Eur J Appl Physiol (2010) 110:207–213
DOI 10.1007/s00421-010-1449-z

SHORT COMMUNICATION

Changes in the relative contribution of each leg to the control of quiet two-legged stance following unilateral plantar–flexor muscles fatigue

Nicolas Vuillerme · Matthieu Boisgontier

Accepted: 18 March 2010 / Published online: 14 April 2010
© Springer-Verlag 2010

Abstract We used unilateral plantar–flexor muscles fatigue to assess the capacity of the central nervous system to adapt quiet two-legged stance control to a unilateral ankle neuromuscular perturbation. Eighteen young healthy adults stood barefoot with their eyes closed and were asked to sway as little as possible. The Experimental group ($n = 9$) executed this postural task in two conditions, before (pre-test) and following the completion of a fatiguing exercise designed to induce a muscular fatigue in the plantar–flexor muscles of their dominant leg (post-test). For the Control group ($n = 9$), this fatiguing exercise was replaced with a standing rest period corresponding to the fatiguing exercise. Results of the Experimental group showed no significant difference between the weight-bearing index measured in the pre-test condition and that observed in the post-test condition. Results further revealed that unilateral plantar–flexor muscles fatigue yielded different effects on the centre of foot pressure (CoP) displacements under the non-fatigued leg and under the fatigued leg: a wider surface area of the CoP displacements was observed under the non-fatigued than under the fatigued leg, and a higher mean speed of the CoP displacements was observed under the non-fatigued leg only in the post-test relative to the pre-test condition. These findings evidenced that the contribution of each leg to the control of quiet two-legged stance is modified as a result of muscle fatigue of unilateral plantar–flexor muscles. The greater contribution of the non-fatigued leg could be viewed as a fatigue-induced adaptive change in the control of quiet two-legged stance in response to an alteration of the unilateral ankle neuromuscular function induced by unilateral plantar–flexor muscles fatigue.

Keywords Adaptation · Balance · Muscle fatigue · Ankle · Centre of foot pressure · Unilateral · Humans

Communicated by Susan Ward.

N. Vuillerme (✉) · M. Boisgontier
Laboratoire TIMC-IMAG, Faculté de Médecine,
Equipes AFIRM/AGIM3/SPM, UMR UJF CNRS 5525,
38706 La Tronche Cedex, France
e-mail: nicolas.vuillerme@imag.fr

Introduction

Localised muscle fatigue, known to hamper sensorimotor system function (e.g. Enoka and Duchateau 2008; Taylor et al. 2000), has been proven to provide a relevant experimental framework to investigate the capacity of the central nervous system (CNS) to adapt postural and motor behaviours to transient neuromuscular perturbation acting on the individual (e.g. see Côté et al. 2002; Fuller et al. 2009; Missenard et al. 2009; Schmid et al. 2006; Vuillerme et al. 2002b). For instance, when localised to plantar–flexor muscles of both lower limbs, muscle fatigue has successfully been used to increase our knowledge about the sensory re-weighting mechanisms involved in the control of quiet two-legged stance. Indeed, (1) a decreased reliance on proprioceptive cues from the ankles (Ledin et al. 2004; Vuillerme et al. 2002a)—degraded by the fatiguing exercise (Vuillerme et al. 2007; Vuillerme and Boisgontier 2008, 2009)—and (2) an increased reliance on vision (Ledin et al. 2004; Vuillerme et al. 2006), cutaneous inputs from the foot and shank (Vuillerme and Demetz 2007), vestibular and neck somatosensory inputs (Pinsault and Vuillerme 2008) and haptic cues from the finger (Vuillerme and Nougier 2003)—providing more reliable sensory information—have been reported. While the above-mentioned studies have evidenced the capacity of the CNS to dynamically and selectively adjust the relative contributions of sensory inputs ("sensory weights") to maintain bipedal upright stance under condition of *bilateral* plantar–flexor muscles fatigue, very little is known about the capacity of the CNS to adapt quiet two-legged stance control to an *unilateral* plantar–flexor muscles fatigue (Lin et al. 2009). Therein lies the purpose of the present study. From a fundamental perspective in the neurosciences area, separate analyses of plantar centre of foot pressure (CoP) displacements under the non-fatigued leg and under the fatigued leg should gain insight into the possible adaptive changes in their relative contribution to bipedal postural control following unilateral ankle neuromuscular perturbation. Understanding of bipedal postural control adaptation to unilateral neuromuscular alteration at the ankle is also important to provide valuable insight into various clinical concerns associated with patients suffering from lateralised unilateral impairment at the ankle.

