Journal of Human Kinetics volume 66/2019, 7-18 DOI: 10.2478/hukin-2018-0063
Section I – Kinesiology

Unilateral Knee and Ankle Joint Fatigue Induce Similar Impairment to Bipedal Balance in Judo Athletes

by
Amine Ghram[1,2,4], James D Young[3], Rahman Soori[1], David G Behm[3]

The purpose of this study was to compare the effects of unilateral ankle fatigue versus the knee muscles with and without vision on bipedal postural control. Elite judo athletes who competed at the national level with at least 10 years of training experience, were randomised into KNEE (n = 10; 20 ± 2 years) and ANKLE (n = 9; 20 ± 3 years) groups, who performed dynamic isokinetic fatiguing contractions (force decreased to 50% of initial peak torque for three consecutive movements) of the knee flexors and extensors or ankle dorsiflexors and plantar flexors, respectively. Static bipedal postural control (French Posturology Association normative standards) with eyes open and eyes closed was examined before and immediately after the fatiguing task. Postural variables examined were the centre of pressure (CoP) sway in the medio-lateral and antero-posterior directions, total CoP area sway and CoP sway velocity. Although unilateral ankle and knee fatigue adversely affected all bipedal postural measures, with greater disturbances with eyes closed, there were no significant main group or interaction effects between KNEE and ANKLE groups. Unilateral lower limb fatigue adversely affected bipedal balance, with knee extension/flexion fatigue affecting bipedal postural control to a similar extent as unilateral ankle dorsiflexion/plantar flexion fatigue. Hence unilateral fatigue can affect subsequent bilateral performance or also have implications for rehabilitation exercise techniques. Our findings may be limited to judo athletes as other populations were not tested.

Key words: *postural control, unilateral fatigue, bipedal stance, crossover fatigue.*

Introduction

The ability to maintain balance with a bipedal stance is required for activities of daily living and can be severely challenged in many sporting activities. Postural control is important for developing and optimising an athlete's fundamental motor skills. Postural control involves interactions between external forces and the orientation of various body segments, all of which is regulated by the neuromuscular system (Massion, 1994). Muscle fatigue is an inevitable result of physical activity and exercise that must be controlled by the central nervous system (Vuillerme et al., 2009; Maszczyk et al., 2018). The onset of neuromuscular fatigue introduces a unique challenge to the postural control system.

The effect of unilateral fatigue on homologous contralateral (crossover fatigue) or distant (non-local muscle fatigue) muscle force (Halperin et al., 2014; Kawamoto et al., 2014), and fatigue endurance (Halperin et al., 2014) has been well documented (Halperin et al., 2015). Fatigue-induced deterioration in postural control during the unipedal and bipedal stance has also been observed for unilateral and bilateral muscle groups, respectively (Paillard et al., 2010; Soleimanifar et al., 2012). Alterations in bipedal

---

[1] - *Department of Exercise Physiology, Faculty of Physical Education and Sport Sciences, University of Tehran, Tehran, Iran.*
[2] - *Unité de recherche sur les pathologies de l'appareil locomoteur UR12ES18, hôpital Habib Bourguiba, Université du Sud, Sfax, Tunisie.*
[3] - *School of Human Kinetics and Recreation, Memorial University of Newfoundland, St. John's, Newfoundland, Canada, A1M 3L8.*
[4] - *Department of Cardiac Rehabilitation, Tehran Heart Center, Tehran University of Medical Sciences, Tehran, Iran.*

Authors submitted their contribution to the article to the editorial board.
Accepted for printing in the Journal of Human Kinetics vol. 66/2019 in March 2019.

postural stability have also been reported following fatiguing unilateral tasks (Berger et al., 2010, Paillard and Borel, 2013; Vuillerme et al., 2009) for the plantar flexors (Berger et al., 2010), hip abductors (Vuillerme et al., 2009), and quadriceps (Paillard and Borel, 2013). However, the findings are not all in agreement as Arora et al. (2015) reported no effect of contralateral unilateral knee extensor fatigue on balance assessment consisting of transition from double to single leg standing and also single leg standing trials. Halperin et al. (2015) in their review indicated that non-local muscle fatigue effects were more consistently apparent with endurance tasks in the non-exercised limbs compared to single or short duration contractions (i.e. short duration postural control).

