Attentional demands and postural sway: the effect of the calf muscles fatigue

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ABSTRACT

VUILLERME, N., N. FORESTIER, and V. NOUGIER. Attentional demands and postural sway: the effect of the calf muscles fatigue. Med. Sci. Sports Exerc., Vol. 34, No. 12, pp. 1907–1912, 2002. Purpose: The purpose of the present experiment was to investigate whether the calf muscle fatigue affects postural sway in bipedal stance and requires additional attentional demands. Methods: Nine healthy university students had to respond as rapidly as possible to an unpredictable auditory stimulus while maintaining stable seated and upright postures with their eyes closed in two conditions of no-fatigue and fatigue of the calf muscles. Center of foot pressure (COP) displacements were recorded using a force platform. Reaction times (RTs) values were used as an index of the attentional demand necessary for regulating postural sway. Results: Fatigue yielded a significant anterior shift of mean position of the COP and increased range, mean speed, and dispersion of COP displacements. An increased attentional demand for regulating postural sway also was observed with fatigue. Conclusions: These results suggest that muscular fatigue may put the individuals at higher risk of falling, especially when engaging in concurrent tasks. Key Words: ATTENTION, BALANCE, ANKLE FATIGUE, HUMANS

The ability to maintain an upright stance is essential in gait and in the initiation of voluntary movements that are vital not only for sportive but also for daily living activities. Postural control requires accurate afferent inputs and efferent outputs from the joints and muscles that are involved (9). Under normal circumstances, it is believed that ankle proprioception is critical for the establishment of an internal reference, allowing the stabilization of the body with respect to an external gravitational reference (3). In fact, several authors have proposed that, during quiet standing, humans behave as an inverted pendulum (11) with the ankle response being sufficient to counteract minor perturbations occurring during normal stance. The muscular fatigue represents an inevitable phenomenon for physical and daily activities that the central nervous system has to take into account. This fatigue, defined as a decreased force-generating capacity (4), also modifies both the peripheral proprioceptive system and the central processing of proprioception (21). Muscle weakness has been shown to impair postural control (12,28), and a recent study has evidenced an alteration of the position sense at the ankle induced by muscular fatigue (6). Consequently, it seems reasonable to expect an increased postural sway after lower limbs muscular fatigue (13,17,26,29).

In recent years, a growing number of investigations have used dual-task paradigms to investigate the attentional demand of postural control (e.g., 1,2,8,15,16,19,22–24,30). In general, these studies have evidenced that even tasks considered automated and/or involving lower order operations required attentional resources. In addition, a decreased balance, caused either by injury (8), pathology (2,30), or aging (16,19,22,23) or induced by manipulating the difficulty of the postural task (1,15,16,30), or the availability of the sensory information (19,22–24) requires increased attentional demands necessary for regulating postural sway. It is surprising that there is an absence of data showing whether and how the attentional demand associated with postural control is modified with muscular fatigue.

The purpose of the present experiment was to investigate whether the calf muscle fatigue affects postural sway in bipedal stance and requires additional attentional demands. It was hypothesized that muscular fatigue increases postural sway. More important, we hypothesized that regulating postural sway requires more attentional resources in condition of muscular fatigue.

METHODS

Subjects

Nine healthy university students (mean age = 22.0 ± 3.1 yr; mean body weight = 69.0 ± 8.6 kg; mean height = 176.9 ± 7.6 cm) participated in the experiment. They were naïve as to the purpose of the study. They gave written consent to the experimental procedure as required by the
None of the subjects presented any history of motor problem, neurological disease, or vestibular impairment.

**Apparatus**

A force platform (AMTI model OR6-5-1; AMTI, Watertown, MA) was used to measure displacements of the center of foot pressure (COP). Signals from the force platform were sampled at 100 Hz (12-bit A/D conversion) and filtered with a second-order Butterworth filter (10 Hz).

For the secondary task, auditory stimuli (100 ms, 1000 Hz) were computer delivered randomly. Subjects gave their response by pressing a handheld button (500-Hz sampling frequency).

