></td>
</tr>
<tr>
<td>POST</td>
<td>18.44 ± 6.97</td>
<td></td>
<td>1.09 ± 0.51</td>
<td>1.61 ± 0.60</td>
<td>9.53 ± 1.23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>T = 32 (p &gt; 0.05)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>CGv movements</th>
<th>Δ(Δ²), ML (mm²)</th>
<th>Δt AP (s)</th>
<th>Δ(Δ²), AP (mm²)</th>
<th>Hₐ ML</th>
<th>Hₐ AP</th>
<th>Hₑ ML</th>
<th>Hₑ AP</th>
</tr>
</thead>
<tbody>
<tr>
<td>BUB PRE</td>
<td>4.01 ± 3.98</td>
<td>0.64 ± 0.21</td>
<td>4.44 ± 4.21</td>
<td>0.49 ± 0.01</td>
<td>0.17 ± 0.12</td>
<td>0.49 ± 0.02</td>
<td>0.18 ± 0.09</td>
</tr>
<tr>
<td>POST</td>
<td>4.42 ± 3.81</td>
<td>0.57 ± 0.17</td>
<td>3.13 ± 3.45</td>
<td>0.49 ± 0.00</td>
<td>0.12 ± 0.06</td>
<td>0.49 ± 0.01</td>
<td>0.20 ± 0.05</td>
</tr>
<tr>
<td>T = 27 (p &gt; 0.05)</td>
<td>T = 7 (p &lt; 0.05)</td>
<td>T = 5 (p &lt; 0.05)</td>
<td>T = 13 (p &gt; 0.05)</td>
<td>T = 23 (p &gt; 0.05)</td>
<td>T = 27 (p &gt; 0.05)</td>
<td>T = 21 (p &gt; 0.05)</td>
<td></td>
</tr>
<tr>
<td>BBB PRE</td>
<td>3.05 ± 2.59</td>
<td>0.55 ± 0.14</td>
<td>3.83 ± 3.17</td>
<td>0.45 ± 0.01</td>
<td>0.09 ± 0.06</td>
<td>0.45 ± 0.02</td>
<td>0.23 ± 0.07</td>
</tr>
<tr>
<td>POST</td>
<td>4.71 ± 5.06</td>
<td>0.65 ± 0.28</td>
<td>4.75 ± 3.78</td>
<td>0.45 ± 0.01</td>
<td>0.08 ± 0.06</td>
<td>0.45 ± 0.04</td>
<td>0.19 ± 0.11</td>
</tr>
<tr>
<td>T = 25 (p &gt; 0.05)</td>
<td>T = 16.5 (p &lt; 0.05)</td>
<td>T = 222 (p &gt; 0.05)</td>
<td>T = 31 (p &gt; 0.05)</td>
<td>T = 32 (p &gt; 0.05)</td>
<td>T = 19 (p &gt; 0.05)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>CP – CGv movements</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BUB PRE</td>
<td>2.12 ± 0.85</td>
<td></td>
<td>2.61 ± 1.04</td>
<td>0.84 ± 0.05</td>
<td>0.48 ± 0.01</td>
<td>0.85 ± 0.09</td>
<td>0.48 ± 0.01</td>
</tr>
<tr>
<td>POST</td>
<td>2.20 ± 0.79</td>
<td></td>
<td>2.4 ± 1.10</td>
<td>0.86 ± 0.03</td>
<td>0.48 ± 0.01</td>
<td>0.89 ± 0.08</td>
<td>0.48 ± 0.01</td>
</tr>
<tr>
<td>T = 29 (p &gt; 0.05)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>BBB PRE</td>
<td>2.41 ± 1.00</td>
<td></td>
<td>3.65 ± 0.97</td>
<td>0.83 ± 0.09</td>
<td>0.51 ± 0.02</td>
<td>0.87 ± 0.07</td>
<td>0.51 ± 0.01</td>
</tr>
<tr>
<td>POST</td>
<td>2.44 ± 0.92</td>
<td></td>
<td>3.71 ± 0.89</td>
<td>0.84 ± 0.09</td>
<td>0.51 ± 0.02</td>
<td>0.80 ± 0.17</td>
<td>0.51 ± 0.01</td>
</tr>
<tr>
<td>T = 22 (p &gt; 0.05)</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* BUB = bipedal–unipedal–bipedal; BBB = bipedal; CGv = center-of-gravity vertical projection; CP = center of pressure; fBm = fractional Brownian motion; AP = anteroposterior; ML = mediolateral; PRE = reference condition; POST = postexercise condition; Hₛ = short latency; Hₑ = long latency.

