Degraded postural performance after muscle fatigue can be compensated by skin stimulation

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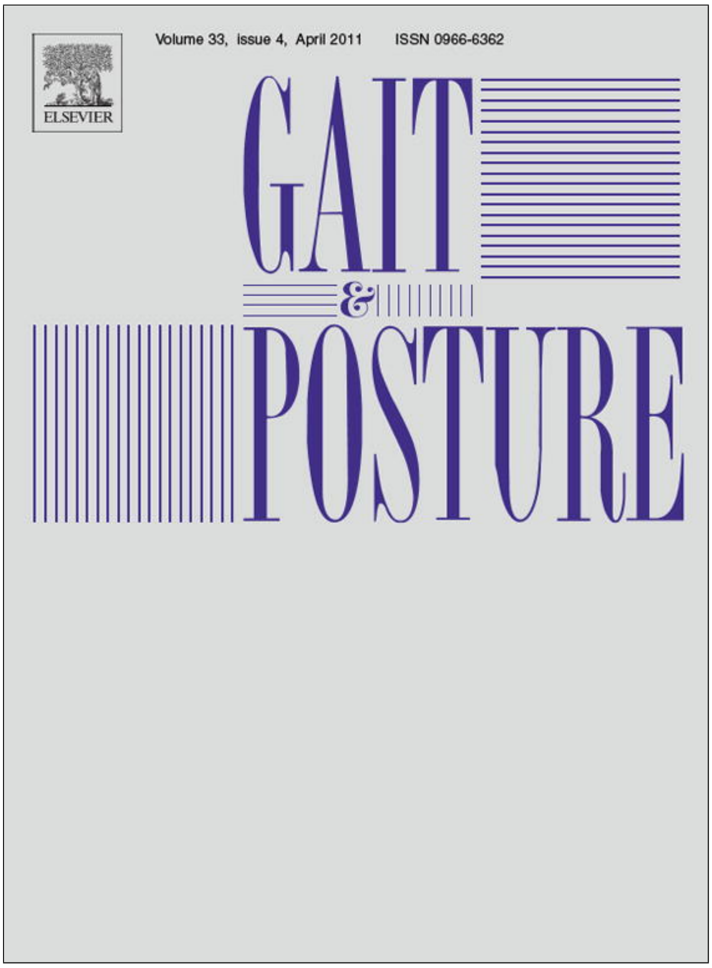
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Degraded postural performance after muscle fatigue can be compensated by skin stimulation

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ABSTRACT

It has been shown that the ability of humans to maintain a quiet standing posture is degraded after fatigue of the muscles at the ankle. Yet, it has also been shown that skin stimulation at the ankle could improve postural performance. In the present study, we addressed the issue of the interaction of these two effects. Subjects were tested with the eyes closed in four conditions of quiet stance: with or without skin stimulation and before and after a fatigue protocol. The skin was stimulated with a piece of medical adhesive tape on the Achilles' tendon. The fatigue protocol consisted of multiple sets of ankle plantar flexion of both legs on stool. Without fatigue, we did not observe a significant effect of the tape. With fatigue, subjects decreased their postural performance significantly, but this effect was cancelled out when a piece of tape was glued on the Achilles' tendon. This indicated that the beneficial effect of the tape was unveiled by the degraded postural performance after fatigue. We conclude that, when the muscular sensory input flow normally relevant for the postural system is impaired due to fatigue, the weight of cutaneous information increases for the successful representation of movements in space to adjust postural control.

1. Introduction

Postural performance in quiet standing is dependent on sensory input flow [1]: degradation of visual [2,3], vestibular [4] or proprioceptive [2–7] input flow systematically results in more postural sway. Tendinous vibration [7], ischemia bloc [5], anesthesia [6], muscle fatigue [2,8–11] or foam under the feet [12] results in the same effects: on the one hand, the accuracy of the proprioceptive information is lowered [9,11,13–15] and, on the other hand, postural performance is lowered [2,5,7,8,10]. These combined changes suggest that body oscillations are indeed useful for controlling upright standing. Increasing body sway seems to be a functional strategy to force the generation of information flow about body stability. Stated differently, humans need to sway to perceive the equilibrium status of their bipedal posture. In accordance with this suggestion, Bringoux et al. [16] showed that without sways humans are unable to perceive body tilt.

