ORIGINAL ARTICLE

Effects of knee and ankle muscle fatigue on postural control in the unipedal stance

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Abstract The aim of this study was to compare the effects of acute muscle fatigue of the ankle and knee musculature on postural control by immediate measures after performing fatiguing tasks (POST condition). One group of subjects ($n = 8$) performed a fatiguing task by voluntary contractions of the triceps surae (group TRI) and the other ($n = 9$) performed a fatiguing task by voluntary contractions of the quadriceps femoris (group QUA). Each muscle group was exercised until the loss of maximal voluntary contraction torque reached 50% (isokinetic dynamometer). Posture was assessed by measuring the centre of foot pressure (COP) with a force platform during a test of unipedal quiet standing posture with eyes closed. Initially (in PRE condition), the mean COP velocity was not significantly different between group TRI and group QUA. In POST condition, the mean COP velocity increased more in group QUA than in group TRI. The postural control was more impaired by knee muscle fatigue than by ankle muscle fatigue.

Keywords Fatigue · Postural control · Plantar flexor muscles · Knee extensor muscles

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Introduction

Fatigue reduces the ability of a muscle to generate force or power. According to Gandevia (2001), the failure to maintain the initial maximal force depends on peripheral fatigue occurring distal to the point of nerve stimulation (failure at the neuromuscular junction and beyond) and on central fatigue resulting from a failure to activate the muscle voluntarily (failure to drive motoneurons). Peripheral and/or central muscle fatigue induced by metabolic and/or neurologic changes also impairs neuromuscular control (Enoka and Stuart 1992). Aspects of neuromuscular control may be quantified through measures of postural control (Gribble and Hertel 2004a). Indeed, muscle fatigue induced by exercises strongly soliciting energy metabolism (e.g. running, cycling, walking, triathlon, ironman triathlon and biathlon shooting) negatively influences postural stability and elicits changes in the behavior of motor units and/or central drive characteristics (Lepers et al. 1997; Nardone et al. 1997, 1998; Derave et al. 1998, 2002; Gauchard et al. 2002; Nagy et al. 2004; Vuillerme and Hintzy 2007). These exhausting physical activities deteriorate sensory proprioceptive and exteroceptive information and/or their integration and/or also decrease the muscular system efficiency (Lepers et al. 1997; Nardone et al. 1997; Gauchard et al. 2002; Nagy et al. 2004).

Moreover, fatigue induced by simple segmental movements strongly soliciting postural tonic muscles (i.e. ankle plantar flexors and dorsiflexors, ankle invertors and evertors, knee extensors, hip flexor–extensors, hip abductor–adductors, lumbar erector spinae or neck muscles) affects postural control (Gribble and Hertel 2004a, b; Gribble et al. 2004; Yaggie and McGregor 2002; Vuillerme et al. 2002; Corbeil et al. 2003; Caron 2003; Johnston et al. 1998; Harkins et al. 2005; Gosselin et al. 2004; Salavati et al. 2007).

However, some experiments have not produced evidence of impairments of postural control after fatiguing exercises are applied on ankle plantar flexors (Adlerton and Moritz 1996) and ankle evertors and invertors (Gribble and Hertel 2004a). Other authors reported that for a given muscle group (e.g. ankle musculature), the postural stability disturbance proportionally varied according to the amplitude of strength loss (Harkins et al. 2005). Hence, one can, therefore, wonder if postural stability is more disturbed by the fatigue of certain muscles than by that of others when the proportional strength loss is comparable between the various muscles tested. Some studies have already been conducted to answer this question. Fatigue of hip musculature led to postural control impairment, while fatigue of ankle musculature did not impair postural control (Gribble and Hertel 2004a). Salavati et al. (2007) observed that the fatigue of ankle musculature impaired postural control more than the fatigue of hip musculature. Miller and Bird (1976) reported that fatigue of knee and hip flexors and extensors affected postural performance more than that of ankle plantar flexor and dorsiflexor muscles. These authors, however, measured dynamic balance by stabilization times, without using a force platform which would have produced other information on postural behaviours. Gribble and Hertel (2004b) moreover observed that fatigue of different hip, knee and ankle muscles impaired postural control in identical ways in the sagittal plane, but the impairment was larger for hip and knee musculature fatigue than for ankle musculature fatigue in the frontal plane. Dickin and Doan (2008) did not observe any difference between the fatigue effects of knee musculature and ankle musculature in impairments of postural control. More recently, Bellew and Fenter (2006) have showed that with older women postural stability (the length of time a subject could remain standing on the dominant limb with eyes closed) could decrease after fatigue of ankle musculature, but not after fatigue of knee musculature. These studies do not present a real consensus. Therefore, the aim of this study was to compare the effects of acute fatigue of the ankle and knee musculature resulting from an equal degree of strength loss on postural control.