Experimental procedures

Subjects

Eighteen healthy young male adults voluntarily participated in this study. Subjects were randomly distributed in two groups: (1) Control (9 subjects, age 26.2 ± 1.4 years; body weight 77.3 ± 7.0 kg; height 179.4 ± 8.7 cm; mean ± SD) and (2) Experimental (9 subjects, age 25.1 ± 2.9 years; body weight 74.9 ± 10.1 kg; height 180.1 ± 7.7 cm).

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 injury, surgery or pathology to either lower extremity that could affect their ability to perform the experiment.

Note that this study involved healthy young males insofar as the age and sex of the participants previously have been shown to influence the ability to perform repeated one-leg heel-rise test of ankle plantar flexors used in the present experiment (see "Postural task") (Jan et al. 2005).

Study design

The Experimental group executed a static postural task in two experimental conditions, before (pre-test) and following the completion of a fatiguing exercise designed to induce a muscular fatigue in the plantar–flexor muscles of their dominant leg (post-test). For the Control group, this fatiguing exercise was replaced with a standing rest period corresponding to the fatiguing exercise.

Postural task

Eyes closed, subjects stood barefoot, the medial sides of their feet touching each other, their hands hanging at the sides, on a plantar pressure data acquisition system (Force Sensitive Applications (FSA) Orthotest Mat, Vista Medical Ltd.). This pressure mat (sensing area 350 × 350 mm = 122,500 mm^2) contains a 32 × 32 grid of piezo resistive sensors (sensors number 1024; sensors dimensions 3.94 × 3.94 mm; space between sensors 2.7 mm; 0.84 sensor/cm^2). It allows the magnitude of pressure exerted on each left and right foot sole at each sensor location to be transduced into the calculation of the positions of the plantar CoP under the left and right foot, respectively (10-Hz sampling frequency). Subjects' task was to sway as little as possible; postural measurements included three 30-s trials (Pinsault and Vuillerme 2009).

Fatiguing exercise

The fatiguing procedure was designed to induce a muscular fatigue in the plantar–flexor muscles of the dominant leg.

To identify the dominant leg, subjects were asked their preference for kicking a ball (e.g. Gribble and Hertel 2004). As previously done in other studies (e.g. Springer and Pincivero 2009; Vuillerme et al. 2007; Vuillerme and Boisgontier 2008, 2009), subjects performed monopodal standing heel rise test. They were instructed to stand straight and to rise and lower on the balls of their dominant foot 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 exercise (157 s on average). Immediately on the cessation of exercise, the subjective exertion level was assessed through the Borg CR-10 scale (Borg 1990). Subjects rated their perceived fatigue in the plantar–flexor muscles as almost "extremely strong" (mean Borg ratings of 8.6 ± 1.0). To ensure that measurements in the fatigue condition were obtained in a real fatigued state, i.e. to limit recovery effect, various rules were respected (e.g. Ledin et al. 2004; Pinsault and Vuillerme 2008; Vuillerme and Nougier 2003; Vuillerme et al. 2006; Vuillerme and Demetz 2007). (1) The fatiguing exercise took place beside the experimental set-up to minimise the time between the end of the exercise and the balance measurements (30 s), (2) the fatiguing exercise was repeated prior to each postural trial and (3) the examiner checked that the subjects showed visible signs of fatigue and failed to perform the exercises due to fatigue. In doubtful cases, the examiner encouraged the subject to continue with a few more exercises. Note that we used the repeated single-leg standing heel-rise test to the point of volitional failure insofar as this exercise has previously demonstrated to induce EMG signs of fatigue in the plantar–flexor muscles (Österberg et al. 1998; Svantesson et al. 1998a, b) and to impair joint position sense (Vuillerme et al. 2007) and force sense at the ankle (Vuillerme and Boisgontier 2008, 2009) of the fatigued leg.