Studies using light-touch have shown an improvement of postural performance in the elderly, diabetic and even young subjects [12,17,18]: the digit touching an external object such as a table resulted in a systematic drop in postural oscillations. The interpretation of this robust empirical result is manifold. First, it is now accepted that postural sways are controlled to facilitate the supra-postural performance [1]. As a consequence, it might be that the lower postural sway in light-touch condition is the result of a different postural control, where the posture is enslaved to the supra-postural task. A second interpretation is that the added cutaneous stimulation could compensate for the sensory deficit of muscle spindle and facilitate the detection of postural sway. In this case, skin stimulation provides the central nervous system (CNS) with a more relevant sensory inflow that in turn can lead to better movement detection [14,21], more accurate joint position sense [22] or better postural performance [15,23]. Finally, it can be raised out that the digit touching an external object (such as a table) provides an exocentric frame of reference. For instance postural performance is better when the cutaneous stimulation is distant to the ankle joint [19,20]. As quiet standing can be considered an inverted pendulum with the ankle joint as the axis of rotation, it is rather consistent that the farther the support point from the pivot point of the pendulum, the lower the postural sways.

Several external devices have been shown to positively influence postural stability. On the one hand, sports medicine studies used braces or bandages at the ankle to stimulate cutaneous sensory information and to reinforce proprioceptive inflow [15,23]. Yet, as underlined by Bennell et al. [24], brace and bandage have probably also reduced the capacity of subjects to sway by a restriction of degrees of freedom. On the other hand, skin stimulation by an adhesive tape was demonstrated to be an

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important sensory input to conscious movement perception and to help the CNS in localisation of which joint is in movement [13]. A tape applied in a plane perpendicular to the axis of joint movement was found to improve movement detection [14,21] and precision [22]. Because skin movement is restricted under the adhesive tape, skin stretch is enhanced in the tape periphery, and this probably allows for an easier reaching of the cutaneous discharge threshold [21].

Following this logic, the present study wants to evaluate the effect of skin stimulation on the stability of quiet standing using an experimental design without supra-postural task and without direct external spatial referential. Moreover, to enhance the sensitivity of our protocol, we used muscular fatigue as a means to negatively influence postural stability. If skin stimulation brings additional sensory input flow, postural performance should be improved, and this effect might be even stronger when muscle function is altered by fatigue.

2. Methods

2.1. Subjects

Eight healthy young subjects (7 males and 1 female, age: 22.8 ± 2.0 years, height: 175.8 ± 8.6 cm, body weight: 71.0 ± 8.4 kg) volunteered to participate in the study and gave informed, written consent prior to the experiments. None of the subjects reported recent lower extremity injury or a history of chronic ankle injuries in the last six months. The study was approved by the local ethics committee and complied with the Declaration of Helsinki for human experimentation.

2.2. Experimental protocol

Before the experimental session, each subject performed a familiarisation session to get used to the equipment and procedures. A few days later, subjects performed one 90 min session in a quiet room at a temperature of 20.5 ± 0.5 °C. Subjects were tested in two randomised conditions of quiet stance: with or without skin stimulation, before and after a fatigue protocol. Before the fatigue protocol, 8 trials were realized, 4 with and 4 without tape. After the fatigue protocol, 4 trials were performed, 2 with and 2 without tape (Fig. 1). Before each post-fatigue trial, we verified that the subject was still unable to perform more than 50% of maximal voluntary repetition (MVR) of ankle flexors of both legs.

A quiet stance trial lasted for 51.2 s and subjects had 30 s of rest between each trial. During stance acquisition, subjects were standing on a balance platform with their eyes closed. All subjects wore shorts to avoid skin stimulation on legs, with the same socks (not covering the ankles) and without shoes. The position of the feet was standardized: the feet were oriented at an angle of 15° from the sagittal midline, with the heels 4 cm apart. Subjects' arms were relaxed alongside of their body. Subjects were instructed to find a comfortable position and to minimize the amplitude of their postural sway. Data acquisition began when subjects were ready.

