TITLE

The effect of high-intensity cycling training on postural sway during standing under rested and

fatigued conditions in healthy young adults

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ABSTRACT

Purpose The purpose of this study was to investigate whether high-intensity cycling training leads to adapted responses of balance performance in response to exercise-induced muscle fatigue. **Methods** Eighteen healthy adults were assigned to either 3-weeks (n = 8, age 20.1 ± 2.6 years, height 177 ± 5 cm, mass 73.6 ± 5.1 kg) or 6-weeks (n = 10, age 24.3 ± 5.8 years, height 179 ± 6 cm, mass 81.0 ± 15.8 kg) of high- intensity training (HIT) on a cycle ergometer. The centre of pressure (COP) displacement in the anteroposterior (COP_{AP}) direction and COP path length (COP_L) were measured before and after the first and final high intensity training sessions. **Results** Pre-training, exercise-induced fatigue elicited an increase in COP_{AP} (3-weeks; $p = 0.001$, 6-weeks; $p = 0.001$) and COP_L (3-weeks; $p = 0.002$, 6-weeks; $p = 0.001$) returning to pre-exercise levels within 10-min of recovery. Following 3-weeks of training, significant increases in COP_{AP} ($p = 0.001$) and COP_L ($p = 0.002$) were observed post fatigue, returning to pre-exercise levels after 15-min of recovery. After 6-weeks of training no significant increases in sway (COP_{AP}; $p = 0.212$, COP_L; $p = 0.998$) were observed following exercise-induced fatigue. **Conclusions** In summary, 3 weeks of HIT resulted in longer recovery times following fatigue compared to pre-training assessments. After 6 weeks of HIT, postural sway following fatigue was attenuated. These results indicate that HIT could be included in injury prevention programs however, caution should be taken during early stages of the overreaching process.

Key Words: Endurance training, postural stability, fatigue, cycling, recovery, balance

INTRODUCTION

Postural control is a complex, multifaceted function that requires the integration of visual, vestibular and somatosensory inputs within the central nervous system, while modulating efferent outputs to the postural musculature. The maintenance and control of a stable upright stance represents an essential prerequisite for many sporting, physical and daily activities (Lepers et al. 1997). Muscle fatigue represents an inevitable consequence of physical, occupational and recreational tasks (Vuillerme, Sportbert and Pinsault 2009) which is known to alter the quality of proprioceptive information and/or integration within the central nervous system (Paillard 2012) and reduces the muscles force-generating capacity (Taylor, Butler and Gandevia 2000). In recent years, the immediate post-exercise effects of cycling on postural stability have received growing interest. Although findings are difficult to compare across experiments, it is commonly reported that an acute bout of stationary cycling increases the magnitude and speed of postural sway in both young (Hill *et al.* 2014; Vuillerme and Hintzy 2007; Wright, Lyons and Navalta 2013) and older adults (Hill *et al.* 2015; Stemplewski et al. 2012). Altered somatosensory input and decreased neuromuscular control linked to muscle fatigue may increase the likelihood of falling (Yaggie and McGregor 2002) and make joint structures more susceptible to traumatic injury (Yaggie and Armstrong 2004).

Although aerobic conditioning has rarely been included in fall prevention studies, a well-developed endurance capacity might attenuate fatigue-induced declines in postural stability during physical, sporting or daily activities (Donath, van Dieen and Faude 2015). For example, it is commonly reported that 6-12 weeks of moderate intensity endurance training (60 – 75% peak oxygen uptake) elicits numerous physiological adaptations that enhance the ability of skeletal muscles to generate energy via oxidative metabolic pathways (Burgosmaster et al. 2008; Gollnick *et al.* 1973), which may contribute to delay the onset of fatigue during strenuous physical activities. These adaptations include enhanced mitochondrial biogenesis, increased myoglobin content and capillary density and enhanced oxidative enzymatic activity (Bishop *et al.* 2011). In support of this, Hassanlouei and co-workers (2014) reported that 6 weeks of moderate intensity cycling training for 20 – 45 min and at intensities corresponding to 50 – 75% of heart rate reserve, improved the ability to control balance in response to postural perturbations in the presence of muscle fatigue. Similarly, Stemplewski *et al.* (2013) reported a significantly greater increase in the centre of pressure (COP) velocity and anteroposterior COP

displacement after 20-min of acute cycling in older adults with lower levels of habitual physical activity (~60 %) compared to older individuals with higher levels of habitual physical activity (~ 20%). These findings may indicate that functional and/or aerobic fitness status could directly influence the magnitude of postural impairment in response to acute exercise. However, conventional moderate intensity cycling training is time consuming and appears to elicit small (Buchner *et al.* 1997a) or even negligible (Buchner *et al.* 1997b) long term benefits to balance performance and fall risk among older adults.

High-intensity training (HIT) at high power outputs (150 – 300 % $\dot{V}O_{2PEAK}$) over ~6 weeks produce similar results to those reported following a comparable duration of moderate intensity endurance training (MacDougall *et al.* 1998). A series of studies have shown that as few as six HIT sessions in 2 weeks increased skeletal muscle oxidative capacity, reflected by the maximal activity and/or protein content of mitochondrial enzymes (Burgomaster *et al.* 2005; 2008; Gibala *et al.* 2006; Talanian *et al.* 2007). Low volume HIT may therefore represent a time-efficient strategy to rapidly increase general aerobic fitness which may subsequently contribute to greater safety during activities of daily life and sports-related tasks (Hassanlouei *et al.* 2014). However, a single session of HIT elicits a transient impairment of balance performance for up to 30 min in older adults (Donath et al. 2015). Thus, the potential advantages of HIT with regards to time efficiency are debatable when considering the detrimental effects on neuromuscular function.