According to the literature, ankle and hip strategies are the two most predominant postural control modulators (Chua et al., 2014). Several studies have compared the effects of unilateral proximal (hip and knee) and distal (ankle) muscle fatigue on unipedal standing (Bizid et al., 2009; Soleimanifar et al., 2012). They found that unilateral hip and/or knee muscle fatigue altered the unipedal stance more than ankle muscle fatigue. Since the bipedal stance is more representative of postural functional abilities during gait and quiet standing in men, more research is needed to compare the effects of contralateral (unilateral) knee extension/flexion fatigue to dorsiflexion/plantar flexion fatigue on bilateral postural control. Furthermore, it is important to understand the relationship between judo athlete’s unilateral fatigue and their bilateral postural control since many injuries are associated with the ankle and knee in judo. Many athletes including those practising judo use unilateral training on the ankle and knee in their rehabilitation process. In addition, although judo involves a bipedal stance, the pivot and the sweeping leg have specific and different roles, emphasizing the unilateral nature of their functions. If unilateral training has implications for bilateral postural stability, it would be an important consideration for the order of training exercise for judo athletes, other athletes and fitness practitioners. For example, training the sweep leg first could adversely affect the quality performance of subsequent bilateral movement training.

Vision has a strong effect on postural control (Ghram et al., 2016). Several authors have reported that postural control improves when visual information is provided (Ghram et al., 2016). Studies investigating the effects of unilateral muscle fatigue on bipedal postural control have been performed using blinded participants to prevent vision from contributing to the regulation of postural behaviors (Paillard and Borel, 2013). Furthermore, the effects of muscle fatigue on unipedal postural control have been examined with eyes opened (EO) and eyes closed (EC) to assess the effect of vision on postural sway and to determine whether an interaction existed between vision and fatigue (Boyas et al., 2011; Soleimanifar et al., 2012). It would be interesting to know how the addition or removal of vision influences unilateral fatigue-induced alterations in bipedal postural control, that was not considered in previous studies.

Otherwise, the absence of vision significantly disturbed postural control for all groups of athletes, as observed previously with many other sports such as judo (Hammami et al., 2014; Paillard et al., 2002). This finding could be explained by the fact that postural regulation developed in terms of visual control with sports training is not always transferable to the upright stance (Asseman et al., 2004). Since dependence on vision is related to the nature of the sport, clarifying the influence of the type of activity and the importance of vision on changes in balance performance appears to be important (Hammami et al., 2014). Since judo athletes remain in contact with each other throughout a large part of the bout, periodically their vision can be obstructed when grappling. Krabben et al. (2018) indicated that this sport might even be performed quite adequately without vision. Vision is typically considered the predominant sense for guiding performance as blind judo athletes perform worse in competition than their partially sighted opponents and sighted judo athletes perform worse when fighting blindfolded (Krabben et al., 2018). Thus, including the absence of visual information on postural demands especially with fatigue could have an impact on performance. Judo is a contact sport, with a major objective being to disrupt the opponent’s balance. Success necessitates that balance and coordination must be optimal to repeatedly perform the demanding complex defensive and offensive skills. Balance disruptions due to judo falls and throws can also lead to knee (28% of injuries) (Cynarski and Kudlacz, 2008) and ankle injuries (16% of injuries) (Yard et al., 2007) and thus the effects of unilateral fatiguing training exercises on bilateral balance would be important to investigate.

It is not known whether fatiguing the knee or ankle joint muscles, respectively, has a greater impact on balance. Considering such a high participation rate in a combat sport and the relatively high injury risk (Cynarski and Kudlacz, 2008) especially associated with muscle fatigue, research on judo muscle fatigue would be essential to identify risk factors. In addition, unilateral exercise can effectively enhance muscle strength of the contralateral homologous muscles (Carroll et al., 2006). Unilateral fatiguing contractions transiently modulate neural activation patterns and motor performance in the non-fatigued, contralateral homologous (Kawamoto et al., 2014) and heterologous muscles (Šambaher et al., 2016), Hence, we conducted the present study to investigate the effect of unilateral muscle fatigue on static balance in judo.

Literature comparing the effects of unilateral knee versus ankle fatigue on bipedal postural control for judo athletes is lacking. Ankle proprioception, which can be altered by injuries and fatigue provides essential information to control balance with ankle adjustments and upper body movements, in order to successfully perform complex motor tasks (Han et al., 2015). Studies are needed to directly assess the effects of fatigue on ankle and knee neuromuscular functions in judo athletes.

Therefore, the purpose of the present study was to compare the effects of unilateral knee and ankle fatiguing tasks on bipedal postural control, with and without visual information. It was hypothesized that: (1) knee muscle fatigue (proximal muscle) would induce greater postural control alterations than ankle muscle fatigue (distal muscle), and (2) removal of visual information would alter postural sway.