Methods

Protocol

The experiment was designed to compare the postural disturbance induced by two different fatiguing exercises. Two groups of subjects participated, the first performed a fatiguing task by voluntary muscle contractions of the triceps surae (group TRI) and the second performed a fatiguing task by voluntary muscle contractions of the quadriceps femoris (group QUA). Postural control in both groups was evaluated before (pre-fatigue or PRE) and immediately after (post-fatigue or POST) the completion of the two muscle exercises.

Subjects

Seventeen healthy male students in sport sciences, who had been free of any known balance disorder and/or neuro-musculoskeletal impairments in the last 2 years, volunteered for the experiment. Only males were selected to avoid a possible sex effect on the postural measures (e.g. linked to body mass index, anthropometric distributions). During the 6 months before the study, none of the subjects had any ankle, knee or hip injury. They avoided strenuous activity before the data collection session and gave their informed consent to participate in the experiment in accordance with the declaration of Helsinki. The subjects were randomized into two groups (Group TRI, $n = 8$; Group QUA, $n = 9$). The subjects' morphological characteristics showed no difference between the two groups (Table 1).

Apparatus

A PostureWin force platform with three strain gauges (Techno Concept, Cereste, France) was used to sample the displacements of the centre of foot pressure (COP) at 40 Hz.

An isokinetic dynamometer (Biodex^{TM}, System 3 Pro, Shirley, USA) was used to exhaust the plantar flexor and knee extensor muscles.

Procedure

Postural control was analyzed before (pre-fatigue or PRE) and immediately after (post-fatigue or POST) the fatiguing task. The subjects were asked to stand for 25 s on the platform barefooted as immobile as possible on one leg. When the subjects had a dominant right leg for kicking a ball, then the left leg was the supporting leg (and inversely when the subjects had a dominant left leg). The foot was placed according to precise land-marks with respect to the X and Y axis of the platform. The other foot was lifted so that the

Table 1 Comparison of the subjects' morphological characteristics between the two groups (one-factor ANOVA)

	Group TRI ($n = 8$)	Group QUA ($n = 9$)
Age (years)	21.1 ± 1.2	26.2 ± 3.7
Height (cm)	174.8 ± 8.4	176.3 ± 3.7
Weight (kg)	74.7 ± 7.6	75.8 ± 8.0
BMI (kg m^{-2})	24.45 ± 1.3	24.39 ± 1.7

None of the inter-group differences were significant (values are means ± SD)

BMI body mass index

subject's big toe touched the medial malleolus of the supporting leg. The closed eyes condition (subjects were asked to close their eyes) was chosen in order to prevent vision from interfering with the induced postural behaviours.