† In each case, the values obtained from PRE and POST conditions are compared, and the statistical results are given.

Note the statistically significant results from the fBm parameters (Δ(Δ²), Δt) along the AP axis for the BUB protocol.
Classical Analysis
The analysis of surface variances along the ML and AP axes and mean velocity of CG\(_v\) and CP\(_2\)CG\(_v\) movements showed no significant difference between PRE and POST conditions. In addition, no difference was noted in CG\(_v\) mean positions between the 2 experimental conditions (Table 1).

Fractional Brownian Motion Modeling
The variograms computed from the various trajectories display a slope inflexion or transition points intervening for a shorter time interval \(\Delta t\) in the POST condition compared to in the PRE condition. This is particularly true along the AP axis \((T = 7; \ p < 0.05)\), as illustrated in Figure 3. Moreover, the spatial coordinates of the transition point of the CG\(_v\) movements were also reduced along the same AP axis \((T = 5; \ p < 0.05)\).

On the contrary, no significant difference was observed for the transition points of CP\(_2\)CG\(_v\) and CG\(_v\) movements along the ML axis.

No significant difference was noted between PRE and POST conditions for the \(H\) values, indicating that the slopes of the line portions characterizing the shortest and longest \(\Delta t\), from which \(H_s\) and \(H_l\) were computed, respectively, were not affected by the experimental conditions (Table 1). In other words, the degree to which the various movements were controlled remained identical throughout the BUB protocol.

**DISCUSSION**
The main goal of this study was to investigate the short-term effects on 2-legged stance control resulting from the repetition of a simple postural exercise such as standing on 1 leg.

Our results outlined a lack of statistically significant results for the classical analysis (mean positions, surface, variances, and mean velocity), whereas the fBm demonstrates a modification in the control mechanisms called into play. The constant mean positions of the CG\(_v\) movements throughout the BUB protocol indicate that the postural changes observed cannot account for a body weight distribution asymmetry (15) or a leaning effect (24). The inability of the surface variances and mean velocity calculated from the CG\(_v\) and CP\(_2\)CG\(_v\) displacements to highlight postural changes can be mainly explained by the fact that the CP displacements along the ML and AP axes are involved in their computation and that various movements occurring around different joints (ankle and hip) determine CP displacements. In contrast, as emphasized by the fBm modeling, standing on each foot produces a decrease in both spatial and temporal coordinates \((\Delta x^2\) and \(\Delta t\), respectively) of the transition point along the AP axis for the CG\(_v\) movements. These results indicate that the distance covered by the CG\(_v\) and the time spent before the onset of a corrective process are less in the POST than in the PRE condition. These concomitant decreases underline the capacity of the central nervous system
to engage a motor correction more rapidly. Unfortunately for the subjects, these decreased thresholds observed along the AP axis are accompanied by a lessened control of the CG trajectories during the longest time intervals, explaining why no improvement was observed for the classical parameters in the end. Finally, the unchanged surfaces and spatial coordinates of the CP – CGG movements suggest that the muscular activity does not vary from before to after the 1-legged exercises, ruling out a possible relation between the level of muscular activity and the ability to better detect body movements.

The reasons for which postural control can be improved after a training period remain to be discussed. According to Ashton-Miller et al. (1), the improvement of the postural performance might largely be imputed to a better motor response, that is, greater efficiency in muscular function. In our case, this latter hypothesis seems improbable because of the short delay between the end of the exercise and the measurement. In addition, no real effect was found for the CP – CGG movements, which express the horizontal acceleration communicated to the CG and thus the global neuromuscular activity (23), nor from the scaling regimes $H_0$, which indicate the degree to which the CG movements are controlled over the longest time intervals.

To explain this behavior, one can suggest greater sensitivity in the sensory proprioceptive system. Indeed, because the subjects were tested with their eyes closed, a change in the tactile sensitivity cannot be suspected a priori, and because the vestibular thresholds are too low to be taken into account by a healthy subject in controlling undisturbed upright stance (14), only a change in the proprioceptive sensitivity could explain this modification. An alternative hypothesis could be a change in the integrative mechanisms, leading to a more powerful role of the proprioceptive inputs to the detriment of other sensory cues. This recalls the demonstration that repeated peripheral sensory stimulations can induce long-lasting local somatosensory remodeling (9).