From this perspective, the main purpose of this study was investigate the effects of 3 weeks or 6 weeks of HIT on balance performance before (i.e., rested state) and during the recovery (i.e., fatigued state) from exercise-induced muscle fatigue. In order to determine the volume of training required for stationary cycling to produce a significant benefit to postural stability, we took the classic 6 week training model as the starting point. To determine the time-course of changes in postural sway we used an arbitrary 50% of the volume as an interim benchmark. Centre of pressure measures of postural sway have previously been used as the main outcome measure when investigation the effects of muscle fatigue (Donath et al. 2015; Hill et al. 2014; Vuillerme and Hintzy 2007; Wright, Lyons and Navalta 2013) and training (Hassanlouei et al. 2014; Jakobsen et al. 2011) on neuromuscular function. As a proof of concept, we included young healthy adults for comparative purposes with previous studies (e.g.,

Hassanlouei et al. 2014). We hypothesised that it should be possible to substantially improve postural stability during pre-fatigued and fatigued conditions following 3 or 6 weeks of HIT.

METHODS

Participants

Eighteen healthy, non-cycling trained adults were randomly assigned to either 3 weeks (n = 6 males and 2 females, age 20.1 ± 2.6 years, height 177 ± 5 cm, mass 73.6 ± 5.1 kg) or 6 weeks (n = 10 males, age 24.3 ± 5.8 years, height 179 ± 6 cm, mass 81.0 ± 15.8 kg) of high-intensity training on a cycle ergometer. All participants were recreationally active undertaking 2 to 3 exercise sessions per week in a range of sports (e.g. football, rugby, swimming, badminton and/or running). The study was carried out in accordance with the guidelines outlined in the declaration of Helsinki (1964) and the study procedures were approved by the institutional ethics committee. Participants provided written consent before any involvement in the study. None of the participants reported any contraindications to exercise or had neurological or vestibular disorders, orthopaedic pathology or musculoskeletal problems.

Study design

Prior to 3 or 6 weeks of HIT participants initially visited the laboratory to complete a graded incremental exercise test to determine peak minute power (W_{PEAK}) and peak oxygen uptake ($\dot{V}O_{2PEAK}$). The training period consisted of 3 weeks or 6 weeks of high-intensity cycling each interspersed by one full rest day (i.e. training on Monday, Wednesday, Friday). Each group completed 3 training sessions per week which consisted of two repeated sprint sessions at 7.5% of body mass and cycling to volitional exhaustion at a constant load equivalent to 100% W_{PEAK} at 70 rev.min^{-1} (T_{LIM}). Postural sway was assessed before and after the first and final T_{LIM} training sessions in both groups (Fig. 1). We measured postural sway before and after T_{LIM} because this type of constant power output exercise was the most controlled of the training sessions we adopted and ensured the most accurate determination of changes in postural sway before and after training. On completion of the training participants completed a second incremental test to determine post-training W_{PEAK}. The post-training T_{LIM} trials were identical to the pre-training trials.

*** FIGURE 1 ABOUT HERE ***

Peak oxygen uptake tests

Participants undertook a preliminary incremental exercise test to determine W_{PEAK} on a cycle ergometer (Monark 824E Ergomedic, Monark, Varberg, Sweden). Following 5 min of seated rest, participants exercised at an initial power output of 70 W with subsequent increases in power output of 35 W every 3 min until volitional exhaustion. The cadence was set at 70 rev·min⁻¹. Heart rate (HR) was continually monitored (Polar Electro, Oy, Finland) and recorded in the final 5 s of each incremental stage and immediately upon reaching volitional exhaustion. A rating of both local (working muscles; RPE_L) and central (cardiorespiratory; RPE_C) perceived exertion using the 6–20 point Borg scale (Borg, 1982) was obtained at the same time as HR and immediately upon reaching volitional exhaustion. Expired gas was analysed continually using a breath-by-breath online gas analysis system (MetaMax, Cortex Biophsik, Borsdorf, Germany) for oxygen uptake ($\dot{V}O_2$), minute ventilation ($\dot{V}_E$), and respiratory exchange ratio (RER). Fingertip arterialised capillary blood samples were obtained at rest, volitional exhaustion and after 5 min of passive recovery following standard operating procedures. Blood was collected and mixed in 20-µL capillary tubes and analysed for blood lactate using an automatic lactate analyser (Biosen C_Line, EKF Diagnostic, Germany). Throughout each test participants were verbally encouraged to exercise for as long as possible until volitional exhaustion or until the prescribed cadence of 70 rev·min⁻¹ could not be maintained for longer than 10 s (Higgins, James and Price 2013).

High-intensity training program

Participants completed nine (3 weeks) or eighteen (6 weeks) training sessions performed on a cycle ergometer (Monark 824E Ergomedic, Monark, Varberg, Sweden). The training programme was tapered in the final three weeks for the 6 week training group to minimise possible effects of overtraining. Throughout the training period participants were asked to continue with their normal diet, activity and usual training commitments. Session 1 involved two bouts of ten repeated sprints against a load of 7.5% body mass. Sprint duration increased from 6 s to 8 s to 10 s in both groups (weeks 1, 2 and 3, respectively) and decreased from 10 s to 8 s to 6 s (weeks 4, 5 and 6, respectively) for the 6-week group. Session 3 involved 30-s sprints against a load of 7.5% body mass. The number of sprints increased from 3 to 4 to 5 in both groups (weeks 1, 2 and 3, respectively) and decreased from 5 to 4 to 3 (weeks 4, 5 and 6, respectively) for the 6-week group. Recovery between sprints was kept constant at 30-s and between bouts at 300-s. Session 2 consisted of cycling to volitional exhaustion at a constant

load equivalent to pre training 100% W_{PEAK} (T_{LIM}). Ratings of perceived exertion were recorded at the end of every training session to provide an indication of training intensity. A stationary start was adopted for all training sessions which has previously been used in evaluating high-intensity cycling in a laboratory setting in none specifically trained adults (Wittekind, Micklewright and Beneke 2011). Following the completion of training, participants returned for a final time and completed a graded incremental exercise test to determine post-training W_{PEAK} as previously described.