Data analysis

Three dependant variables were used to describe subject's postural behaviour:

1. the weight-bearing index, the ratio of body weight put on the non-dominant or non-fatigued leg divided by body weight put on the dominant or fatigued leg, as a measure of symmetry in body weight distribution;
2. the surface area covered by the trajectory of the CoP separately computed under the non-dominant or non-fatigued leg and under the dominant or fatigued leg, as a measure of the CoP spatial variability;
3. the mean speed of the CoP displacements separately computed under the non-dominant or non-fatigued leg and under the dominant or fatigued leg, constituting a good index of the amount of activity.

Statistical analysis

The means of the three postural measurements recorded in the No fatigue condition and between the three postural measurements recorded in the Fatigue condition were used for statistical analyses. A Kolmogorov–Smirnov test of equality of variances first showed that the distributions used for the analysis did not depart from normality ($P > 0.05$).

For each Control and Experimental group, data obtained for the weight-bearing index were submitted to a one-way analysis of variance (ANOVA). Two Conditions (pre-test vs. post-test) and data obtained for the surface area covered by the trajectory of the CoP and the mean speed of the CoP displacements separately computed under the non-dominant or non-fatigued leg and under the dominant or fatigued leg were submitted to separate two Conditions (pre-test vs. post-test) × 2 Legs (non-dominant or non-fatigued vs. dominant or fatigued) ANOVAs with repeated measures on both factors.

Post-hoc analyses (LSD test) were performed whenever necessary. Level of significance was set at 0.05.

Results

Control group

Analysis of the weight-bearing index did not show any main effect of Condition [$F(1,8) = 0.13$, $P > 0.05$].

Analysis of the surface area covered by the trajectory of the CoP separately computed under each leg did neither show any main effects of Condition [$F(1,8) = 0.03$, $P > 0.05$] and Leg [$F(1,8) = 0.05$, $P > 0.05$] nor significant interaction Condition × Leg [$F(1,8) = 0.00$, $P > 0.05$].

Analysis of the mean speed of the CoP displacements separately computed under each leg did neither show any main effect of Condition [$F(1,8) = 0.01$, $P > 0.05$] and Leg [$F(1,8) = 1.37$, $P > 0.05$] nor significant interaction Condition × Leg [$F(1,8) = 0.03$, $P > 0.05$].

Experimental group

Analysis of the weight-bearing index did not show any main effect of Condition [$F(1,8) = 0.45$, $P > 0.05$; Fig. 1].

Analysis of the surface area covered by the trajectory of the CoP separately computed under each leg showed main effects of Condition [$F(1,8) = 8.23$, $P < 0.05$] and Leg [$F(1,8) = 5.87$, $P < 0.05$], and a significant interaction Condition × Leg [$F(1,8) = 10.84$, $P < 0.05$]. As illustrated in Fig. 2, the decomposition of this interaction into its main effects indicated that:

1. The post-test condition yielded an increased CoP surface area relative to the pre-test condition under the dominant fatigued leg ($P < 0.05$), and this effect was more accentuated under the non-dominant non-fatigued leg ($P < 0.001$).
2. The post-test condition yielded an increased CoP surface area under the non-fatigued leg relative to the fatigued leg ($P < 0.001$), whereas no significant difference between the CoP surface area measured under the non-dominant leg and that measured under the dominant leg was observed in the pre-test condition ($P > 0.05$).