Methods

Participants

Nineteen young, healthy, male judo athletes were randomised into two groups: Group KNEE (n = 10; age: 20 ± 2 years, body height: 181 ± 5 cm, body mass: 71.9 ± 8.6 kg) performed a fatiguing task with dynamic isokinetic contractions of the knee flexors and extensors; Group ANKLE (n = 9; age: 20 ± 3 years, body height: 180 ± 5 cm, body mass: 73 ± 9 kg) performed a fatiguing task with dynamic isokinetic contractions of the ankle dorsiflexors and plantar flexors.

All participants competed at the national level, performed similar amounts of weekly training (10-14 hours) and competed in national tournaments. They had practiced judo for at least 10 years and attained a competency level between 1st and 3rd dan. None of the participants had ceased training for more than three weeks during the six months before the study. All judo athletes had right lower limb dominance (the preferred leg to kick a ball). Fourteen judo athletes had a right handed grip and five had a left handed grip.

Exclusion criteria were acute illness or pain that would affect participation, a history of back or lower extremity injury that required surgical intervention or had been persistent (within the last 6 months), balance difficulties or vestibular dysfunction, or current injuries making the athletes unable to participate. This study was approved by the University of Tehran research ethics committee and all participants gave informed written consent.

Procedures

Volunteers attended one laboratory session and refrained from performing lower body exercise other than activities of daily living for at least 48 hours prior to testing. The isokinetic dynamometer (Cybex Norm II; Medimex) was calibrated 30-min prior to testing. After a brief 5-min warm-up on a cycle ergometer (Monark 894E, Stockholm, Sweden) at 70 rpm (Ghram et al., 2016, 2017), the participants were positioned for dynamic evaluation of flexion and extension movements of the knee joint. They remained seated with the hips at 90° of flexion, secured to a chair with a belt. To ensure consistency, the test was performed with the dominant limb, defined as the preferred leg to kick a ball. Since accomplished judo athletes should be able to alternate both legs as their pivot and sweeping legs, these functions could not be used to distinguish a particular limb. Many studies that assessed balance control in athletes have identified the dominant leg by the limb that kicks the ball with the other leg as the supporting limb. Furthermore, leg dominance may play a role in directional balance and when choosing to manipulate an opponent, the dominant foot is favored. The knee joint was evaluated by positioning the lateral condyle of the femur in alignment with the mechanical axis of the dynamometer. The axis of rotation at the ankle joint was parallel to the axis of the dynamometer and passed through the midpoint of both malleoli.

Regarding the isokinetic ankle test, the participant lay in a supine position with the hip and knee straight. Velcro straps secured the chest, pelvis, thigh and foot. An anti-slip mat was placed under the back, and a towel was folded under the straight knee to minimise uncomfortable hyperextension. The arms were kept crossed over the chest. The axis of rotation just distal to the lateral malleolus was aligned with the rotational axis of the lever arm on the dynamometer. The ankle joint range of motion was set at 10° dorsiflexion and 40° plantar flexion. The 90° position of the ankle joint was regarded as the neutral 0° position.

Regarding the isokinetic knee test, each participant was positioned on an adjustable chair with the back set at 90° of posterior inclination. The sitting position was set according to the manufacturer’s recommendations. The knee range of motion was set at 90° (from 100° to 10° of flexion; 0° corresponding to the complete extension of the knee) after having aligned the leg segment to anatomical zero. Finally, a measurement of gravity for the leg segment to be tested was carried out over the entire range of motion.

In order to determine the initial peak torque (IPT) values, participants performed two sets of dynamic contractions at 60°/s for both target muscle groups. The first set was a familiarisation task consisting of three submaximal and three maximal contractions. The second set included three maximal effort contractions performed in succession. One minute of rest was given following each contraction. The highest peak torque of the three repetitions was recorded as IPT (Soleimanifar et al., 2012). In order to determine the IPT values, the isokinetic strengths were examined at 60°/s throughout a 90° range of motion during the concentric contraction (Yahia et al., 2011).

After a 3 min interval, according to the fatigue protocol, participants performed continuous concentric/concentric plantar/dorsiflexion movements at 60°/s for both muscles (Soleimanifar et al., 2012). Knee flexors and extensors were fatigued using the same protocol. Fatigue was achieved when flexion and extension torque output dropped below 50% of IPT for three consecutive movements (Soleimanifar et al., 2012). Verbal encouragement was provided. Participants were exhorted to push or contract harder when a single contraction decreased below 50% IPT. After completing the fatigue protocol, participants conducted a postural stability task with a delay of no more than 40 seconds (see Table 1 for the experimental design).