Posturography

Before the first and final T_{LIM} training session (i.e., pre-fatigue), each group completed posturographic trials consisting of three eyes open (EO) and three eyes closed (EC) conditions. All participants stood barefoot on a force platform (AMTI, AccuGait, Watertown, MA) in an upright bipedal position, with the feet abducted at 30° and the medial extremities of each calcaneus separated by 3 cm and arms hanging by their sides (Pinsault and Vuillerme 2009). Each participant was asked to distribute their body mass symmetrically on both feet and stand as still as possible by avoiding any extraneous movements. Each participant stood for 30 s with their EO or EC (Pinsault and Vuillerme 2009). The order of visual conditions were randomly assigned for each participant. During EO trials participants were instructed to look straight ahead at a fixed target 2 m away which was adjusted to the eye level of each participant, thus preventing vestibular disturbance. During pre-fatigue conditions, rest periods of 60 s were provided between each trial to allow participants to sit down. In the subsequent analyses, a mean of the three resting trials were used. Vertical ground reaction forces were sampled at 100 Hz using the accompanying data acquisition software package (AMTI, Netforce®, Watertown, MA). Displacement of the centre of pressure (COP) in the anteroposterior (COP_{AP}) direction and the COP path length (COP_{L}) were computed using a specialist software package (AMTI, BioAnalysis, Version 2.2, Watertown, MA). These parameters of postural sway were used for comparative purposes with previous investigations (e.g., Donath et al. 2015) with the validity and reliability of these parameters computed with a force platform accepted in previous literature (Pinsault and Vuillerme 2009). Following T_{LIM} sessions (i.e., post-fatigue), posturographic trials were performed 1 min after exercise and at 5, 10 and 20-min of seated recovery, in both EO and EC conditions, completed in a randomised order.

Statistical analysis

A 3-way mixed model analysis of variance (ANOVA) with repeated measures on all factors (training status; *pre and post* $\times$ group; *3 weeks and 6 weeks* $\times$ time; *0 (pre), 1, 5, 10 and 20*) was conducted to examine fatigue induced changes on postural sway outcomes measures before and after training. Additionally, all cardiorespiratory and perceptual variables were analysed by 3-way (training status $\times$ group $\times$ time) repeated measures ANOVA. Where significance was achieved for main effects pairwise comparisons (least significant difference) were undertaken. For interactions, Tukeys' post hoc analysis was undertaken by calculating the difference required between means for significance at the level of $p \leq 0.05$ (Vincent 1999). For ANOVA, effect sizes are reported as partial eta-squared value (η^2) where appropriate. Cohen's *d* effect sizes are reported for pairwise comparisons. Effect sizes of 0.2, 0.6, 1.2 and 2.0 indicate small, medium, large and very large effects, respectively. Statistical analysis was completed using SPSS (IBM v17 and 20, Chicago, USA).

RESULTS

Anteroposterior COP displacement

A significant time $\times$ group $\times$ training status interaction was observed for COP_{AP} for EO ($F_{(4,160)} = 5.912$, $p = 0.011$, $\eta^2 = 0.129$) and EC ($F_{(4,160)} = 3.404$, $p = 0.011$, $\eta^2 = 0.078$) conditions (Fig. 2 & 4). Pre-training, acute cycling elicited an increase in COP_{AP} from pre to immediately post exercise (EO_3, $p = 0.001$, $d = 2.2$, EO^6, $p = 0.001$, $d = 2.0$; EC_3, $p = 0.040$, $d = 1.4$, EO^6, $p = 0.001$, $d = 3.7$), returning to baseline levels within 10-min of recovery for both groups and visual conditions ($p < 0.05$). The magnitude of change from pre to post fatigue was large or very large for both groups. Following 3-weeks of training, significant increases in COP_{AP} (EO_3; $p = 0.001$, $d = 2.8$, EC_3; $p = 0.001$, $d = 2.4$) were observed after acute cycling, returning to pre-exercise levels after 15-min of recovery. The increases in postural sway following 3 weeks of training were very large. However, after 6-weeks of training no significant increases in COP_{AP} (EO^6; $p = 0.212$, $d = 0.2$, EC^6; $p = 0.999$, $d = 0.2$) were observed following acute cycling.

*** FIG. 2 ABOUT HERE ***

COP path length

A significant time $\times$ group $\times$ training status interaction was observed for COP_L for EO ($F_{(4,160)}$ = 3.043, p = 0.019, η^2 = 0.071) but not EC ($F_{(4,160)}$ = 1.441, p = 0.223, η^2 = 0.035) conditions (Fig. 3 & 4). Pre-training, acute cycling elicited an increase in COP_L from pre to immediately post exercise (EO_3, p = 0.001, ES = 2.3, EO^6, p = 0.001, ES = 2.0, EC_3, p = 0.029, ES = 1.8, EC^6, p = 0.009, ES = 1.4), returning to baseline levels within 10-min of recovery (p < 0.05). The magnitude of effects were large or very large. Following 3-weeks of training, significant increases in COP_L (EO_3; p = 0.002, d = 2.0, EC_3; p = 0.025, d = 1.4) were observed after acute cycling, returning to pre-exercise levels after 15-min of recovery. The magnitude of effects were large and similar to those reported before training. However, after 6-weeks of training no significant increases in COP_L (EO^6; p = 0.999, d = 0.3, EC^6; p = 0.999, d = 0.1) were observed following acute cycling.