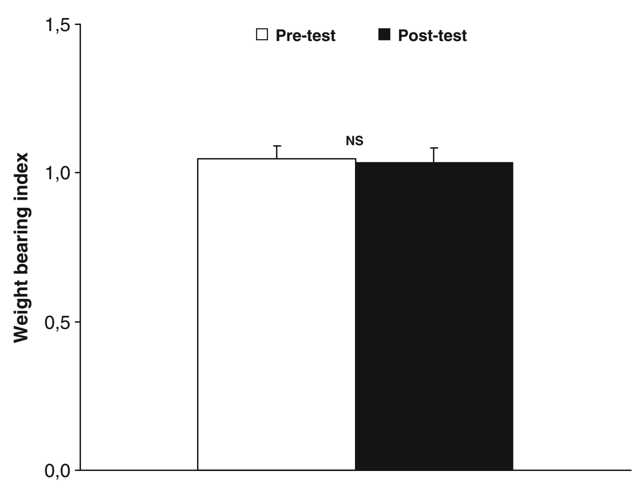

Fig. 1 Mean and standard error of mean of the weight-bearing index obtained in the two pre-test and post-test experimental conditions (*NS* not significant; $P > 0.05$)

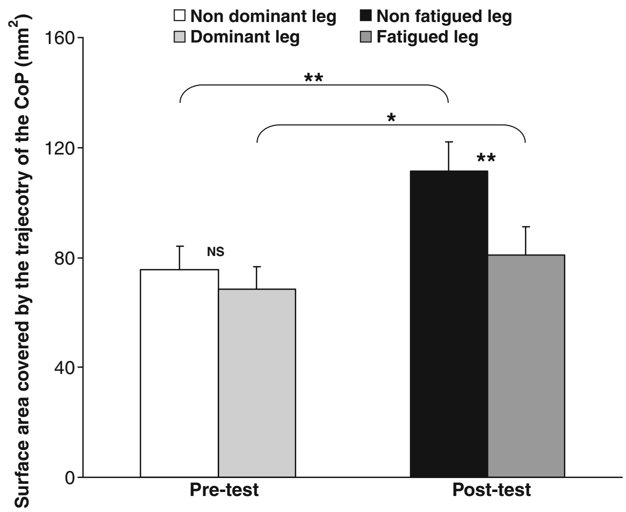

Fig. 2 Mean and standard error of mean of the surface area covered by the trajectory of the centre of foot pressure (CoP) obtained under the non-dominant or non-fatigued leg and under the dominant or fatigued leg in the two pre-test and post-test experimental conditions (*NS* not significant; $P > 0.05$; $^{*}P < 0.05$; $^{***}P < 0.001$)

Analysis of the mean speed of the CoP displacements separately computed under each leg showed a significant interaction Condition × Leg [$F(1,8) = 5.33$, $P < 0.05$]. As illustrated in Fig. 3, the decomposition of this interaction into its main effects indicated that:

1. The post-test condition yielded an increased mean speed of the CoP under the non-fatigued leg surface area relative to the pre-test condition ($P < 0.01$), whereas no significant difference was observed under the fatigued leg ($P > 0.05$).
2. The post-test condition yielded an increased mean speed of the CoP under the non-fatigued leg relative to the fatigued leg ($P < 0.05$), whereas no significant difference between the mean speed of the CoP measured under the non-dominant leg and that measured under the dominant leg was observed in the pre-test condition ($P > 0.05$).

