The Effects of Uni- and Bilateral Fatigue on Postural and Power Tasks

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The aim of this study was to investigate the effects of unilateral and bilateral fatigue on both postural and power bipedal tasks. Ten healthy subjects performed two tasks: bipedal quiet standing and a maximal bipedal counter-movement jumping before and after unilateral (with either the dominant or nondominant lower limb) and bilateral (with both lower limbs) fatigue. We employed two force plates (one under each lower limb) to measure the ground reaction forces and center of pressure produced by subjects during the tasks. To quantify the postural sway during quiet standing, we calculated the resultant center of pressure (COP) speed and COP area of sway, as well as the mean weight distribution between lower limbs. To quantify the performance during the countermovement jumping, we calculated the jump height and the peak force of each lower limb. We observed that both unilateral and bilateral fatigue affected the performance of maximal voluntary jumping and standing tasks and that the effects of unilateral and bilateral fatigue were stronger in the dominant limb than in the nondominant limb during bipedal tasks. We conclude that unilateral neuromuscular fatigue affects both postural and power tasks negatively.

Keywords: neuromuscular fatigue, countermovement jump, asymmetries, motor control, posture

Quite a few research studies have demonstrated that neuromuscular fatigue on only one of the lower limbs (unilateral fatigue) affects the performance of voluntary movements (Ament & Verkerke, 2009; Augustsson et al., 2006; Bizid et al., 2009; Gribble & Hertel, 2004; Rodacki et al., 2001; Salavati et al., 2007; Thomson et al., 2009; Yaggie & McGregor, 2002; Yiou et al., 2009), as well as postural control in motor tasks performed with both lower limbs simultaneously (bipedal tasks) (Berger et al., 2010; Dietz & Berger, 1984; Vuillerme et al., 2009).

However, these studies selected only one of the two lower limbs to induce unilateral fatigue. Whether limb dominance plays a role in the effects of fatigue on the performance of maximal voluntary jumping and postural control in bipedal tasks remains unknown. Investigating this question will allow for a better understanding of the effects of fatigue on the overall performance of complex tasks in daily activities, sports, and clinical conditions (i.e., patients with lateralized sensorimotor impairment).

Therefore, the aim of the current study was to investigate the effects of uni- and bilateral fatigue on both postural and power bipedal tasks. We hypothesized that: (i) uni- and bilateral fatigue will affect the performance of both maximal voluntary jumping and standing bipedal tasks, and (ii) the effects of uni- and bilateral fatigue will be stronger in the dominant limb than in the nondominant limb during bipedal tasks.

Methods

Subjects

Ten healthy, male, sedentary adult volunteers took part in the study (mean ± *SD* age: 25 ± 4 years, height: 176 ± 8 cm, and weight: 73 ± 12 kg). No subjects reported any history of neurological or musculoskeletal disease. None practiced any sport modality more than once a week. They engaged in occasional physical activity, such as running, soccer, basketball, or volleyball but on a recreational level. The additional inclusion criteria were, (1) no previous surgery on the lower extremities, (2) no history of injury with residual symptoms (e.g., pain, "giving-away" sensations, or endurance loss) in the lower extremities in the year before recruitment (3) no evidence of a leg-length discrepancy (i.e., difference of distance from the anterior superior iliac spine to the superior surface of the most prominent aspect of the medial malleolus) of more than 1 cm. The University of São Paulo's local ethics committee approved this study, and all volunteers provided written informed consent before participation.

Procedures

Before data collection, subjects were asked which leg was preferred for kicking a ball. The preferred kicking

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leg was considered the dominant leg (Maulder & Cronin, 2005). Of the 10 subjects, 8 had the right leg as dominant.

To understand the effects of fatigue of each limb (or of both) on postural and power tasks, subjects performed two tasks: bipedal quiet standing and maximal bipedal countermovement jumping before and after unilateral (in the dominant or in the nondominant lower limb, randomly selected) and bilateral (in both lower limbs) fatigue.