Balance evaluation

Postural control was evaluated using a force platform (SATEL ®; 40 Hz frequency, 12-bit A/D conversion, 480x480 mm, Blagnac, France), supported by three sensors, to record the displacement of the center of pressure (CoP) (Yahia et al., 2011). Postural control was examined before (PRE) and immediately after (POST) the fatiguing task. Participants were required to stand barefoot on a force plate as still as possible in a double leg stance (Arora et al., 2015). Following the French Posturology Association normative standards, each trial lasted approximately 51.2 s (Yahia et al., 2011). Participants were positioned in an upright posture on the platform with arms at their sides, heels placed 5 cm apart, and feet separated by an angle of 30°. The measurements were performed in randomised order for each participant with eyes open (EO) and eyes closed (EC). During the EO condition, participants were instructed to focus on a mark placed at the eye level, 1.5 m directly in front of them. During the EC condition, participants were required to close their eyes and keep their gaze straight-ahead. To evaluate postural control of participants, four postural variables were considered. CoP sway (mm) in the medio-lateral (ML) and antero-posterior (AP) directions, total CoP area sway (mm^2) represented by the area of the 95% confidence ellipse, and CoP sway velocity (mm/s) represented by the total CoP displacement over time. Four variables were used to provide a comprehensive analysis of the amplitude and velocity of changes in the centre of pressure.

Statistical analysis

Data was assessed and did exhibit normality and homogeneity of variance using the Shapiro-Wilk and Levene's tests, respectively. Mean, standard deviation (SD) and standard error of the mean (SEM) values were calculated for each dependent variable. The IPT and the number of contractions performed during the fatiguing tasks were compared between the two groups using a Student's t-test. A three-way within subjects' ANOVA (2 groups × 2 fatigue × 2 vision) was used to assess differences between groups (KNEE vs. ANKLE), fatigue protocol (PRE vs. POST), and vision (EO vs. EC) in the dependent variables: ML sway, AP sway, CoP area sway, and CoP sway velocity. Bonferroni post-hoc analysis was performed. Greenhouse Geisser adjustment was reported in cases where the sphericity assumption was violated. We assessed this type of reliability with the intraclass correlation coefficient (ICC). The ICC indicates the error in measurements as a proportion of the total variance in scores. As a general rule, we considered an ICC over 0.90 as high, between 0.80 and 0.90 as moderate and below 0.80 as insufficient (Vincent, 1999). All statistical tests were processed using STATISTICA Software (version 8.0; StatSoft, France). Cohen effect size statistics (ES) were conducted to evaluate the magnitude of the changes to the criterion of >0.70 large; 0.40-0.70 medium and <0.40 small (Cohen, 1988).

Results

The majority of measures were classified as moderate to high reliability (Table 2).

In PRE condition, IPT was significantly different between KNEE and ANKLE groups (KNEE: 300.4 ± 25.29 N·m; ANKLE: 153.66 ± 15.84 N·m; t-value = 14.94, $p < 0.001$). In order to reach 50% decline of the measured peak torque for the three consecutive contractions, The ANKLE group performed significantly (t = 9.11, $p < 0.001$) more concentric contractions (57 ± 5) than the KNEE group (37 ± 4).

There were no significant main group effects between KNEE and ANKLE groups for all variables. However, there was a significant main effect of fatigue for all dependent variables; ML sway (degree of freedom (df) = 1, F = 1.53, $p < .001$, Partial eta-squared $\eta^2 = 0.5$, observed power = 0.97), AP sway (df = 1, F = 40.43, $p < .001$, $\eta^2 = 0.7$, observed power = 0.99), CoP area sway (df = 1, F = 4.47, $p = .04$, $\eta^2 = 0.2$, observed power = 0.51) and CoP sway velocity (df = 1, F = 26.3, $p < .001$, $\eta^2 = 0.6$, observed power = 0.99). There was no interaction with fatigue between groups for any variable. Significant main effects for vision were observed for ML sway (df = 1, F = 23.14, $p < .001$, $\eta^2 = 0.57$, observed power = 0.99), AP sway (df = 1, F = 43.7, $p < .001$, $\eta^2 = 0.71$, observed power = 0.99), CoP area sway (df = 1, F = 54.41, $p < .001$, $\eta^2 = 0.76$, observed power = 0.99) and CoP sway velocity (df = 1, F = 28.21, $p < .001$, $\eta^2 = 0.62$, observed power = 0.99) (Figures 1 and 2).