**Task and Procedures**

**Primary tasks.** Subjects were asked to perform two primary tasks: sitting and standing upright. For the sitting task, subjects were sitting normally with their back supported by the backrest of the chair. For the standing upright task, subjects stood barefoot on the force platform, feet together, with their eyes closed, and were asked to sway as little as possible. Foot position was standardized using perpendicular taped lines on the force platform to ensure a fixed position of the ankles. These two primary tasks were executed under two states of muscular fatigue. The no-fatigue condition served as a control session. Five trials for each posture were presented randomly. In the fatigue condition, the measurements were performed immediately after a fatiguing procedure. Five additional trials for each posture were executed randomly, for a total of 20 trials. The muscular fatigue in the calf muscles of the two legs was induced until maximal exhaustion by asking the subjects to stand as long as possible on the tiptoes, sustaining an isometric foot plantar flexion of the two legs (7,26). Loud, verbal encouragement was provided. The fatigue level was reached when subjects were no more able to maintain the posture on the toes. The recovery process after fatigue procedures is often considered as a limitation for all fatigue experiments. In the present study, to ensure that balance measurement in the seated position, for which no postural measures were taken, only served to establish a baseline RT value for each subject. However, a primary threat to the validity of the dual-task paradigm is attention switching or performance tradeoff on the primary task to increase performance in the secondary task. To ensure that the subjects did not neglect postural control in favor of attending to the auditory stimulus, the standing upright task was also performed without the performance of the RT task (five “baseline” trials for each condition of no-fatigue and fatigue).

**Secondary task.** While performing the postural task, subjects also performed a probe-reaction time (RT) task. The RT task consisted of responding as rapidly as possible to an unpredictable auditory stimulus by pressing a handheld button. This technique is central to several information-processing models proposing that the nervous system has a limited central capacity. It is assumed that performing a task requires a given portion of this capacity, and that if two tasks performed simultaneously require more than the total capacity, the performance of one or both tasks will be affected negatively (14,27). In the present experiment, subjects were asked to consider the postural task as the primary task. The RT task was the secondary task. For each trial (20 s), a maximum of five randomly presented auditory stimuli separated by at least 2 s could be presented. The number and timing of the stimuli delivered were similar for each condition. Within this procedure, the so-called dual-task paradigm, any change in RT presumably would reflect changes in the resources necessary for performing the postural task. Note that the seated position, for which no postural measures were taken, only served to establish a baseline RT value for each subject. However, a primary threat to the validity of the dual-task paradigm is attention switching or performance tradeoff on the primary task to increase performance in the secondary task. To ensure that the subjects did not neglect postural control in favor of attending to the auditory stimulus, the standing upright task was also performed without the performance of the RT task (five “baseline” trials for each condition of no-fatigue and fatigue).

**Data Analyses**

Four dependent variables were used to describe the subjects’ postural sway. The mean antero-posterior (AP) COP position (mm) and the mean medio-lateral (ML) COP position (mm) represent the average position of COP for AP and ML directions, respectively. The origin of the force platform coordinate system was translated such that it was aligned with the internal malleolus of the ankles. This procedure allowed the COP position to be expressed relative to the internal malleolus of the ankles. In a hypothetical situation in which COP does not experience any AP and ML sway, the mean AP and ML COP position would be zero. In addition, positive values for AP and ML mean position of COP indicate an anterior and a right mean position of the COP relative to the internal malleolus of the ankles, respectively. The range of COP displacements (mm) indicates the maximal deviation of the COP in any direction. It is a global measure that allows to estimate overall postural performance. The mean speed of COP displacements (mm·s⁻¹) is the sum of the displacement scalars (i.e., the cumulated distance over the sampling period) divided by the sampling time. It represents the amount of activity required to regulate postural sway and provides a more functional measure of postural control. Finally, a measure of sway derived from the density histograms of the sway path (10.25) was used to assess the dispersion of the COP. Specifically, density histograms give a qualitative description of the distribution of the postural sway. Distributions were quantified by calculating an average COP and the percentage of time the subjects spent in 12 arbitrarily defined concentric circles around the average COP in radial increments of 5 mm. Each of these areas was labeled from area 0–5 mm (closest to mean COP) to area 55–60 mm (farthest from mean COP). A wider or spreader sway behavior is thus indicated by a higher percentage of time spent away from the average COP.
RT (ms) served for determining the attentional demand associated with regulating postural sway. RT was defined as the temporal interval between the presentation of the auditory stimulus and the subjects’ responses (pressing the button).