After the first completion of the postural control test, standardized warm-up and familiarization exercises were performed before the performing of fatiguing tasks. Before starting the tests, the subjects performed a warm-up for 15 min on a cycle ergometer. Then, the isometric strength (the same leg evaluated on the force platform) was measured on the isokinetic dynamometer. The subjects of both groups were placed in a sitting position with a 90° hip flexion. The subjects of group TRI were placed with a 90° shank/foot flexion and a 45° thigh/shank flexion (0° = thigh/leg aligned) and performed isometric contractions with the plantar flexors. The subjects of group QUA were placed with a 90° knee flexion and performed isometric contractions with the knee extensors. Stabilisation straps were positioned across the subject's chest and pelvis. The arms were crossed on the chest. The subjects of both groups performed three isometric maximal contractions that lasted 5 s. A duration of 30 s separated each contraction. The best performance (peak torque in N.m) was retained. After a 2-min rest period, the subjects began the fatigue protocol. Maximal isometric plantar flexions (group TRI) or knee extensions (Group QUA) lasted 5 s, each contraction being separated by a 2-s rest. These plantar flexions or knee extensions continued until the torque output for both muscle groups dropped below 50% of the measured peak torque for three consecutive contractions (Yaggie and McGregor 2002; Gribble and Hertel 2004a). At the end of the fatiguing task, the subjects were removed from the dynamometer and began postural control post-testing as quickly as possible. The force platform was positioned at 3 m from the isokinetic dynamometer. The time from the end of the fatiguing task to the initiation of postural control measure in POST condition was less than 30 s (from 25 to 30 s).

Data analysis

COP signals were smoothed using a fourth-order zero-lag Butterworth filter with a 6-Hz low-pass cut-off frequency (Eklund and Lofstedt 1970; Cherng et al. 2003) before computing the mean COP velocity (mm s^{-1}). The mean COP velocity (sum of the cumulated COP displacement divided by the total time) in both the antero/posterior (AP) and the medio/lateral (ML) planes of movement characterizes the postural control of the subjects (Geurts et al. 1993).

Statistical analysis

The number of contractions performed during the fatiguing tasks was compared between the two groups using a one-factor ANOVA. Postural data was analyzed using a two-factor ANOVA. The analysis studied the effects of the group factor (TRI vs. QUA) and the condition factor (two levels with repeated measures: PRE and POST). The PRE and POST conditions were compared as a within-subject variable. When significant treatment effects occurred, Newman–Keuls post hoc was used to test the difference among means. The P value was determined a priori at $P \leq 0.05$.

Results

Initially (in PRE condition), the mean COP velocity in both the AP and ML directions was not significantly different between the two groups (Figs. 1, 2).

In PRE condition, the isometric maximal strength was significantly different between triceps surae and quadriceps
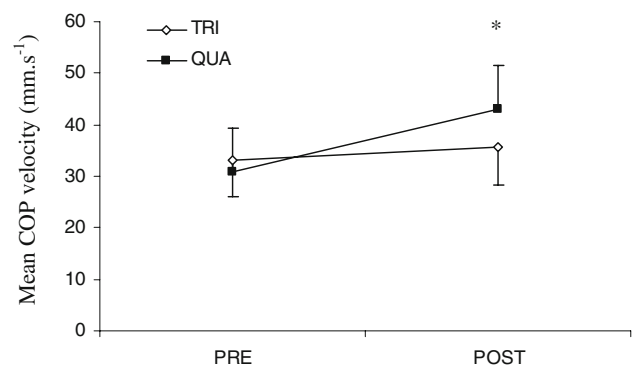

Fig. 1 Mean values and standard deviations of COP velocity in the medio/lateral (ML) plane for the two groups (*TRI* voluntary muscle contractions of triceps surae, *QUA* voluntary muscle contractions of quadriceps femoris) in two conditions (*PRE* pre-fatigue condition, *POST* immediate post-fatigue condition). * Indicates a significant group × condition interaction ($P < 0.05$)
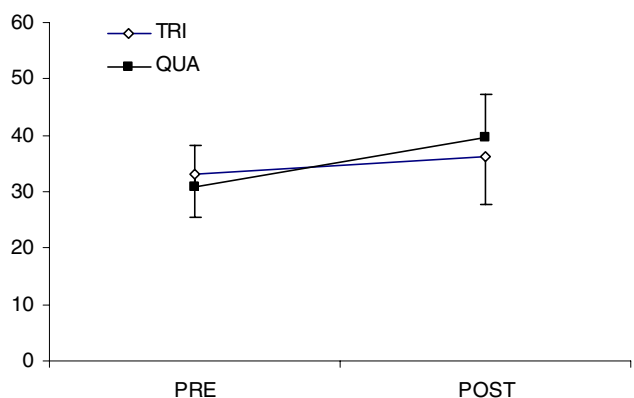