For each limb fatigued, the experimental protocol consisted of (1) a prefatigue test (three trials of bipedal quiet standing and three trials of maximal bipedal countermovement jumping), (2) fatigue induction, (3) a control task (where subjects performed maximal countermovement jumping with the fatigued lower limb to verify that fatigue was induced), and (4) a postfatigue test (three trials of maximal bipedal countermovement jumping, and one trial of bipedal quiet standing). Then, subjects had at least 10 min to rest. After this recovery period, we conducted a control task where subjects performed maximal countermovement jumping with the previously fatigued lower limb(s). If the jump height was below 10% of the prefatigue condition, subjects were given additional rest time to guarantee total recovery. After full recovery, subjects repeated the same series, but with a different fatiguing condition (unilateral or bilateral). The sequence of unilateral fatiguing conditions was randomized among subjects; however, the final condition always involved fatigue in both lower limbs.

Standing Task. The subjects were asked to select a comfortable standing position for 30 s, with their feet approximately a hip width apart and their arms crossed on their chest. The subjects stood with each foot on a different force plate. They were instructed to stand as still as possible looking straight at a point about 2 m ahead at head height. For the jumping task, subjects were asked to stand in the same posture as before and then to perform the highest possible jump, keeping their knees straight during the flight phase.

Fatigue Protocols. To determine the maximal load for the fatigue protocol, subjects performed a 1RM leg-press test (Cybex, Int., USA) with the dominant leg (Brown, 2008). The fatigue protocol used the same leg-press exercise to target the main muscles responsible for the lower-limb extension movement involving the hip, knee and ankle joints, until concentric muscular failure. The starting and ending position for the knee-extension exercise (leg press) was seated with approximately 90 degrees of knee flexion angle and 90 degrees of range of motion realized. To induce fatigue, subjects were asked to perform two sets of 50 repetitions, separated by 30 s, at a self-selected cadence, using the following loads: 40% of 1RM leg press for unilateral fatigue and 60% of 1RM leg press for bilateral fatigue (Orishimo & Kremenic, 2006). A loud verbal encouragement was given to subjects during all sets.

Data Analysis

The forces and moments measured by the force plates (OR6, AMTI, USA) were recorded at a 1080Hz sampling frequency, and all of the data were analyzed with a program writing in Matlab (Mathworks Inc., EUA). The center of pressure (COP) and the vertical component of the ground reaction force (Fz) were the measurements used for analysis.

For the quiet standing trials, the COP data were filtered with a fourth-order 10 Hz low-pass, zero-lag Butterworth filter. To quantify the body sway, we used the mean speed, the excursion area of the net COP data, calculated using the COP and the Fz data from each force plate (right and left), given by:

$$COP_{net} = \frac{COP_{right} \times Fz_{right} + COP_{left} \times Fz_{left}}{Fz_{right} + Fz_{left}}$$

The resultant COP speed was calculated by dividing the net COP resultant displacement by the total period of the trial. The COP area was estimated by fitting an ellipse that encompassed 95% of the net COP data (Freitas et al., 2005). We also included the COP speed and COP standard deviation in both directions: anteroposterior (ap) and mediolateral (ml). To quantify how each lower limb was used in the bipedal quiet standing task, we computed the weight distribution during the quiet standing task, defined as the mean value of Fz in each force plate divided by the total Fz during the whole quiet standing trial.

For the jumping trials, the performance was quantified by jump height, computing the total Fz (the sum of the Fz in each force plate), which was used to calculate the velocity of the body center of mass at takeoff ($v_{takeoff}$), and then the jump height using the following formula: $v_{takeoff}^2/(2g)$, where g is the acceleration of gravity, 9.8 m/s^2 (Dowling & Vamos, 1993). To quantify how each lower limb was used during the bipedal jumping, we computed the peak force on each lower limb, defined as the maximal value of Fz in each force plate during the propulsive phase of the countermovement jumping normalized by the total body weight (BW).

Statistical Analysis

The mean across trials for each variable was used in the statistical analysis. Normality and homogeneity of variances of the data were confirmed by the Kolmogorov-Smirnov and Levene tests, respectively. For the dependent variables of jump height, resultant COP speed, COP area, COP speed and COP standard deviation (ap and ml directions), repeated-measure one-way ANOVAs were employed, having the fatigue condition as a factor (prefatigue, dominant fatigue, nondominant fatigue, and both lower limbs fatigue). For the dependent variables of weight distribution and peak force, repeated-measure two-factor ANOVAs were employed, with factors dominance (dominant and nondominant limb) and fatigue condition (prefatigue, dominant fatigue, nondominant fatigue and both lower limb fatigue). Post hoc comparisons were performed using the Sidak test. An alpha of 0.05 was used for all statistical tests which were performed using SPSS version 18.0 (SPSS, Chicago, IL).