Table 1

Experimental Design

	KNEE Group (n = 10)	ANKLE Group (n = 9)
Initial Peak Torque (IPT)	3 reps of isokinetic concentric knee flexion and extension at $60^0 \cdot s^{-1}$ to determine IPT	3 reps of isokinetic concentric dorsiflexion and plantar flexion at $60^0 \cdot s^{-1}$ to determine IPT
Intervention	Isokinetic concentric knee flexion and extension at $60^0 \cdot s^{-1}$ till failure (torque output of 3 consecutive contractions <50% of IPT)	Isokinetic concentric dorsiflexion and plantar flexion at $60^0 \cdot s^{-1}$ till failure (torque output of 3 consecutive contractions <50% of IPT)
Test Measures	Static Bilateral Postural Stability (French Posturology Association Normative Standards) Eyes Opened Eyes Closed	

reps : repetitions

Table 2

Reliability analysis of Center of Pressure (CoP) measures for both groups (PRE-KNEE and PRE-ANKLE) (KNEE: n = 10; ANKLE: n = 9)

	Eyes Opened				Eyes Closed			
	ICC	95% CI	*p*	SEM	ICC	95% CI	*p*	SEM
ML sway (mm)	0.78	0.02 - 0.95	0.02	26.64	0.95	0.79 - 0.98	0.000	16.33
AP sway (mm)	0.62	-0.64 - 0.91	0.09	27.23	0.75	-0.09 - 0.94	0.032	50.22
CoP area sway (mm²)	0.87	0.44 - 0.97	0.004	27.99	0.9	0.58 - 0.97	0.001	43.05
CoP sway velocity (mm/s)	0.75	-0.06 - 0.94	0.02	0.66	0.85	0.34 - 0.96	0.007	0.96

ICC: intraclass correlation coefficient; SEM: standard error of measurement; 95% CI: 95% of Confidence Interval; ML: medio-lateral; AP: antero-posterior; COP: center of pressure

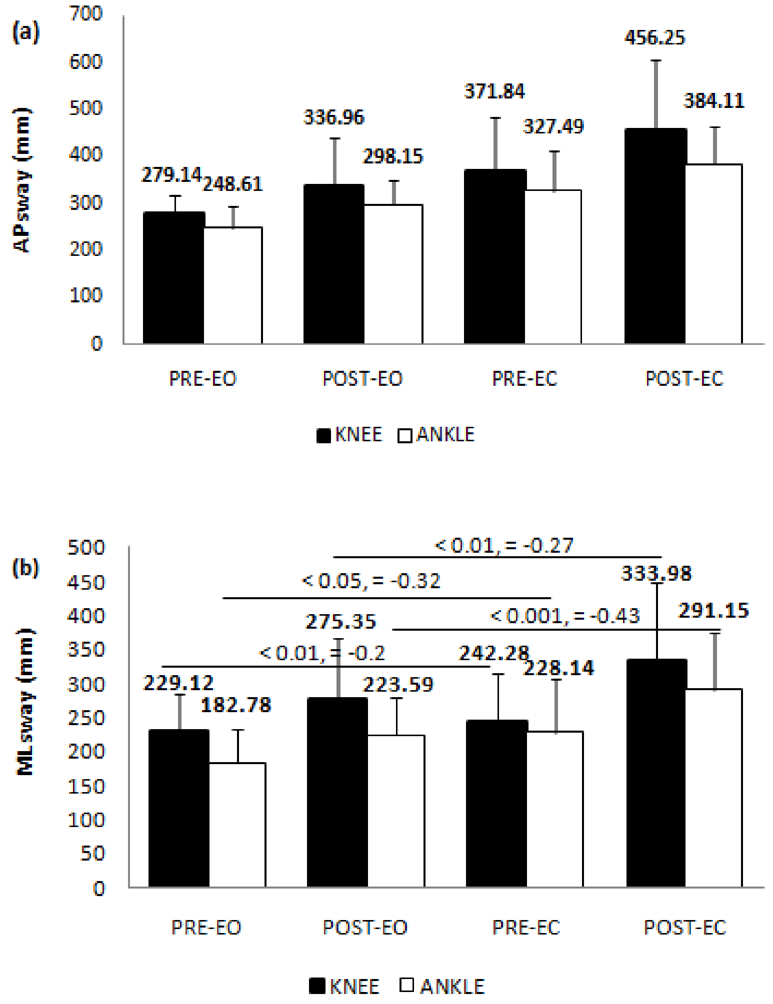

Figure 1

Mean values and standard deviation (SD) of (a) AP (antero-posterior) sway; and (b) ML (medio-lateral) sway in the two conditions of PRE (pre-fatigue) and POST (post-fatigue) for two groups (KNEE, ANKLE). p-values and effect sizes (e.g. Cohen´s d) are shown.