Fig. 2 Mean values and standard deviations of COP velocity in the antero/posterior (AP) plane for the two groups (*TRI* voluntary muscle contractions of triceps surae, *QUA* voluntary muscle contractions of quadriceps femoris) in two conditions (*PRE* pre-fatigue condition, *POST* immediate post-fatigue condition)

femoris (Group TRI: 127 ± 23 N.m; Group QUA: 266 ± 37 N.m; $F = 60.06$, $P < 0.001$).

In order to reach 50% decrement of the measured peak torque for three consecutive contractions, group TRI performed 54 ± 13 maximal voluntary contractions and group QUA performed 32 ± 7 maximal voluntary contractions. The number of contractions was significantly different between group QUA and group TRI ($F = 19.14$, $P < 0.001$).

In POST condition, concerning the mean COP velocity in the ML direction, the condition factor was significant ($F = 4.14$; $P < 0.05$) (Fig. 1). Moreover, the statistical analysis showed a significant group × condition interaction ($F = 7.03$; $P < 0.01$). The mean COP velocity in the ML direction increased more in group QUA than in group TRI after performing the fatigue protocol (Fig. 1). As regards the mean COP velocity in the AP direction, the condition factor and the group × condition interaction were not significant (Fig. 2).

Discussion

In this investigation, postural control was examined before (PRE) and immediately after (POST) a fatiguing task of knee extensors or ankle plantar flexors. In POST condition, the mean COP velocity in the ML direction had increased more in the QUA group than in the TRI group. This suggests that quadriceps muscle fatigue produces a greater deficit in postural control in the ML direction than calf muscle fatigue. Several anatomical and mechanical and/or physiological factors could explain this phenomenon.

In relation to the anatomical and mechanical factors, two reasons could be proposed to explain the differences between the effects of knee musculature fatigue and the effects of ankle musculature fatigue on postural control. First, the fact that the mean COP velocity increased more in group QUA than in group TRI only in the ML direction would mean that the ankle musculature fatigue induced the use of other muscles to compensate for the impairment of postural control, which would not occur when the knee musculature is fatigued. The mediolateral stabilizers of the ankle (ankle invertors and evertors) may have assumed a more important role in maintaining postural control when the anterior–posterior stabilizers of the ankle were fatigued (Harkins et al. 2005) whereas the fatigue of knee extensors (anterior–posterior stabilizers) may not be compensated for since the knee has no specific stabilizer muscles to prevent its movements in frontal plane. This would explain why the postural control was significantly disturbed only in the ML direction and not in the AP direction. Second, proximal musculature fatigue could affect postural control more than distal musculature fatigue (Gribble and Hertel 2004a, b; Harkins et al. 2005). Indeed, distal musculature fatigue