Analyses of variance (ANOVA) was used for statistical comparisons of the different test conditions. Level of significance was set at 0.05. Post hoc analyses (Newman-Keuls) were used whenever necessary. Effect sizes ($\eta^2$) also were calculated.

RESULTS

COP displacements. Figure 1 illustrates representative COP displacements from a typical subject for the two conditions of no-fatigue (left panel) and fatigue (right panel).

Data obtained for the mean AP COP position, the mean ML COP position, the range and the speed of COP displacements were submitted to separate one-way ANOVAs (2 fatigues (no-fatigue vs fatigue)). Results are presented in Figure 2.

Analysis of the mean AP COP position showed a main effect of fatigue with a more anterior shift of the mean COP position in the fatigue than in the no-fatigue condition (53.93 ± 9.56 vs 44.54 ± 8.32 mm from the internal malleolus of the ankles, for the fatigue and no-fatigue conditions, respectively, $F$ (1,8) = 9.58, $P < 0.05$; $\eta^2 = 0.55$) (Fig. 2A).

Analysis of the mean ML COP position did not show any main effect of fatigue (6.63 ± 17.38 vs 3.71 ± 9.31 mm

from the internal malleolus of the ankles, for the fatigue and no-fatigue conditions, respectively, $F$ (1,8) = 0.35, $P > 0.05$; $\eta^2 = 0.04$ (Fig. 2B).

Analysis of the range of the COP displacements showed an effect of fatigue with larger range in the fatigue than in the no-fatigue condition (23.53 ± 9.05 vs 13.75 ± 5.80 mm, for the fatigue and no-fatigue conditions, respectively, $F$ (1,8) = 15.58, $P < 0.01$; $\eta^2 = 0.66$) (Fig. 2C).

Analysis of the mean speed of the COP displacements showed a main effect of fatigue with faster speed in the fatigue than in the no-fatigue condition (19.43 ± 5.76 vs 11.73 ± 2.86 mm·s$^{-1}$, for the fatigue and no-fatigue conditions, respectively, $F$ (1,8) = 21.93, $P < 0.01$; $\eta^2 = 0.73$) (Fig. 2D).

Data obtained for the dispersion of COP displacements were submitted to a 2 fatigues (no-fatigue vs fatigue) × 12 areas (0–5 vs . . . vs 55–60 mm) ANOVA with repeated measures on both factors. Results showed a significant interaction of fatigue × area ($F$ (11,88) = 11.31, $P < 0.001$; $\eta^2 = 0.90$). The ANOVA also confirmed the main effect of area ($F$ (11,88) = 72.74, $P < 0.001$; $\eta^2 = 0.59$). As illustrated in Figure 3, subjects spent less time in areas 0–5 and 5–10 mm, in the fatigue than in the no-fatigue condition (11.71 ± 5.69 vs 23.66 ± 8.26% and 24.86 ± 7.17 vs 34.85 ± 8.32% in areas 0–5 and 5–10 mm, for fatigue and no-fatigue, respectively, $Ps < 0.001$), whereas they spent
more time in areas 15–20 and 20–25 mm in fatigue than in the no-fatigue condition (15.46 ± 2.16 vs 10.06 ± 6.11% and 11.48 ± 4.36 vs 4.89 ± 4.54% in areas 15–20 and 20–25 mm, for the fatigue and no-fatigue conditions, respectively, Ps < 0.01). In other words, subjects contained their COP displacements within a larger area in the fatigue than in the no-fatigue condition.

**Attentional demands.** An important prerequisite of the dual-task paradigm consists of verifying that the addition of the RT task procedure does not affect the performance of the primary task. “Baseline” COP data (without RT task) were compared with experimental COP data (with RT task). For all postural sway measures and each condition of no-fatigue and fatigue, there was no effect of the introduction of the probe (Ps > 0.05). This suggests that subjects did not switch attention from the primary task to the secondary task during dual-task conditions and therefore validates the RT data as a valid index of the attentional demands required by the postural task.