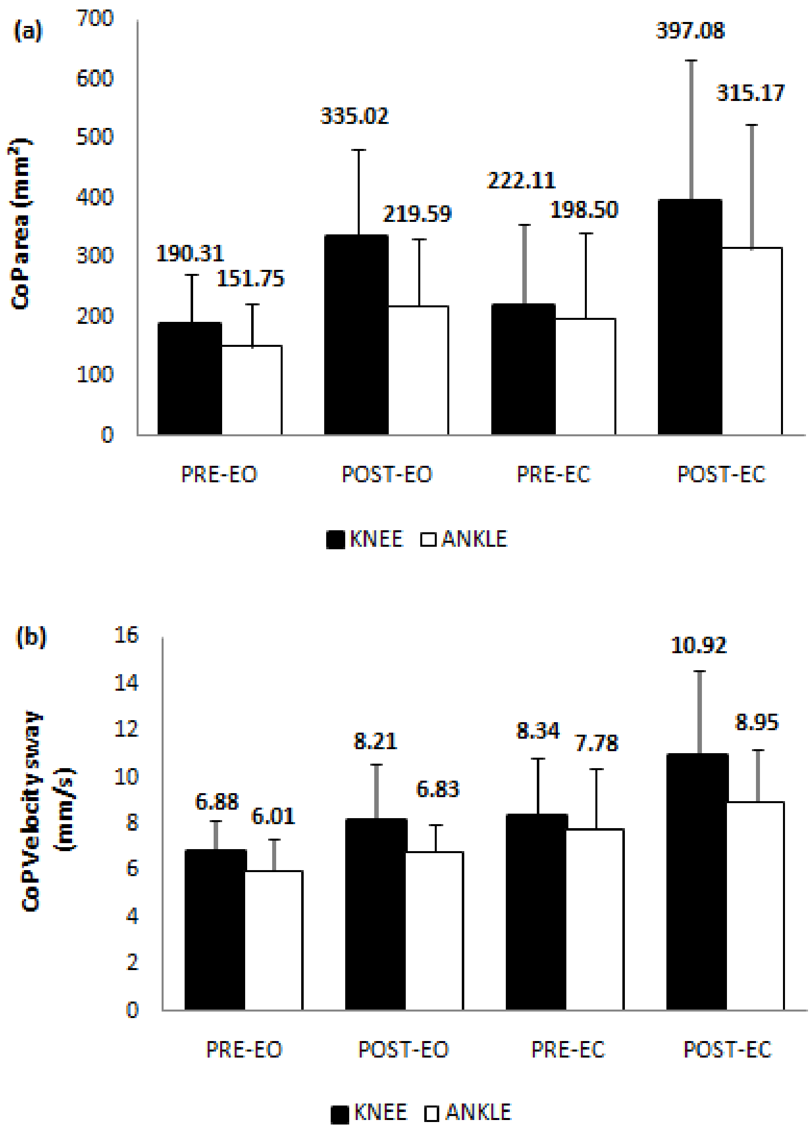

Figure 2

Mean values and standard deviation (SD) of (a) CoP (center of pressure) area sway; and (b) CoP sway velocity in the two conditions of PRE (pre-fatigue) and POST (post-fatigue) for two groups (KNEE: knee muscle; ANKLE: ankle muscle).

There was an interaction between fatigue and vision for ML sway (df = 1, F = 11.33, *p* = .003, η^2 = 0.39, observed power = 0.88). ML sway increased significantly after fatigue for EO and EC condition irrespective of the group. In both PRE and POST fatigue, ML sway increased more in EC conditions for both KNEE (PRE-EO vs. PRE-EC, *p* < .01, Cohen's d = - 0.2, r = -0.1; POST-EO vs. POST-EC, *p* < .01, Cohen's d = -0.5, r = -0.27) and ANKLE (PRE-EO vs. PRE-EC, *p* < .05, Cohen's d = - 0.69, r = -0.32; POST-EO vs. POST-EC, *p* < .01, Cohen's d = -0.5, r = -0.27; POST-EO vs. POST-EC, *p* < .001, Cohen's d = -0.95, r = -0.43) (Figures 1 and 2).