could induce the recruitment of other proximal musculature which is not possible when fatigue is localized at the proximal musculature level. From this postulate, Harkins et al. (2005) suggested that in young subjects balance strategies may have changed—from ankle strategy to hip strategy—when the fatigue is localized at the ankle musculature level, whereas one might suppose that when the fatigue is localized at the knee musculature level, this change of strategy may become impossible to perform. This possible phenomenon would reinforce the views of Brumagne et al. (2004) and Vuillerme et al. (2006), who concluded that fatigue of the ankle muscles (distal musculature) induces less reliable ankle proprioceptive signals and compensates by increasing the gain at more proximal joints (e.g. hips, lumbar spine). Kinetic and kinematic measures will be necessary to determine whether a change of strategy occurred or not after the fatiguing protocols of knee and ankle musculatures. Indeed, in older women the static postural control in unipedal stance was impaired after ankle musculature fatigue but not after knee musculature fatigue (Bellew and Fenter 2006). The paradox is that young subjects preferentially adopt an ankle strategy (Horack and Nashner 1986) and older subjects mainly use a hip strategy (Woollacott et al. 1986) in bipedal stance. In addition, it exists interindividual variabilities in segmental stabilisation strategies to control balance (Isableu et al. 2003). Therefore, to answer this question, future protocols should determine how each subject organizes the activation of his different lower limb muscles for regulating his posture in the unipedal stance before and after fatiguing tasks.

In relation to the physiological factor, two reasons could also be proposed to explain the differences between the effects of knee musculature fatigue and the effects of ankle musculature fatigue on postural control. First, one can observe that group TRI completed more isometric contractions than group QUA. Babault et al. (2006) reported that isometric actions induce central fatigue first, followed by peripheral fatigue. These authors reported that metabolite concentration might be higher during isometric fatiguing procedure compared with concentric fatiguing (the intermittent nature of the concentric procedure may favour blood flow and, therefore, the evacuation of metabolic by-products) and would first increase the inhibitory effect of small diameter afferents (groups III and IV) and involve a α-motoneuron inhibition at the spinal level. More precisely, a high metabolite concentration induces recurrent inhibition (Loscher et al., 1996), presynaptic inhibition of Ia afferents (Rossi et al., 1999), stretch-reflex disfacilitation (Avela et al. 2001) and responsiveness of Golgi tendinous organs (Zytnicki et al. 1990). Hence, a high metabolite concentration generates a decrease in the contribution of proprioceptive input, and thus would affect the efficiency of the postural regulation mechanism. In practice, this phenomenon

could involve a deterioration of postural control. Vuillerme and Hintzy (2007) have already showed that a high blood lactate concentration contributes to degrade postural control. Moreover, Gandevia (2001) reported that the magnitude of the blood lactate concentration may vary between different muscles, due to the preponderant type of motoneuron (larger, i.e. that which activates fast-twitch highly fatigable fibres vs. small, i.e. that which activates slow-twitch fatigue resistant fibres). After fatiguing tasks generating an equal degree of strength loss [quadriceps femoris containing faster or larger motoneurons than triceps surae (Harridge et al. 1996)], it was observed that, on the one hand, the strength of quadriceps declines more quickly (observed here by the number of isometric actions) than that of triceps surae and, on the other hand, postural control is more affected by the quadriceps femoris fatigue than by the triceps surae fatigue. Second, the fatiguing exercise for the knee musculature may have been more energetically demanding than the ankle musculature since its muscle volume is substantially larger. Hence, one can expect that both respiration and heart rates were elevated more after the quadriceps femoris exercise than after the triceps surae exercise. As the respiratory and cardiac mechanics contribute to amplify body sways (Bouisset and Duchêne 1994), the energetic effects induced by the thigh exercise would thus negatively affect postural control more than those induced by the calf exercise. However, respiratory rate might have only a minor effect on body sways after treadmill walking and cycle ergometer fatiguing exercises (Nardone et al. 1997); thus, this phenomenon is not very probable after local fatigue exercises.

In conclusion, the postural control is more impaired by knee muscle fatigue than by ankle muscle fatigue. Moreover, future studies could be conducted to determine which anatomical, mechanical or physiological factor constitutes the principal cause of deterioration of postural control. In this case, in addition to the measures that were performed in this study, these studies should include electromyographic analyses (for each muscle group) and kinematic analyses during the balance test in both conditions (PRE and POST). It would also be relevant to measure the reflex inputs from muscle afferents immediately before the balance test in both conditions. However, in practice, all these measurements would augment the time from the end of the fatiguing task to initiation of postural control measure which would increase the recovery time, and thus limit the fatigue effects.

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