Results

The comparison between the tasks before and after fatigue (i.e., the height of the unipedal jump for unipedal tasks and the height of the bipedal jump for the bilateral tasks) indicated that fatigue was indeed induced. After unilateral fatigue, the height of the unipedal jump with the dominant lower limb decreased $17 \pm 5\%$ ($t(9) = 7.13$, $p < .001$) and with the nondominant lower limb $17 \pm 4\%$ ($t(9) = 7.65$, $p < .001$). In addition, the number of repetitions during the unilateral fatigue protocol was similar for dominant and nondominant lower limbs: 81 ± 20 and 78 ± 19, respectively ($p = .49$).

With regard to the bipedal jump performance during fatigue, an ANOVA revealed a main effect of the fatigue condition on jump height ($F(3,27) = 14.13$, $p < .001$). The mean and standard deviation values across subjects for the height and peak force of the bipedal jump for all the fatigue conditions (without fatigue and fatigue in the dominant limb, nondominant limb, or both limbs) (Figure 1).

(a)

(b)
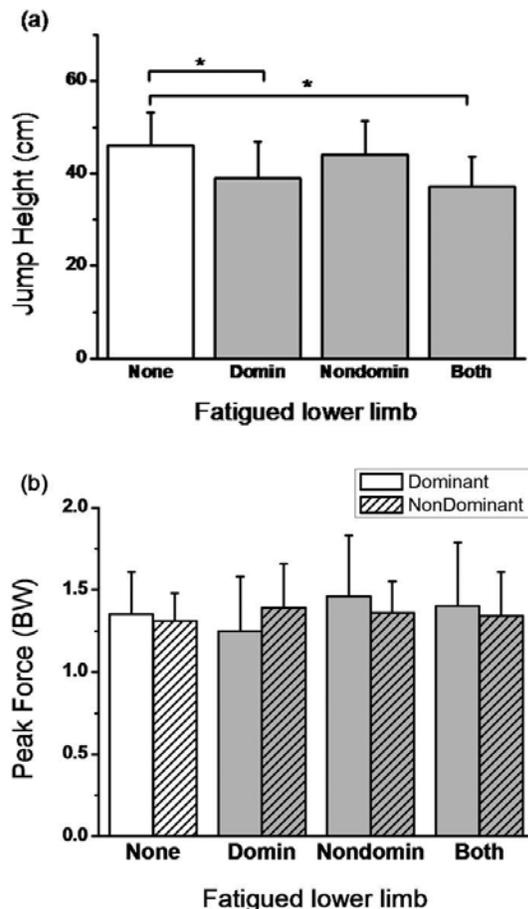
Figure 1 — Mean $\pm$ *SD* across subjects of the jump height (a); and peak force (b) during maximal countermovement jump at the conditions without fatigue (None), after fatigue of the dominant lower limb (Domin), nondominant lower limb (Nondomin), and both limbs (Both). White bar: before fatigue task; green bar: after fatigue task. *$p < .05$.

The post hoc analysis revealed that jump height after fatigue in the dominant lower limb, and in both limbs as well, was significantly shorter than with the prefatigue condition ($p = .027$ and $p = .008$, respectively). For the peak force variable, no main effects were observed for lower-limb dominance ($F(1,9) = 0.061$, $p = .81$) or the fatigue condition ($F(3,27) = 1.07$, $p = .37$).