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Physiological adaptations

After 3 weeks high-intensity training W_{PEAK} increased by 14 ± 9 % (d = 0.7) although both absolute $\dot{V}O_{2PEAK}$ (l.min^{-1}) and relative $\dot{V}O_{2PEAK}$ (ml.kg^{-1}.min^{-1}) decreased by -5 ± 14 % (d = -0.3) and -6 ± 13 % (d = -0.2), respectively (Table 1). However, the reductions in both absolute and relative $\dot{V}O_{2PEAK}$ following training were not statistically significant (both p > 0.05). After 6 weeks high-intensity training W_{PEAK} increased by 12 ± 10 % (d = 1.0). In contrast to the 3 weeks training group both absolute $\dot{V}O_{2PEAK}$ (l.min^{-1}) and relative $\dot{V}O_{2PEAK}$ (ml.kg^{-1}.min^{-1}) improved by 15 ± 14% (d = 1.1) and 13 ± 14 % (d = 0.6), respectively. Following 3 weeks and 6 weeks of high-intensity training, T_{LIM} increased by 55 ± 38 % (pre; 334 ± 125 s, post; 528 ± 269 s) and 70 ± 57 % (pre; 382 ± 78 s, post; 667 ± 318 s), respectively (Fig. 5).

*** TABLE 1 ABOUT HERE ***

DISCUSSION

The overall main result of the study was that 3 or 6 weeks of high-intensity cycling training did not result in any reductions in postural sway during pre-fatigued conditions. However, a major novel finding from the present study was that following 6 weeks of HIT, participants were better able to maintain balance in the presence of fatigue, despite continuing fatiguing exercise for longer in post-training assessments. In contrast, following 3 weeks of HIT the effects of acute fatigue on postural sway were more profound and the time taken to recover postural stability was longer in post-training assessments. Impaired postural stability following 3 weeks of HIT is possibly due, in part, to the initial development of overreaching. To our knowledge, the present study is the first to determine the time-course of high-intensity cycling training effects on postural stability during pre-fatigued and fatigued conditions.

Physiological adaptations

Several studies have reported that 6-7 weeks of high-intensity training elicit significant improvements in $\dot{V}O_{2PEAK}$ (MacDougall et al. 1998; Rodas, Ventura and Cadefau 2000; Tabata et al. 1996). Following 6 weeks of HIT, our participant's relative W_{PEAK} and $\dot{V}O_{2PEAK}$ improved by 14 ± 11 % and 12 ± 10%, respectively. In contrast, although 3 weeks of training elicited a similar increase in W_{PEAK} (14 ± 9%) to the 6 week group, relative $\dot{V}O_{2PEAK}$ decreased by -6 ± 13%. Indeed, several studies have reported significant increases in exercise performance without increases in $\dot{V}O_{2PEAK}$ (Burgomaster et al. 2005; 2006; Carter, Rennie and Tarnopolsky 2001). These findings support the idea that, with HIT, an increase in $\dot{V}O_{2PEAK}$ requires a specific amount of exercise (Talanian et al. 2007). Nonetheless, the training intensity, frequency and duration in our study were adequate to elicit increases in W_{PEAK} for both training groups. MacDougall et al. (1998) also reported significant increases in peak power output following 7-weeks of repeated sprint training. The authors also reported increases in oxidative and glycolytic enzymes, leading to suggestions that improved peak power output may have been due to increased maximal glycolytic enzyme activity and Na^+-K^+ pump activity. The training stimulus may have also been sufficient to elicit neuromuscular changes such as motor unit recruitment, firing rate and synchronisation (Creer et al. 2003).

Pre-fatigued postural sway

According to the present results, the isolated practice of high-intensity stationary cycling training does not improve bipedal standing balance performance during pre-fatigued conditions. Intense cycling has previously been shown to transiently increase postural sway in the anteroposterior direction (Gauchard et al. 2002; Hill et al. 2014; Nardone et al. 1997; Vuillerme and Hintzy 2007). Cycling mainly involves lower extremity muscle activity of the sagittal plane movers (e.g., ankle plantar/dorsi flexors, knee and hip flexors/extensors). Therefore, we initially assumed that high-intensity cycling training would provide a significant neuromuscular/musculoskeletal stimulus to improve balance performance in the anteroposterior direction (Vuillerme and Hintzy 2007). Similar to our findings, Hassanlouei et al. (2014) reported that 6 weeks of moderate intensity cycling training had no effects on anteroposterior sway during pre-fatigued conditions. One explanation for these findings is that cycling does not involve body movements which stress, and therefore improve, balance (Buchner et al. 1997a). In contrast, Jakobsen et al. (2011) reported that 12-weeks of high-intensity interval running elicited reductions in COP path length and sway area in healthy young adults. The differences in postural sway adaptations to training between the present study and those reported by Jakobsen et al. (2011) are likely explained by the fact that running and cycling differ in terms of the topography and nature of muscle action completed. For example, running provokes greater mechanical constraints at the level of the active muscle, tendons and cutaneous receptors than cycling exercise (Paillard 2012). Therefore, it is possible that the perturbation demands of high-intensity interval running would elicit larger neuromuscular adaptations in the somatosensory system and antigravity muscles compared with cycling. Therefore, it is possible that cycling training could improve risk factors for falls and injuries that were not ascertained by this study, such as improving gait, **agility** dynamic balance performance.

Post-fatigue postural sway

High-intensity exercise induced muscle fatigue tends to be predominantly peripheral in origin (Girard, Bishop and Racinais 2013; Lattier et al. 2004). For example, intracellular potassium concentration and the accumulation of metabolic by-products such as inorganic phosphate and hydrogen ions are likely to alter muscle excitability and excitation-contraction coupling (Girard, Mendez-Villanueva and Bishop 2011), resulting in an inability to maintain a desired muscular force output (Hunter et al. 2004). In addition, following repetitive muscular contractions the sensitivity of sensory fibres is increased

(Hassanlouei et al. 2014) and the accuracy of myotatic proprioceptive afferents are altered (Paillard 2012). Altered muscle spindle sensitivity is likely to elicit an internal disturbance in the postural musculature and generate a degradation of postural stability (Paillard 2012). The detrimental effects of high-intensity walking/running have already been reported during unipedal and bipedal stance in young and older adults (Donath et al. 2015; Degache et al. 2014), and therefore our data allow us to confirm these findings.