2.3. Fatigue protocol

The fatiguing protocol consisted of multiple sets of ankle plantar flexion of both legs (Fig. 2). A first series of plantar flexion was realized to evaluate the MVR for each subject. Next, subjects were requested to perform the maximal number of series at 75% of MVR with one flexion by second. Between each series, a rest period equal to the duration of exercise was observed. When subjects were unable to perform more than 50% of MVR in the same time compared to the first series, the exercise was stopped.

During the fatigue protocol, subjects stood on a footstool with their forefeet on it (heels in space) and could touch the wall with their hands to avoid falling. Subject's forefeet coincided with the edge of the footstool. During the down phase it was asked to the subjects to go below the level of the footstool to increase eccentric muscle activity. To control that subject realized the same amplitude at each plantar flexion (up on one's tiptoe), two markers were positioned for the high and low positions of the heel (Fig. 2).

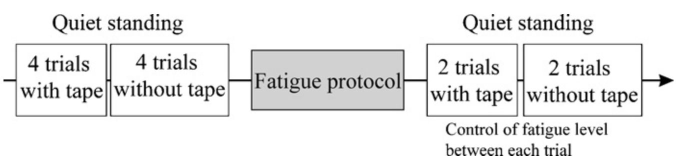

Fig. 1. Illustration of the whole experimental protocol for one subject.

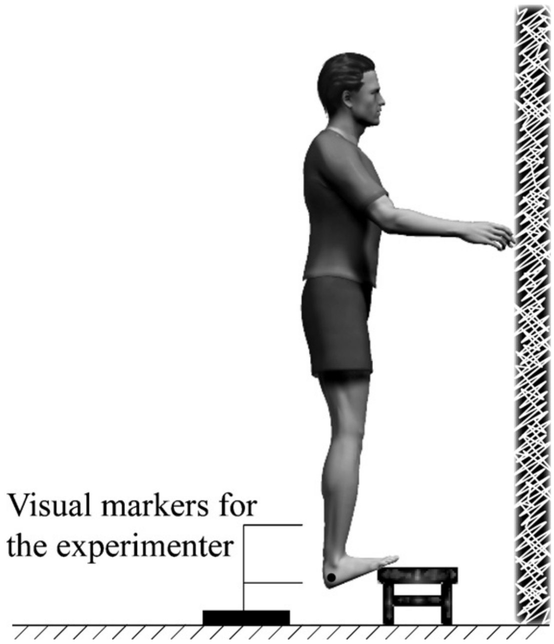

Fig. 2. The fatigue protocol consisted of a series of plantar flexion with controlled timing and amplitude. Visual markers were used to check the amplitude of the ankle movement.

2.4. Apparatus

Postural performance was evaluated with the help of a balance platform (Médicapteurs®, Toulouse, France) sampled at a frequency of 40 Hz. The center of pressure (CoP) was recorded by dedicated software (Win-posturo version 1.6, Balma, France). The following characteristics of postural performance were calculated from the CoP data: sway area, sway path length, mean velocity, and the antero-posterior (A-P) and medio-lateral (M-L) path length.

2.5. Skin stimulation

Skin stimulation was obtained with medical adhesive tape (3 M^{TM} Transpore^{TM}, 3 M, USA) glued directly on the skin. As shown in Fig. 3, a piece of tape measuring 10 cm by 2.5 cm was applied on both Achilles' tendon in the longitudinal direction from the calcaneus's tuberosity. A new piece of adhesive tape was applied before each trial of quiet stance.

2.6. Statistical analyses

The data were analyzed using Statistica software (StatSoft France 2006, STATISTICA, version 7.1, France). Each measured variable was tested for normality using the Shapiro–Wilk test and the Levene test for equality of variance. To test the

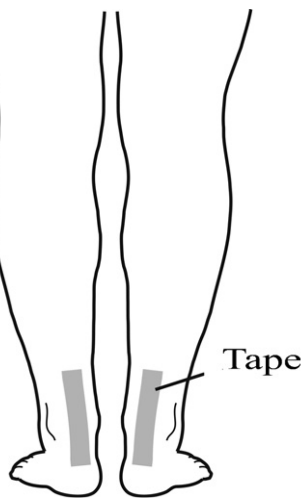

Fig. 3. Location of the adhesive tape on the Achilles' tendon.