With regard to the bipedal standing performance during fatigue, an ANOVA revealed a main effect of fatigue condition only for the resultant COP speed variable ($F(3,27) = 7.90$, $p = .001$). The ANOVA did not reveal a main effect of fatigue condition for the COP speed (ap and ml directions) variables ($F(3,27) = 0.26$, $p = .85$) and ($F(3,27) = 1.67$, $p = .19$), respectively or the COP standard deviation (ap and ml directions) variables ($F(3,27) = 2.91$, $p = .53$) and ($F(3,27) = 2.35$, $p = .94$), respectively. The mean and standard deviation values across subjects for the COP area, resultant COP speed, and weight distribution variables during quiet standing for all of the fatigue conditions (Figure 2). The post hoc analysis revealed that resultant COP speed was significantly higher for all postfatigue conditions in comparison with the prefatigue condition ($ps < 0.035$). For the COP area variable, no main effects were observed for lower-limb dominance ($F(1,9) = 1.68$, $p = .188$) or for the fatigue condition ($F(3,27) = 0.90$, $p = .767$). For the weight distribution variable, there were no main effects for lower-limb dominance ($F(1,9) = 2.43$, $p = .153$) or for the fatigue condition ($F(3,27) = 0.94$, $p = .43$). A trend was observed for a weight distribution asymmetry toward the nondominant lower limb: The Fz on the nondominant lower limb was on average $6.5 \pm 9\%$ higher than on the dominant lower limb for all conditions; however, this difference was not statistically significant ($p = .13$, for without fatigue; $p = .27$, fatigue in the dominant limb; $p = .07$, fatigue in the nondominant limb; $p = .23$, fatigue in both limbs).

Discussion

In this study, we investigated the effects of uni- and bilateral fatigue on standing and power bipedal tasks. Our hypotheses were confirmed: (i) uni- and bilateral fatigue affected the performance of both maximal voluntary jumping and standing tasks, and (ii) the effects of uni- and bilateral fatigue were stronger in the dominant limb than in the nondominant limb during bipedal tasks (however this is true only for the jumping task).

Our observation that unilateral fatigue impairs unipedal and bipedal postural control during quiet standing is consistent with previous studies (Berger et al., 2010; Berger et al., 2011; Dietz & Berger, 1984; Vuillerme et al., 2009). In addition, our results indicated that this impairment appeared to be independent of lower-limb dominance. Our results indicate that fatigue on only one side or on both sides of the body had, in fact, similar effects on impairing postural control. Even if only one lower limb was fatigued, we observed an effect of fatigue on the weight distribution between lower limbs
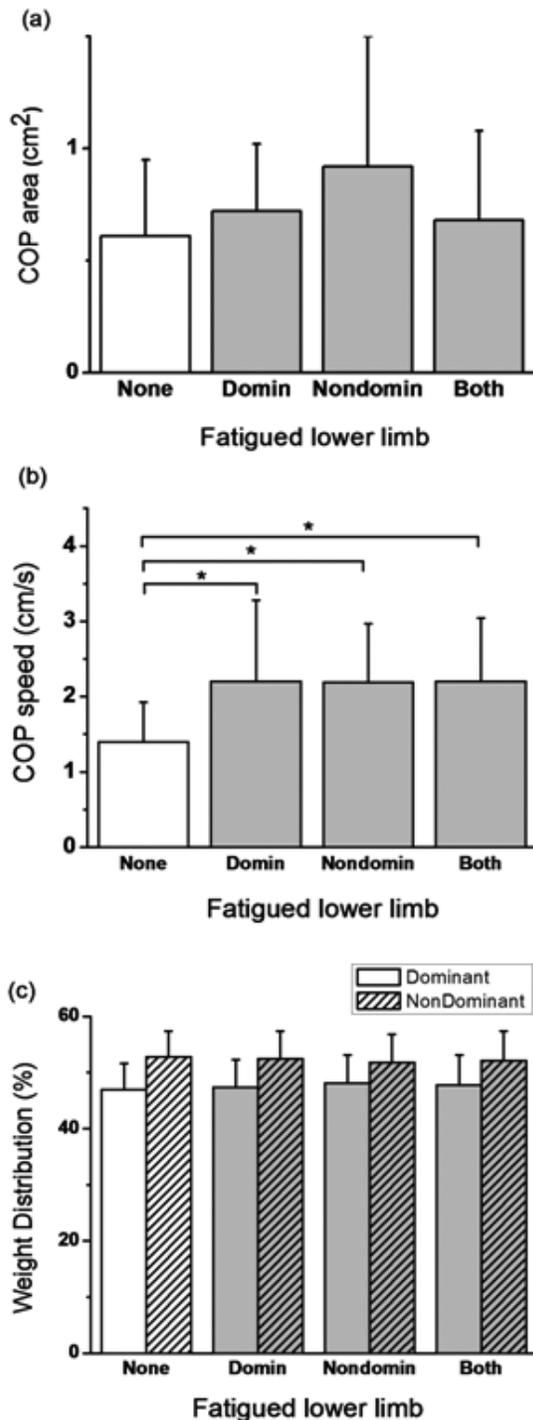
Figure 2 — Mean ± *SD* across subjects of the COP area (a); resultant COP speed (b); and weight distribution (c) during bipedal quiet standing at the conditions: without fatigue (None) and after fatigue of the dominant lower limb (Domin), at the nondominant lower limb (Nondomin), and at both limbs (Both). White bar: before fatigue task; green bar: after fatigue task. *$p < .05$.