The results of the present study suggest that 3 weeks of HIT result in greater increases and longer recovery times in both the magnitude (COP_{AP}) and amount (COP_L) of postural sway in the presence of acute muscle fatigue. Theoretically, this will place the fatigued individual at an increased risk of musculoskeletal injury and/or a fall (Gribble and Hertel 2004). It seems possible that the increase in postural sway in the presence of muscle fatigue after 3 weeks of HIT may be due, in part, to the initial development of overreaching. Residual neuromuscular fatigue following HIT reduces muscle force production and the rate of force application during subsequent sessions, which in turn will attenuate any training stimulus for optimal neuromuscular adaptations (Buchheit and Lauren 2013). However, a decline in exercise performance is necessary to indicate a state of overreaching (Halson and Jeukendrup 2004). In the present study, our participants responded positively to the training, as reflected by an increase in T_{LIM} from week 1 to week 3. Indeed, it seems more likely that the greater disturbances in postural stability following 3 weeks of HIT might be because participants T_{LIM} increased with training, which supports recent findings that the time to task failure significantly influences the magnitude of postural disturbances (Paillard et al. 2014). It could also be possible that balance performance may provide an earlier indication of an early stage in the overreaching process during HIT when compared to exercise performance outcome measures (e.g., T_{LIM}). These data may have direct applications in exercise training and rehabilitation and therefore therapists, coaches and sports trainers should be aware of the deleterious consequences of muscle fatigue on neuromuscular control and subsequent fall and/or injury risk in response to low volume HIT up to 3 weeks.

In contrast, the acute effects of muscle fatigue on postural sway were completely removed by 6 weeks of HIT. These novel findings suggest that the total volume of HIT has a direct influence on the adapted responses of balance performance in response to acute muscle fatigue. As with the 3 week

training cohort, significant increases in T_{LIM} were observed between week 1 and week 6. Theoretically, the postural disturbances following 6 weeks of training should have been even greater than those reported following 3 weeks of HIT, based on the interpretation that time to task failure influences the magnitude of postural disturbance (Paillard et al. 2014). Therefore, differences in the adaptations achieved following 3 and 6 weeks of training likely explain the distinct postural adaptations. In particular, a key component of the 6 week training program was a tapering period in the final weeks to minimise effects of overtraining. The main purpose of tapering is to reduce physiological and psychological load and to remove residual fatigue from previous training sessions (Lehmann et al. 1997). Therefore, a suitable tapering period during HIT may be necessary to unmask any benefits to neuromuscular function, which in this case, is reflected by an enhanced ability to maintain quiet standing balance while fatigued. High-intensity training has been shown to increase muscle oxidative capacity as reflected by the maximal activity of mitochondrial enzymes, increase resting glycogen content, reduce the rate of glycogen utilisation and lactate production, increase the capacity for lipid oxidation, enhance peripheral vascular structure and function and improve time to exhaustion and maximal oxygen uptake (Burgomaster et al. 2005; 2008; Gibala et al. 2006). These adaptations may serve to delay the skeletal muscle anaerobiosis during intense exercise (Hassanlouei *et al.* 2014) and potentially increase the fatigue resistance of the trained musculature and subsequently improve postural stability following acute muscle fatigue. Indeed, Hassanlouei *et al.* (2014) reported that 6-weeks of endurance training on a cycle ergometer at 50 – 75 % of heart rate reserve for between 20 – 45 mins removed the acute negative effects of a cycle ergometer test to volitional exhaustion on postural sway. Together, these findings provide novel evidence that the acute effects of muscle fatigue on postural sway can be attenuated or even removed with an adequate training volume.

Some limitations need to be addressed concerning the present study. Firstly, as with previous investigations (Hassanlouei et al. 2014; Jakobsen et al. 2011) this study reported the effects of fatigue/training on COP measures of postural sway. However, we did not include complimentary methods such as muscle activity, joint kinematics and proprioception. These additional measures may have provided a more thorough interpretation of the data and allowed us to provide mechanisms for the adaptive balance responses to training. Likewise, the main outcome measure of this study was postural sway. It is possible that the training intervention in the present study could improve other performance

indices such as agility, dynamic balance, muscular strength/power and joint range of motion. Due to the transient nature of fatigue effects on postural stability, the study was limited to recordings of the COP during quiet standing. Randomisation between groups was not perfect with regard to gender distribution. For example, in the 6-week training cohort all participants were male (n = 10), while there were two females in the 3-week training group. However, closer inspection of individual data revealed that the female participants (n = 2) showed similar responses to those of the male cohort (n = 6). Finally, as a proof of concept we used a healthy young cohort without balance impairment. It is likely that the effects of this type of training may not be the same in healthy older, or frail, fall prone adults.

CONCLUSION

The total volume of HIT appears to be of importance for adapted responses of balance performance in response to acute muscle fatigue. Specifically, 6 weeks of HIT on a cycle ergometer completely removed the detrimental effects of muscle fatigue on postural sway, which was likely a result of increased fatigue resistance associated with the purported training adaptations, in addition to an appropriate tapering period. In contrast, 3 weeks of HIT resulted in greater amounts of postural sway and longer recovery times in response to fatigue, which may be associated with residual neuromuscular fatigue from previous training sessions. Theoretically, this muscle fatigue may potentially make individuals more susceptible to musculoskeletal injury, and therefore steps should be taken during conditioning of athletes to help prevent muscle fatigue. Therapists, coaches and sports trainers should be aware that cycling training did not improve standing balance during pre-fatigued conditions. Therefore, it remains unclear whether this type of endurance training should be included in exercise-based fall prevention strategies. It would however, be interesting for future studies to determine postural adaptations in response to HIT in a group of fall-risk adults, such as the elderly.