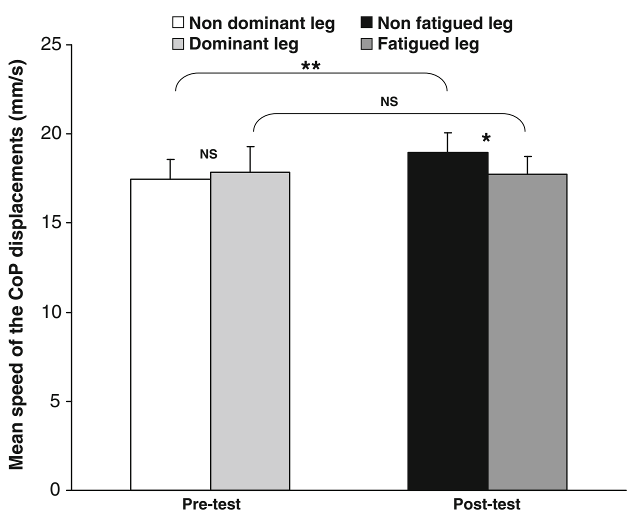

Fig. 3 Mean and standard error of mean of the mean speed of the centre of foot pressure (CoP) displacements obtained under the non-dominant or non-fatigued leg and under the dominant or fatigued leg in the two pre-test and post-test experimental conditions (*NS* not significant; $P > 0.05$; $^{*}P < 0.05$)

Discussion

In the present study, we used unilateral plantar–flexor muscles fatigue to assess the capacity of the CNS to adapt to a lateralised neuromuscular perturbation at the ankle for controlling quiet two-legged stance.

Before presenting the results of the Experimental group, it is important first to point out that no statistically significant differences in the weight-bearing index, the surface area covered by the trajectory of the CoP and the mean speed of the CoP displacements were observed for the Control group ($P > 0.05$), ruling out the possibility that the results observed in the Experimental group to be confounded by a possible learning effect or order-related effect. It is also important to mention that the postural task we used was executed in the absence of visual information since vision has previously been reported to mitigate the destabilising effect induced by plantar–flexor muscles fatigue on postural control during bipedal quiet standing (e.g. Ledin et al. 2004; Vuillerme et al. 2006). The eyes-closed condition thus avoided visual information interfering with the induced postural behaviours and allowed to evaluate the specific effect of unilateral plantar–flexor muscles fatigue on the control of quiet two-legged stance.

The main finding of this study is that the contribution of each leg to the control of quiet two-legged stance is modified as a result of muscle fatigue of unilateral plantar–flexor muscles. Indeed, the observation of significant interactions Condition × Leg observed for the surface area covered by the trajectory of the CoP (Fig. 2) and for the mean speed of the CoP displacements (Fig. 3) indicated that unilateral plantar–flexor muscle fatigue induced different effects on the CoP displacements under the non-fatigued leg and under the fatigued leg, yielding (1) a wider surface area of the CoP displacements under the non-fatigued than under the fatigued leg and (2) a higher mean speed of the CoP displacements under the non-fatigued leg only, respectively.

What could be the possible reasons leading to these observations? At least, two non-exclusive hypotheses could be formulated to account for the present set of data.

Based on recent studies evidencing that asymmetric weight-bearing per se could modify the regulation of the CoP displacements under each leg (e.g. Genthon and Rougier 2005; Anker et al. 2008), a first hypothesis suggests that the induction of unilateral plantar–flexor muscles fatigue may have influenced the ability to control the CoP under each leg via a biomechanical effect of an asymmetrical body weight distribution. However, the observation of an absence of difference between the weight-bearing index measured in the No fatigue condition and that measured in the Fatigue condition (Fig. 1) leads us to exclude this first hypothesis.