during quiet standing. Taken together, these results suggest a central mechanism through the nervous system for adapting to fatigue during quiet standing. Several mechanisms could affect the fatigued lower limb: (1) Small perturbations are attenuated by ankle strategy due to stretch reflex: however, during the fatigue condition, the ability to attenuate small disturbances becomes more difficult and sense of position can be disturbed (Allen & Proske, 2005; Gandevia, 1992; Yaggie & McGregor, 2002); (2) the proprioceptors of the joint capsule can become desensitized and the muscles unable to stabilize the joint (Yaggie & McGregor, 2002); and (3) the fatigue condition could inhibit the ability of surrounding musculature to react to small perturbations (Gribble & Hertel, 2004). We may conclude that the nervous system created an adaptive process for postural control using the non-fatigued lower limb (with the possibility of an increase in the COP displacements to enhance exploratory movements) (Vuillerme et al., 2009). Of note, this impairment was only observed for the resultant COP speed variable, which seemed to be more sensitive to fatigue effects than other measurements of COP sway.

In contrast to the quiet standing task, unilateral fatigue impaired bipedal countermovement jumping, and this effect seemed to be related to lower-limb dominance. We found that only unilateral fatigue of the dominant lower limb affected the performance of maximal bipedal countermovement jumping, with no effects of unilateral fatigue on the nondominant lower limb. Interestingly, the peak force produced by each lower limb during the jump was not affected by fatigue on either side of body in our study. However, the force distribution along the foot could have changed as reported by Berger et al. (2011). The neuromuscular fatigue in the fatigued lower limb may be due to changes in the contractile apparatus and is probably not a result of reduced muscle activation by the central nervous system (Augustsson et al., 2006), still this result suggests that the central nervous system regulates the force produced by the nonfatigued lower limb to produce a similar force to that of the fatigued lower limb (Carson et al., 2002). In our study, only when the dominant lower limb was fatigued did this regulation impair performance, leading to a decrease in jump height. So this force regulation by the central nervous system for bipedal tasks seems to be based on the current state of the dominant limb.

In middle-aged people, Valderrabano et al., (2007) observed more slow fibers in nondominant muscles than in dominant muscles, and they suggested that this was due to the fact that the dominant lower limb is used more in propulsive tasks. Considering that fast fibers are less fatigue resistant (Westerblad et al., 2010), this potential difference in fiber-type content between lower limbs might explain why the dominant lower limb was more affected by unilateral fatigue. However, in our study, we did not observe differences in peak power between the dominant and nondominant leg before fatigue induction.

The lack of a control group might limit the strength of our results, as we cannot guarantee that the results

after the fatigue induction were not influenced by the simple fact that the subjects were performing the same tests by the second (or third) time. At least for the unilateral fatigue condition, the lower limb to be fatigued first was randomly selected, so we are confident that the results for this condition are due to fatigue alone. However, for the bilateral fatigue condition, which was always the last to be performed, we have to admit that there might be a possible repetition effect (although the results are very consistent with the fatigue-decrement hypothesis).

In summary, unilateral neuromuscular fatigue negatively impacts both postural and power tasks, even though they involve different levels of effort. The fatigue seemed to affect the dominant limb more than the nondominant limb only during maximal voluntary jumping tasks, while there appeared to be no difference during quiet standing tasks.

Acknowledgments

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