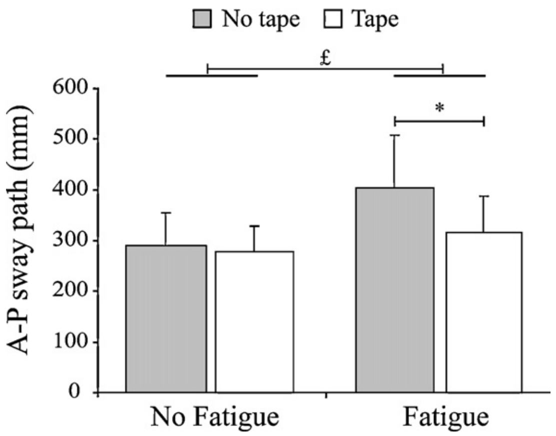

Fig. 4. Mean values for the path length of the antero-posterior (A-P) sway as a function of ankle muscle fatigue and of the presence of an adhesive tape on the Achilles' tendon. Ankle muscle fatigue globally increases postural sway ($p < 0.05$, £ symbol). Yet, this increase is cancelled out when a tape is glued on the Achilles' tendon ($p < 0.05$, * symbol).

assumption of normality and equality of variance, parametric test were performed. The effects of fatigue and tape on the CoP variables were analyzed by a two-way analysis of variance (with or without fatigue × with or without skin stimulus). When useful, HSD Tukey *post hoc* test was applied for multiple pairwise comparisons. Statistical treatment included effect size assessment by calculating partial eta-squared (η^2). The threshold for significance was taken at a p value of 0.05. In the figures, mean values are given with standard deviation (SD).

3. Results

A significant interaction between fatigue and tape was observed for: mean velocity ($F(1,7) = 9.41$, $p < .05$, $\eta^2 = 0.57$), total path length ($F(1,7) = 8.31$, $p < .05$, $\eta^2 = 0.54$), M-L path length ($F(1,7) = 13.27$, $p < .05$, $\eta^2 = 0.65$) and A-P path length ($F(1,7) = 5.70$, $p < .05$, $\eta^2 = 0.44$), expect for sway area ($p = 0.06$). Post hoc analysis showed that the effect of the adhesive tape was significant in the fatigued condition only (example for general pattern: Fig. 4). More precisely, the tape applied on the Achilles' tendons did not significantly influence the postural performance in the no-fatigue condition (mean velocity $p = 0.28$; total path length, $p = 0.19$; M-L path length, $p = 0.47$; A-P path length, $p = 0.12$; sway area, $p = 0.94$).

4. Discussion

In the present study, we evaluated the effect of skin stimulation on postural performance in a situation without supra-postural task and without direct external spatial reference. By adding an adhesive tape on the skin in the Achilles' tendon region, we found that this cutaneous stimulation had no effect on the postural performance before fatigue, but was significantly efficient for counteracting the degraded postural performance when the ankle extensor muscles were fatigued.

After muscle fatigue, the contribution of muscle spindles to the proprioceptive input flow is diminished as it was revealed by a decrease in proprioceptive acuity evaluated by joint position sense [9] or by the ability to detect joint movement (low back muscle [11]). With increasing muscle fatigue, muscle spindle information became less accurate. As a consequence, subjects use a compensatory mechanism, which is necessary when the information from a sensory channel is blurred or suppressed [2–7]: more postural sways generate more important sensory input flow. In the present study, total sway path length, mean velocity, M-L path length and A-P path length increased significantly with fatigue occurrence (+59.3%, +56.1%, +39% and +71.42%, respectively compared to the non-fatigued condition). Similar results have been already observed in various fatigue protocols, yet with a lower magnitude [2,8,10]. For example, the mean sway velocity was reported to increase by 27% after a strenuous run on treadmill [8] and by 20% after repeated plantar flexion of both legs [2]. Similarly, the total sway path increased by up to 45% after an ironman triathlon [10] and by 27% after concentric ankle plantar flexion and dorsiflexion on isokinetic dynamometer [23]. The reason for the higher magnitude of the postural effect in the present study is likely due to a higher degree of muscle fatigue compared to other studies [2,8,10,23]. Moreover, our fatigue protocol relied on severe eccentric muscle contraction when moving the body downward. Eccentric muscle contraction is known to induce higher drop in proprioceptive acuity than concentric contraction, when a similar decrease in muscle force is regarded [9]. Further, it has been proposed that the mechanism for the reduction in muscle spindle input involves a reflex inhibition of fusimotor neurones by small muscle afferents excited by the metabolic by-products due to the exercise and damage to muscle fibers [25]. Noteworthy, all subjects in the present experiment reported severe delayed onset muscle soreness and some subjects encountered walking difficulties 48 h after the protocol.