According to a second hypothesis, the observed asymmetry in the patterns of plantar CoP displacements under both non-fatigued and fatigued legs (Figs. 1, 2) could be viewed as a fatigue-induced adaptive change in the control of bipedal posture in response to an unilateral alteration of the neuromuscular system at the ankle joint. In condition of impaired sensori-motor function of the plantar–flexor muscles of the dominant leg caused by the performance of the repeated one-leg heel-rise to the point of volitional failure test used in the present study (Svantesson et al. 1998a, b; Vuillerme et al. 2007; Vuillerme and Boisgontier 2008, 2009), it would seem appropriate for the CNS to 'rely more' on the non-fatigued leg to control two-legged stance. Considering the mean speed of CoP displacements as an indicator of the amount of regulatory activity necessary to maintain the postural stability characterised by body oscillations (e.g. Maki et al. 1990; Prieto et al. 1996), the observation of an increased mean speed of the CoP displacements under the non-fatigued leg in the Fatigue condition relative to the No fatigue condition is in line with this assumption. Precisely, as proposed by several authors, increasing the mean speed of the CoP displacements under the non-fatigued leg could hence reflect an enhanced exploratory "testing of the ground" movements with sensors of the non-fatigued leg's foot (Ehrenfried et al. 2003; Hlavackova et al. 2009; Riccio et al. 1992; Riley et al. 1997a, b) aimed at providing supplementary somatosensory inputs to the CNS, and a robust efferent compensatory mechanism to generate posture stabilising ankle moments aimed at compensating for the inability of the fatigued leg to control bipedal posture efficiently (Anker et al. 2008; De Haart et al. 2004; Geurts et al. 1992). Interestingly, a similar postural response to *unilateral* neuromuscular perturbation has been reported in two recent studies in which young healthy adults were asked to control their bipedal posture after the completion of a fatiguing exercise consisting in repeating until maximal exhaustion (1) series of hip abductions (Vuillerme et al. 2009) and (2) series of ten toe-lifts, with full extended knee, immediately followed by ten knee flexion with one leg (Berger et al. 2009). In the latter study, however, the imposed fatiguing exercise was associated with muscles soreness in the fatigued muscle group [pain scoring of subjective pain superior to 6 on a 10-level scale—from no pain (0) to extremely sore muscle (10)]. It is thus possible that unilateral muscle pain per se could have affected the change in the relative contribution of each leg to the control of quiet two-legged stance. We are currently performing an experiment to address this issue.

More largely, such an asymmetry in the patterns of plantar CoP displacements under both legs has been previously reported in condition of *absent* ankle musculature. Indeed, unilateral transtibial amputees have been shown to exhibit larger CoP displacements under their intact leg than under their amputated leg (Isakov et al. 1992; Nadollek et al. 2002; Quai et al. 2005) during quiet two-legged stance control. From a clinical point of view, this postural behaviour has been proposed to reflect an adaptation to the loss of the lower leg afferents and efferents because of the unilateral lower-limb amputation (e.g. Duclos et al. 2007, 2009).

In conclusion, the present findings provided further information regarding whether and how the CNS could adapt quiet two-legged stance control to a unilateral ankle neuromuscular perturbation. The increased contribution of the non-fatigued leg to the control of quiet two-legged stance observed in the post-test condition relative to the pre-test condition could be viewed as a fatigue-induced adaptive change in response to an alteration of the unilateral ankle neuromuscular function induced by unilateral plantar–flexor muscles fatigue. In addition to static balance assessment, future research should now involve the investigation of more ecological, dynamic and/or functional tasks. Along these lines, whether and how the CNS is able to cope with unilateral muscle fatigue of the plantar–flexors during gait control is currently being investigated. Finally, complementary to their relevance in the field of neuroscience, we further believe that the present findings could have implications from a clinical perspective for the development of balance assessment and rehabilitation protocols for patients suffering from unilateral neuromuscular impairment at the ankle. Along these lines, a clinical study examining the relative contribution of each leg to the control of two-legged stance in subjects with unilateral chronic ankle instability is included in our immediate plans.

Acknowledgments The authors would like thank subject volunteers and the anonymous reviewers for helpful comments and suggestions. Special thanks also are extended to C. Hoxinel for various contributions. Results of a pilot study of this research have been presented at the XIII Congrès de l'Association Posture-Équilibre, Marseille (France), 8–10 Dec 2006. This manuscript has been presented in abstract form at the XVI Congrès de l'Association Posture-Équilibre, Lille (France), 13–14 Nov 2009.