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ABBREVIATIONS

ANOVA – analysis of variance

COP – Centre of pressure

COP_{AP} – Centre of pressure displacement in the anteroposterior direction

COP_L – Centre of pressure path length

EC – Eyes closed

EO – Eyes open

HIT – High-intensity training

HR – Heart rate

RER – Respiratory exchange ratio

RPE – Ratings of perceived exertion

T_{LIM} – Time to exhaustion

$\dot{V}_E$ – Minute ventilation

$\dot{V}O_2$ – Oxygen uptake

$\dot{V}O_{2PEAK}$ – Peak oxygen uptake
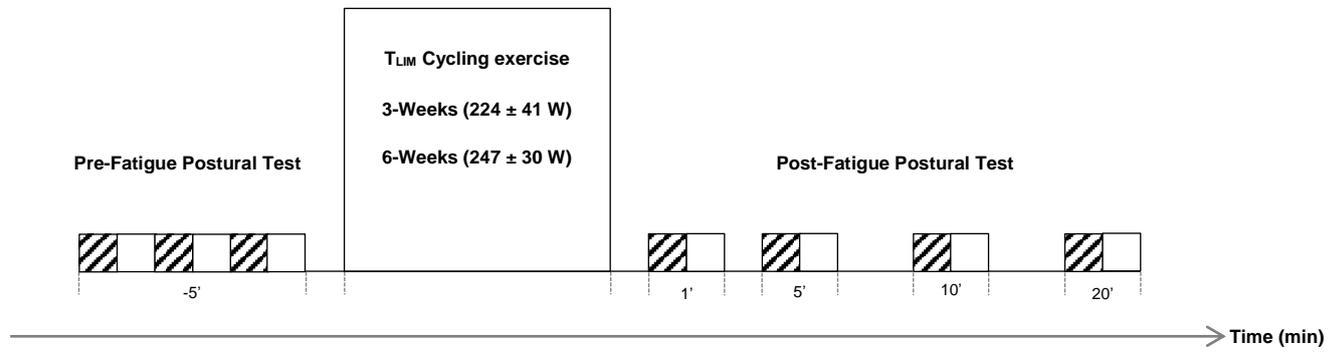
W_{PEAK} – Peak minute power

Pre-Fatigue Postural Test

T$_{LIM}$ Cycling exercise

3-Weeks (224 ± 41 W)

6-Weeks (247 ± 30 W)

Post-Fatigue Postural Test

-5'

1'

5'

10'

20'

Time (min)

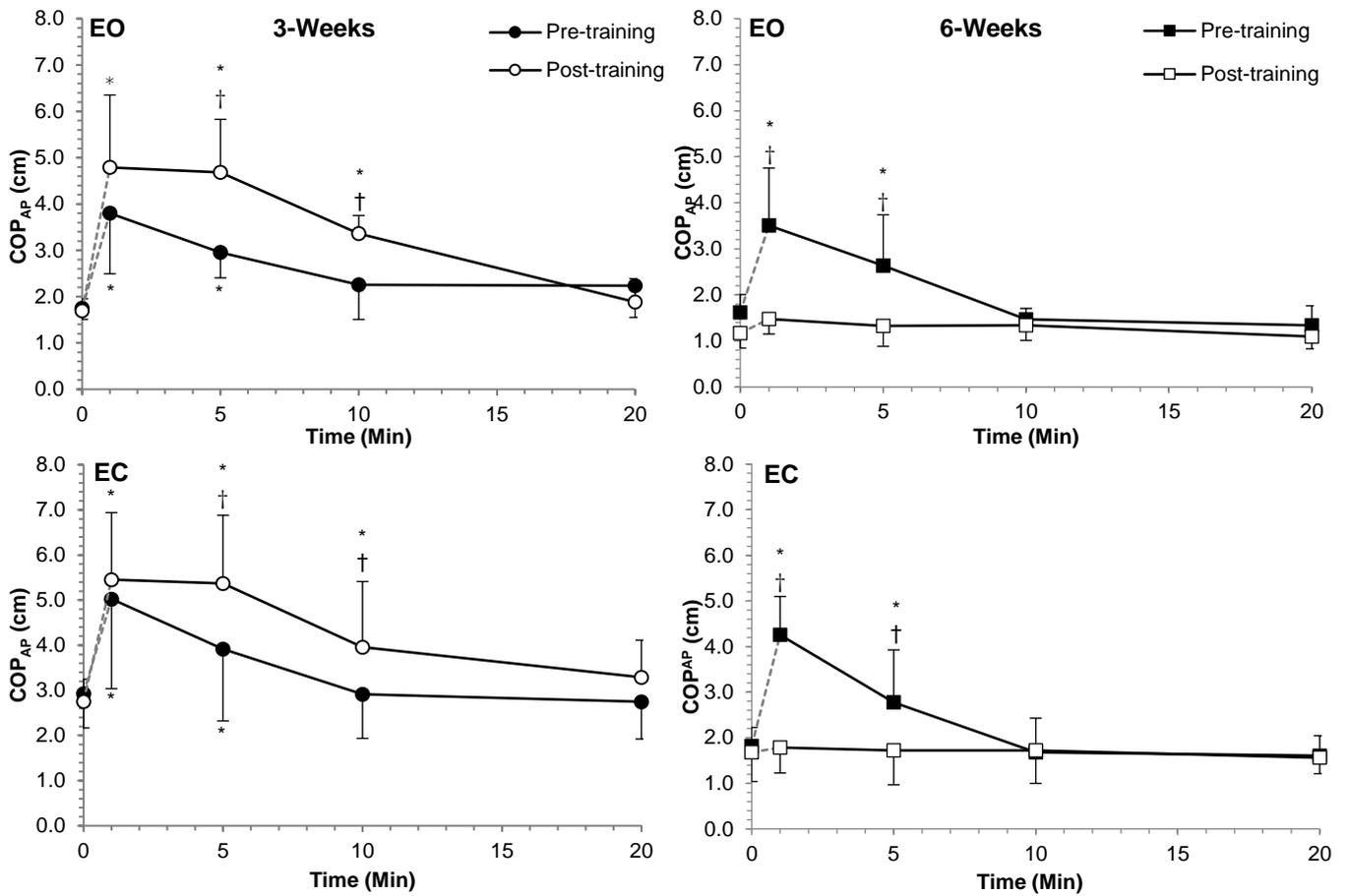**Fig 1.** Schematic representation of the experimental design and measurement periods