In the non-fatigued conditions, when the tape was applied on the Achilles' tendon, we found that subjects did not sway less (Fig. 4).

First, this lack of significant effect is an important result when put into perspective with the classical interpretation of a beneficial effect of added skin information when a finger is used for a light touch on a surface [8,10,12,19,20]. Such light-touch conditions differ from the conditions in the present experiment: for postural stabilisation, the light-touch imposes both an external spatial frame of reference [29] and an adaptation of postural movements to perform supra-postural task with accuracy [1]. For instance, cutaneous information contributes to control the pressure between the finger and the fixed element (e.g., table, button). In the present experiment, skin stimulation was applied on the Achilles' tendon and the task was postural only. Hence, the tape could not provide an exocentric frame of reference and the tape could not induce a supra-postural task. As light-touch experiments always provided an exocentric reference and/or induce a supra-postural task, our work suggests that the postural stabilisation effect in the light-touch conditions mainly stem from the stable reference provided at the fingertip and the consequent redefinition of the task in terms of supra-postural constraints.

Second, this lack of significant effect of the adhesive tape in the non-fatigued condition is somewhat unexpected because we know that a piece of tape applied close to a joint can improve the detection of low velocity movements [14,21] and, more generally, joint position sense accuracy [22]. The fact that this did not happen in the present experiment indicates that the tape-enhanced cutaneous input flow was not used for the control of body sway in this experimental condition. While cutaneous receptors have a good sensibility to movement [28], muscle spindles respond more rapidly than cutaneous receptors [26]. So, it seems plausible that the redundant, but delayed, cutaneous inflow did not contribute much to the improvement of postural performance. In the non-fatigued condition, a higher weight is given to the faster muscle input flow, which contributes strongly to the control of quiet standing [3].

In the fatigued conditions, when the tape was applied on the Achilles' tendon, we found that the postural performance was significantly improved (Fig. 4). What mechanism(s) can account for such a result? Because muscle spindles and cutaneous input are able to provide similar information to the CNS [26], we argue that the tape induced a cutaneous flow of information that the CNS used to compensate for the less usable muscular information after fatigue. There is converging evidence that, to resolve multisensory redundancy, the CNS has to weight the sensory information from each channel as a function of its relevance to the context [27]. In the situation of muscle fatigue, the output of the muscle spindle is less relevant [9,11], so the weight given to cutaneous information could increase and thereby contribute to a better representation of movements in space to adjust postural control.

To conclude, in the present contribution, we showed that an adhesive tape that is adequately placed on the skin can provide sensory information that compensate for the less accurate muscular proprioception after fatigue. The positive results that we obtained with young and healthy subjects could justify further investigations, to better understand how cutaneous stimulation could allow for enhancing postural and, maybe, dynamic movement control. It might be that wearing elastic socks with well designed adhesives parts would help delaying the onset of the perceptual effects of fatigue on posture and movement control. Finally, it is noteworthy that the results in the present study also suggest a new and simple approach towards restoring postural performance in case of lower limb sensory deficits. This would call for further investigations to precisely evaluate if systems designed after the present experiment could be beneficial for postural stability of, for example, an elderly population that is known for a decrease in proprioceptive acuity [30] and a daily adaptation to this deficit.

Conflict of interest statement

The authors want to declare no conflict of interest.

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