References

Anker LC, Weerdesteyn V, van Nes IJ, Nienhuis B, Straatman H, Geurts AC (2008) The relation between postural stability and weight distribution in healthy subjects. Gait Posture 27:471–477

Berger LL, Regueme SC, Forestier N (2009) Unilateral lower limb muscle fatigue induces bilateral effects on undisturbed stance and muscle EMG activities. J Electromyogr Kinesiol. doi: 10.1016/j.jelekin.2009.09.006

Borg G (1990) Psychological scaling with applications in physical work and the perception of exertion. Scand J Work Environ Health 16:55–58

Côté JN, Mathieu PA, Levin MF, Feldman AG (2002) Movement reorganization to compensate for fatigue during sawing. Exp Brain Res 146:394–398

De Haart M, Geurts AC, Huidekoper SC, Fasotti L, van Limbeek J (2004) Recovery of standing balance in postacute stroke patients: a rehabilitation cohort study. Arch Phys Med Rehabil 85:886–895

Duclos C, Roll R, Kavounoudias A, Roll JP, Forget R (2007) Vibration-induced post-effects: a means to improve postural asymmetry in lower leg amputees? Gait Posture 26:595–602

Duclos C, Roll R, Kavounoudias A, Mongeau JP, Roll JP, Forget R (2009) Postural changes after sustained neck muscle contraction in persons with a lower leg amputation. J Electromyogr Kinesiol 19:e214–e222

Ehrenfried T, Guerraz M, Thilo KV, Yardley L, Gresty MA (2003) Posture and mental task performance when viewing a moving visual field. Brain Res Cogn Brain Res 17:140–153

Enoka RM, Duchateau J (2008) Muscle fatigue: what, why and how it influences muscle function. J Physiol 586:11–23 Review

Fuller JR, Lomond KV, Fung J, Côté JN (2009) Posture-movement changes following repetitive motion-induced shoulder muscle fatigue. J Electromyogr Kinesiol 19:1043–1052

Genthon N, Rougier P (2005) Influence of an asymmetrical body weight distribution on the control of undisturbed upright stance. J Biomech 38:2037–2049

Geurts AC, Mulder TW, Nienhuis B, Rijken RA (1992) Postural reorganization following lower limb amputation. Possible motor and sensory determinants of recovery. Scand J Rehabil Med 24:83–90

Gribble PA, Hertel J (2004) Effect of hip and ankle muscle fatigue on unipedal postural control. J Electromyogr Kinesiol 14:641–644

Hlavackova P, Fristios J, Cuisinier R, Pinsault N, Janura M, Vuillerme N (2009) Effects of mirror feedback on upright stance control in elderly trans-femoral amputees. Arch Phys Med Rehabil 90:1960–1963

Isakov E, Mizrahi J, Ring H, Susak Z, Hakim N (1992) Standing sway and weight-bearing distribution in people with below-knee amputations. Arch Phys Med Rehabil 73:174–178

Jan MH, Chai HM, Lin YF, Lin JC, Tsai LY, Ou YC, Lin DH (2005) Effects of age and sex on the results of an ankle plantar-flexor manual muscle test. Phys Ther 85:1078–1084

Ledin T, Fransson PA, Magnusson M (2004) Effects of postural disturbances with fatigued triceps surae muscles or with 20% additional body weight. Gait Posture 19:184–193

Lin D, Nussbaum MA, Seol H, Singh NB, Madigan ML, Wojcik LA (2009) Acute effects of localized muscle fatigue on postural control and patterns of recovery during upright stance: influence of fatigue location and age. Eur J Appl Physiol 106:425–434

Maki BE, Holliday PJ, Fernie GR (1990) Aging and postural control. A comparison of spontaneous- and induced-sway balance tests. J Am Geriatr Soc 38:1–9

Missenard O, Mottet D, Perrey S (2009) Adaptation of motor behavior to preserve task success in the presence of muscle fatigue. Neuroscience 161:773–786

Nadollek H, Brauer S, Isles R (2002) Outcomes after trans-tibial amputation: the relationship between quiet stance ability, strength of hip abductor muscles and gait. Physiother Res Int 7:203–214