Fig 2. Centre of pressure displacement in the anteroposterior direction (COP$_{AP}$) for 3-weeks (left) and 6-weeks (right) of HIT during EO (top) and EC (bottom) conditions. Dashed line represents transition from pre (0-min) to immediately post (1-min) exercise. Solid lines represent recovery data points. All data reported as means and SDs. *Significantly different to rested conditions $P \leq 0.05$. † Significantly different compared to same time point pre-training.
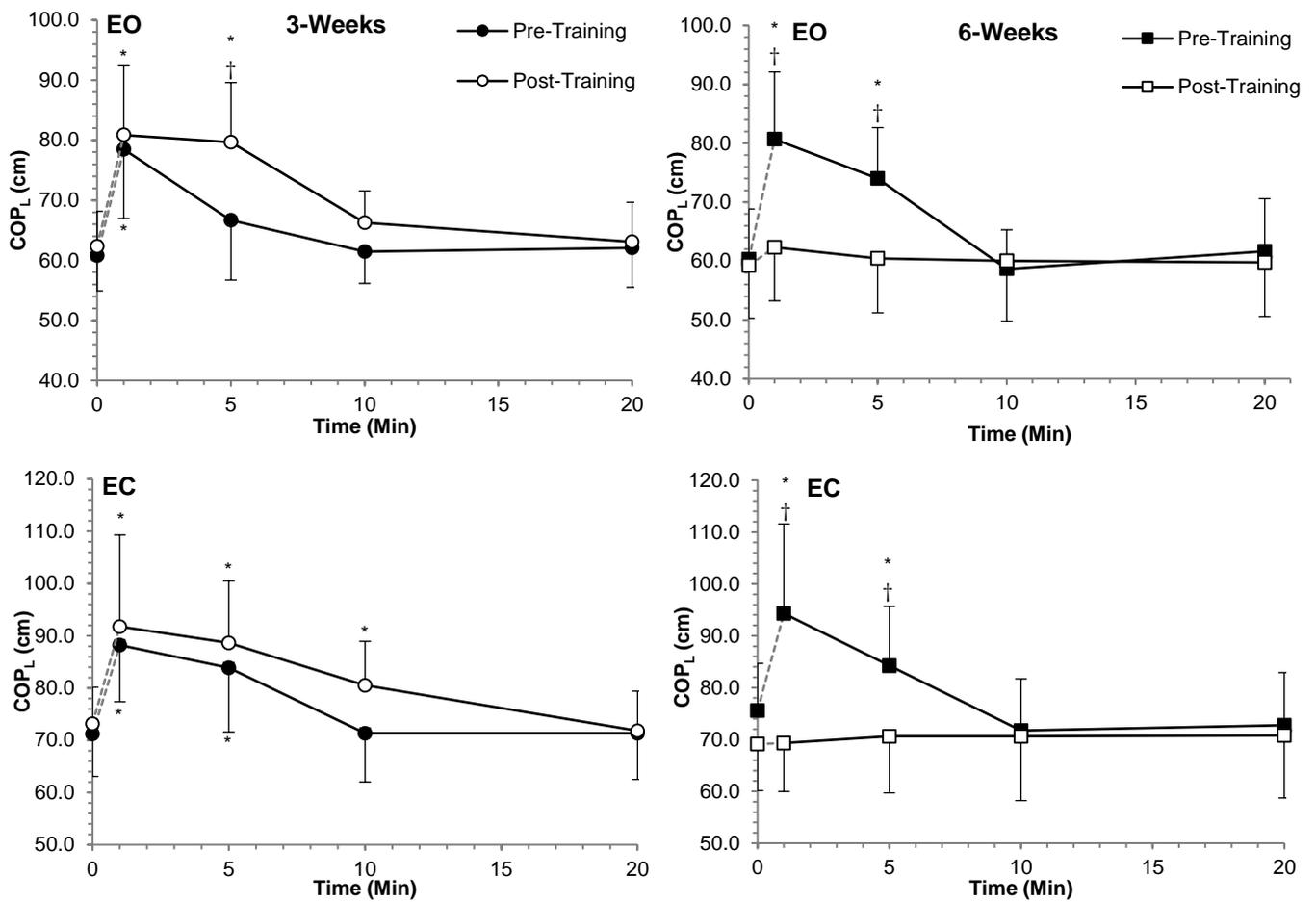
Fig 3. Centre of pressure path length (COP$_L$) for 3-weeks (left) and 6-weeks (right) of HIT during EO (top) and EC (bottom) conditions. Dashed line represents transition from pre (0-min) to immediately post (1-min) exercise. Solid lines represent recovery data points. All data reported as means and SDs. *Significantly different to rested conditions $P \leq 0.05$. **. † Significantly different compared to same time point pre-training.
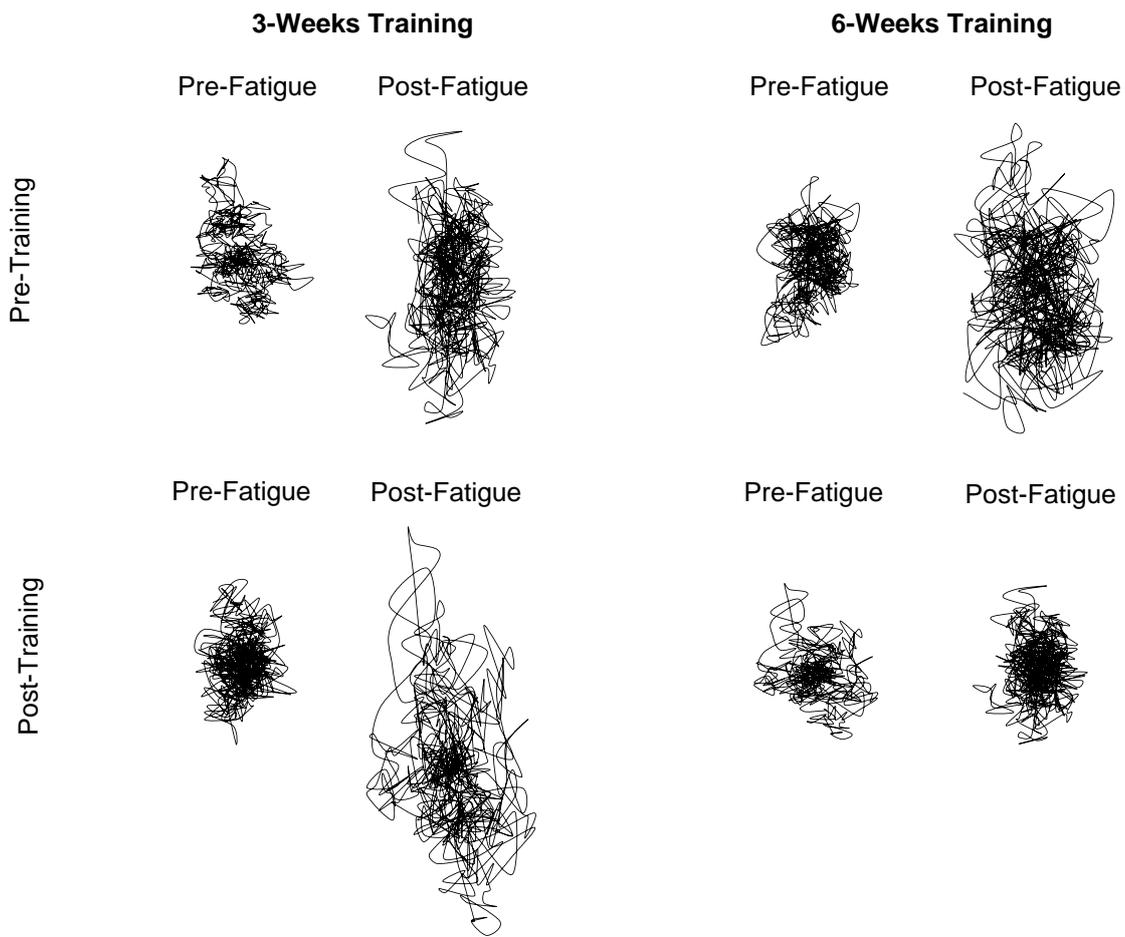
3-Weeks Training   **6-Weeks Training**