Discussion

The purpose of this study was to compare the effects of unilateral knee and ankle fatiguing tasks on bipedal postural control, with and without visual information. It was hypothesized that: (1) knee muscle fatigue (proximal muscle) would induce greater postural control alteration than ankle muscle fatigue (distal muscle), and (2) visual removal would alter postural sway. The major findings of the present study revealed that bipedal postural control was similarly impaired when the knee and ankle joints were fatigued and postural sway was more impaired when visual information was removed.

When visual information was removed, postural sway increased for all dependent variables; however, ML sway increased after fatigue for both groups. To the best of our knowledge, this study is the first to compare unilateral muscle fatigue from two separate muscle groups on the bipedal stance. Postural control was impaired as a function of fatigue and vision, although there were no significant differences between the two muscle groups. Previous work has shown that unilateral muscle fatigue deteriorates bipedal postural control (Berger et al., 2010). These alterations could lead to inappropriate or delayed stabilising muscle activation, resulting in decrements in postural control (Boyas et al., 2011).

Unilateral fatigue effects upon non-exercised muscles (non-local muscle fatigue) have been demonstrated between contralateral homologous muscles (i.e. quadriceps) (Kawamoto et al., 2014) as well as heterologous muscles (i.e. quadriceps fatigue affects elbow flexor force; Halperin et al., 2014). Although Arora et al. (2015) did not report bipedal or unipedal balance impairment following unilateral knee extension fatigue, non-local muscle deficits in force (Halperin et al., 2015) could impede neuromuscular responses to balance perturbations.

The present study did not find any significant difference between knee and ankle muscle fatigue on the bipedal stance. This is in contradiction with previous literature that showed unilateral hip or knee muscle fatigue altered the unipedal postural stance more than ankle muscle fatigue (Bizid et al., 2009). The unipedal stance could amplify postural disturbances compared to the bipedal stance, creating an imbalance in the motor output of the two legs. Therefore, in the bipedal stance, adaptation capabilities of the postural system may limit disturbances induced by unilateral fatiguing tasks (Paillard and Borel, 2013). The ankle and hip strategies are the two most important modulators of postural control. They can be used separately or together in varying degrees to produce optimal and adaptable balance control, depending on the difficulty of the balance task (Chua et al., 2014). The ankle strategy is the first strategy activated following perturbation to maintain balance for minor sway. The hip strategy involves deviation at the hip to maintain the center of mass over the base of support. Both strategies work to maintain balance within the stability limits. However, the present study demonstrates that unilateral quadriceps and hamstrings fatigue can play a similar role as ankle dorsiflexion/plantar flexion fatigue on bipedal postural control with young adult elite judo athletes. Since judo athletes must respond to external perturbations constantly during training and competition, there would be an expectation of greater balance performance. This elite group of participants may have contributed to the lack of significant difference between the knee and ankle muscle fatigue on balance. Furthermore, judo athletes may be able to compensate for lower body fatigue-induced balance impairment by more sensitively modifying the centre of gravity with upper body movements. Similar findings might not be encountered with less athletic participants.

Ankle IPT was significantly lower than knee IPT, which could be a result of the greater number of ankle concentric contraction versus knee contractions. Similar to previously published results (Bizid et al., 2009), there was a significant difference between quadriceps and triceps surae muscles after isometric contractions. It has been suggested that isometric actions induce central fatigue first, followed by peripheral fatigue (Babault et al., 2006). These authors reported that metabolite concentration might be higher during an isometric fatiguing procedure compared with concentric fatigue and would first increase the inhibitory effect of small diameter afferents (groups III and IV) and involve an α-motoneuron inhibition at the spinal level impairing neuromuscular control.

Local muscle fatigue due to a repeated stimulus is characterised by force impairment. Unilateral fatiguing contractions would lead to a transient modulation of neural activation patterns and motor performance in the non-fatigued, contralateral homologous (Kawamoto et al., 2014) and heterologous muscles (Šambaher et al., 2016). In the present study, we evoked fatigue with an isokinetic dynamometer. The majority of the studies on dynamic fatiguing muscle actions have assessed isometric force output in the rested muscles; however, it can be argued that isometric contractions are not pertinent to examine neuromuscular fatigue associated with the dynamic movements involved in daily life activities as well as training programs (Prieske et al., 2017). The specific movement velocity during dynamic muscle actions may influence cross-over motor responses, given that this variable is known to affect force/torque output (Babault et al., 2002), neural drive (Babault et al., 2002; Morel et al., 2015), and metabolic stress (Morel et al., 2015).