Österberg U, Svantesson U, Takahashi H, Grimby G (1998) Torque, work and EMG development in a heel-rise test. Clin Biomech 13:344–350

Pinsault N, Vuillerme N (2008) Differential postural effects of plantar-flexor muscle fatigue under normal, altered and improved vestibular and neck somatosensory conditions. Exp Brain Res 191:99–107

Pinsault N, Vuillerme N (2009) Test-retest reliability of centre of foot pressure measures to assess postural control during unperturbed stance. Med Eng Phys 31:276–286

Prieto TE, Myklebust JB, Hoffmann RG, Lovett EG, Myklebust BM (1996) Measures of postural steadiness: differences between healthy young and elderly adults. IEEE Trans Biomed Eng 43:956–966

Quai TM, Brauer SG, Nitz JC (2005) Somatosensation, circulation and stance balance in elderly dysvascular transtibial amputees. Clin Rehabil 19:668–676

Riccio GE, Martin EJ, Stoffregen TA (1992) The role of balance dynamics in the active perception of orientation. J Exp Psychol Hum Percept Perform 18:624–644

Riley MA, Mitra S, Stoffregen TA, Turvey MT (1997a) Influences of body lean and vision on postural fluctuations in stance. Mot Control 1:229–246

Riley MA, Wong S, Mitra S, Turvey MT (1997b) Common effects of touch and vision on postural parameters. Exp Brain Res 117:165–170

Schmid M, Schieppati M, Pozzo T (2006) Effect of fatigue on the precision of a whole-body pointing task. Neuroscience 139:909–920

Springer BK, Pincivero DM (2009) The effects of localized muscle and whole-body fatigue on single-leg balance between healthy men and women. Gait Posture 30:50–54

Svantesson U, Österberg U, Thomeé R, Grimby G (1998a) Muscle fatigue in a standing heel-rise test. Scand J Rehabil Med 30:67–72

Svantesson U, Österberg U, Thomeé R, Peeters M, Grimby G (1998b) Fatigue during repeated eccentric-concentric and pure concentric muscle actions of the plantar flexors. Clin Biomech 13:336–343

Taylor JL, Butler JE, Gandevia SC (2000) Changes in muscle afferents, motoneurons and motor drive during muscle fatigue. Eur J Appl Physiol 83:106–115

Vuillerme N, Boisgontier M (2008) Muscle fatigue degrades force sense at the ankle joint. Gait Posture 28:521–524

Vuillerme N, Boisgontier M (2009) Effectiveness of a tongue-placed electrotactile biofeedback to improve ankle force sense following plantar-flexor muscles fatigue. Gait Posture 30:556–559

Vuillerme N, Demetz S (2007) Do ankle foot orthoses modify postural control during bipedal quiet standing following a localized fatigue at the ankle muscles? Int J Sports Med 28:243–246

Vuillerme N, Nougier V (2003) Effect of light finger touch on postural sway after lower-limb muscular fatigue. Arch Phys Med Rehabil 84:1560–1563

Vuillerme N, Danion F, Forestier N, Nougier V (2002a) Postural sway under muscle vibration and muscle fatigue in humans. Neurosci Lett 333:131–135

Vuillerme N, Nougier V, Teasdale N (2002b) Effects of lower limbs muscular fatigue on anticipatory postural adjustments during arm motions in humans. J Sports Med Phys Fit 42:289–294

Vuillerme N, Burdet C, Isableu B, Demetz S (2006) The magnitude of the effect of calf muscles fatigue on postural control during bipedal quiet standing with vision depends on the eye-visual target distance. Gait Posture 24:169–172

Vuillerme N, Boisgontier M, Chenu O, Demongeot J, Payan Y (2007) Tongue-placed tactile biofeedback suppresses the deleterious effects of muscle fatigue on joint position sense at the ankle. Exp Brain Res 183:235–240

Vuillerme N, Sporbert C, Pinsault N (2009) Postural adaptation to unilateral hip muscle fatigue during human bipedal standing. Gait Posture 30:122–125