Pre-Fatigue   Post-Fatigue   Pre-Fatigue   Post-Fatigue

Pre-Training

Pre-Fatigue   Post-Fatigue   Pre-Fatigue   Post-Fatigue

Post-Training

Fig. 4: Representative COP signals recorded during pre-fatigued and post fatigue conditions before and after from a representative participant for the 3-week and 6-weeks training groups
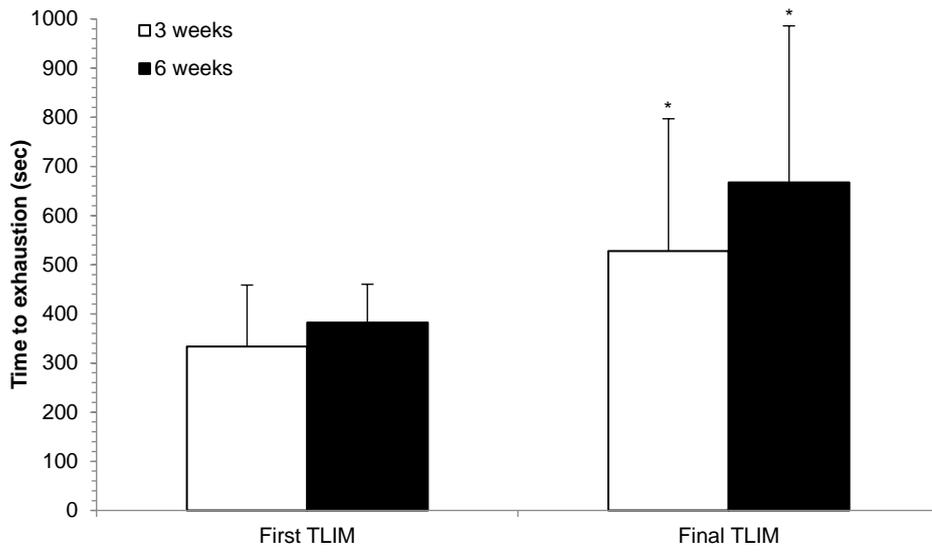
Fig. 5. Time to exhaustion in the first and final training sessions for the 3 week and 6 week training groups. * Significantly different to first T_{LIM} training session