RT data were submitted to a 2 postures (seated vs upright) × 2 fatigues (no-fatigue vs fatigue) ANOVA with repeated measures on both factors. Results showed a significant interaction of posture × fatigue (F(1,8) = 6.24, P < 0.05; η² = 0.44). As illustrated in Figure 4, subjects exhibited similar RT for the seated task in the two conditions of fatigue and no-fatigue (196 ± 14 vs 193 ± 13 ms for the fatigue and no-fatigue conditions, respectively, Ps > 0.05). In addition, RT increased for the upright standing task (P < 0.05 and P < 0.001, for the no-fatigue and fatigue conditions, respectively), but this effect was greater in the fatigue than in the no-fatigue condition (227 ± 14 vs 207 ± 14 ms, for the fatigue and no-fatigue conditions, respectively, P < 0.01). The ANOVA also confirmed main effects of posture (F(1,8) = 18.26, P < 0.01; η² = 0.70) and fatigue (F(1,8) = 7.56, P < 0.05; η² = 0.49).

**DISCUSSION**

The purpose of the present experiment was twofold: 1) investigate the effects of the calf muscles fatigue on postural sway in bipedal stance and 2) determine whether regulating postural sway with fatigue requires an additional attentional demand.

Regarding the first objective, our results showed that subjects sway more in the fatigue than in the no-fatigue condition as indexed by the increased range, mean speed, and dispersion of COP displacements with fatigue. These results are consistent with those of Johnston et al. (13), who showed that lower-limb muscular fatigue affects the ability to maintain balance on an unstable force platform and those of Lundin et al. (17), Vuillerme et al. (26), and Yaggie and McGregor (29), who observed an increased postural sway with fatigue during one-legged stance. In addition, these changes of sway variables were accompanied by a signifi-
Posture increases with fatigue, as indexed by the anterior limits of postural stability (20). Furthermore, if one agrees with the suggestion that “leaning too far or too fast can result in a situation where it is not possible to recover balance” (18), the observed change in COP data in the fatigue condition certainly brought the individuals closer to their stability limits that may increase the likelihood of falling and/or of injury. Empirical observations that injuries occur mostly after a period of intense physical exercise (e.g., 5), when individuals are fatigued, support this suggestion.

The second objective of the present experiment was to determine, using a dual-task paradigm, whether maintaining an upright posture with fatigue would require an additional attentional demands. In this dual-task paradigm, an individual performed the primary task (standing as immobile as possible in the two conditions of no-fatigue and fatigue), while simultaneously performing a secondary task (i.e., the RT task). The assumption of this paradigm is that the performance on the secondary task is inversely proportional to the attentional demands of the primary task. By showing longer RTs in upright than in the seated conditions, our results first confirmed that postural control is not fully automatic but still requires a portion of the attentional resources available (15,16,24,30). More important, our results also showed that the attentional demand for maintaining an upright posture increases with fatigue, as indexed by the increased RT with fatigue. If one thinks of postural control as a sensorimotor process, then fatigue affects both the sensory and the motor side of the process. It is likely that, with fatigue, attention could be required on the motor command side as well as the sensory side. On the motor side, attention would help to compensate for the decreased force-generating capacity induced by fatigue in the postural muscles (e.g., 4). In addition, with regard to the hypothesis of an impairment of proprioceptive information induced by muscular fatigue (6), these results are in line with those by Redfern et al. (19) and Teasdale et al. (24). When the reliability of proprioceptive information was reduced, either by standing on a sway-referenced floor (19) or on a compliant foam surface (24), an increased attentional demand associated with maintaining a stable standing position was observed. Similarly, Courtemanche et al. (2) also demonstrated that a reduced peripheral sensibility caused by diabetic neuropathy increases the attentional demand necessary for regulating gait. More largely, with regard to the postural instability induced by muscular fatigue (13,17,26,29), our results are consistent with the assumption that the dependency on attentional processes is even more apparent when the difficulty of the postural tasks increases (1,15,16,24,30).

In summary, the present findings show that even a well-learned task such as maintaining an unperturbed upright posture is affected by the calf muscles fatigue. Together with the increased attentional demand observed for the postural task, muscular fatigue may put the individuals at higher risk of falling, especially when engaging in concurrent tasks. Finally, it could be interesting to investigate the effects of muscular fatigue on balance in people showing less accurate postural capacities (e.g., elderly persons) for whom the consequences of an impaired postural control could be more dramatic. It could be also of great interest to investigate ergonomic situations in which the workload and fatigue may predispose the workers to an increased risk of accident and injury.

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REFERENCES