From a physiological point of view, it could be assumed that an increased sensitivity of intrafusorial fibers or Golgi tendon organs in bipedal stance could result from the previous acute stimulation of these proprioceptive receptors during a single-leg exercise. Indeed, its has been shown that postural instability during 1-legged stance induces a muscular activity involving both plantar ankle flexors and extensors (i.e., gastrocnemius, soleus, and tibialis anterior muscles), whose activities are recognized as being much more important than during a 2-legged upright standing (as exemplified by the time an individual is able to stand on a single foot as compared to the almost infinite time on 2 legs). The increased sensitivity of the proprioceptive inputs could thus result from a stimulation of intrafusorial twitches. Indeed, it is well known that a coactivation of the $\alpha$ and $\gamma$ fibers occurs during muscular activation (32) such as those induced by postural sways (6). As compared to a 2-legged stance, 1 main feature of 1-legged stance is the necessity to exert double the reaction forces; therefore, one might expect the $\gamma$ fiber activity to be greatly enhanced, hence inducing an improved proprioceptive sensitivity. This hypothesis is in accordance with the results showing an improved knee position sense after an exercise (2) and is also closely akin to 2 recent studies (12,25). The first study suggests that the stimulation of cutaneous receptors of plantar vault through a massage could be at the origin of improved postural control. The second study emphasizes the positive effects upon the proprioceptive cues of a protocol based on a bilaterally prior stretching of the triceps surae muscles. All together, these behavioral effects suggest that, in the absence of visual cues, the postural control system could rely on both tactile and proprioceptive cues and that their stimulation is capable of enhancing the capacity of the postural control system to set corrective movements within a very short delay. It is likely that this improvement of proprioception should also be found in the ankle position sense.

Although postural effects can be positively viewed along the AP axis, as described above, the control along the ML axis is not modified by a 1-legged exercise. This axis dependency could stem from the biomechanical characteristics of the 1-legged task when compared to the 2-legged one. Posture control along the ML axis is indeed mainly based on the capacity of the subject to distribute his or her body weight constantly between the 2 legs (34). A minor contribution stems from the plantar reaction forces, which also seem to intervene in the CP trajectories along the ML axis (23). Conversely, the 1-legged posture control along the ML axis mostly relies on the invertor and evertor foot muscles (30). Moreover, it is worth noting that because of the characteristics of their fibers, the muscles involved in controlling the 1-legged stance along the ML axis are less physiologically prepared to perform this task, explaining the poorer postural performance in that case with the reduced base of support.

Things appear to be rather different when considering the AP axis, where the muscles involved in controlling both 1-legged and 2-legged tasks belong to the same physiological group. Interestingly, a positive and statistically significant correlation for the scaling regimes $H_0$ of the CP along this AP axis were found when comparing these 2 upright postures (5). This feature indicates that the more a subject is able to control the CP displacements along the AP axis on both feet, the more he will be able to do so on 1 foot and vice versa. In our case, the improvement of postural control observed along the AP axis in the POST condition could also be perceived as a simpler skill transfer between 1-legged and 2-legged postures given the similarity of the muscular groups involved along this axis.

To conclude, the present findings show that postural control of healthy adults, and more specifically their capacity to detect the AP body movements more rapidly (as seen from the decreased temporal coordinates of the variograms computed from CGG movements), can be enhanced with the repetition of a simple postural exercise such as standing repeatedly on a single leg. This capacity requires that no counterbalanced effect appear along the orthogonal ML axis and, as shown by fBm modeling, that the 2 other components involved in
postural performance (amplitudes of horizontal accelerations communicated to the CG and the ability to make the CG return unceasingly in a straightforward fashion toward a position where acceleration, and therefore muscular forces, would be minimized) would not be deteriorated at the same time (26).

**Practical Applications**

One may wonder whether these promising effects could be amplified over a longer period of time during which such exercises could be extensively repeated. We would respond affirmatively. Furthermore, it is also conceivable that the effects on a disabled patient might be amplified because his or her improvement potential, because of the deficiency, should be much larger. Consequently, showing that sway detection can be improved by an increased and prolonged muscular activation might have promising developments in the rehabilitation field. By showing that the somatosensory control of a movement can be easily improved, our data could also be of particular interest for the practitioner or the trainer. Many skills in sports and physical activity indeed require efficient control of one or several segments. This is particularly true for activities where a balance-control efficiency is a prerequisite for optimizing performance (e.g., shooting). Further investigations are nevertheless necessary to identify the nature and the duration of such an effect.

**References**