Success in judo necessitates the maintenance of strong postural control and balance. While the opponent is attempting to disrupt that balance, accumulation of fatigue can also deteriorate postural control (Bizid et al., 2009; Paillard and Borel, 2013; Soleimanifar et al., 2012) and could contribte to musculoskeletal injuries. Unilateral exercises can positively affect performance of subsequent bipedal rehabilitation and training exercises.

When visual information is removed, a decrease in postural control (stability) following knee and ankle muscle fatigue is observed. For example, the interaction between fatigue and vision was significant for ML sway, which was in accordance with the literature (Boyas et al., 2011) and suggests that vision can compensate for fatigue-induced impairment in postural control. Vision is typically considered the predominant sense for guiding performance and enhances judo performance (Krabben et al., 2018). Paillard et al. (2002) did not observe any significant difference between the postural performances of two groups of judo athletes at different levels of competition when testing participants with a classical bipedal standing task. These authors showed that judo athletes at the highest level of competition were more dependent on visual information to control their posture. Judo athletes remain in contact with each other throughout a large part of the competition. Grappling and throws can temporarily impair vision of the opponent and the visual field. Blind judo athletes perform worse in competition than their partially sighted opponents and sighted judo athletes perform worse when fighting blindfolded (Krabben et al., 2018). With all the competing visual information (i.e. movement of opponent, location on the mat) the focus of visual contributions to balance may be compromised. Balance testing without vision places a greater emphasis on the proprioceptive contributions to postural stability, which would be relevant to help ensure competitive success. These findings further illustrate the strong influence of vision on postural maintenance and the regulation of postural control.

A limitation of the present study may be the modest number of participants. However, the observed power ranged from 0.88-0.99 indicating strong statistical power. Secondly, there was no direct comparison with a non-judo control group. Nonetheless there have been a number of other studies that have examined the effects of unilateral fatigue on postural control (Arora et al., 2015; Berger et al., 2010, Paillard and Borel, 2013; Vuillerme et al., 2009). In addition, a between but not a within-subject design was used with the latter one providing greater statistical power. Thus, the observed results are affected by group differences per se as well as by differences in terms of the applied fatigue protocol (knee extension/flexion fatigue vs. ankle dorsiflexion/plantar flexion fatigue).

Conclusions

In summary, the present results demonstrated that unilateral lower limb fatigue adversely affected bipedal balance. Secondly, knee extension/flexion fatigue affected bipedal postural control to a similar extent as unilateral ankle dorsiflexion/plantar flexion fatigue. Athletic trainers and physiotherapists should be aware of these effects when determining an appropriate exercise protocol for bipedal postural control after injury. These results could have important implications for rehabilitation in a fatigued judo athlete. Further studies are required to determine the physiological mechanisms of muscular fatigue that contribute to alterations in bipedal balance.

Acknowledgements

We are grateful for all participants who contributed their time and experiences.

References

Arora S, Budden S, Byrne JM, Behm DG. Effect of unilateral knee extensor fatigue on force and balance of the contralateral limb. *Eur J Appl Physiol*, 2015; 115(10): 2177–87. http://doi.org/10.1007/s00421-015-3198-5

Asseman F, Caron O, Crémieux J. Is there a transfer of postural ability from specific to unspecific postures in elite gymnasts? *Neurosci Letters*, 2004; 358(2): 83-6. http://doi.org/10.1016/j.neulet.2003.12.102

Babault N, Desbrosses K, Fabre MS, Michaut A, Pousson M. Neuromuscular fatigue development during maximal concentric and isometric knee extensions. *J Appl Physiol*, 2006; 100(3): 780-5. http://doi.org/10.1152/japplphysiol.00737.2005

Babault N, Pousson M, Michaut A, Ballay Y, Van Hoecke J. EMG activity and voluntary activation during knee-extensor concentric torque generation. *Eur J Appl Physiol*, 2002; 86(6): 541-7. http://doi.org/10.1007/s00421-002-0579-3

Berger LL, Regueme SC, Forestier N. Unilateral lower limb muscle fatigue induces bilateral effects on undisturbed stance and muscle EMG activities. *J Electromy Kinesiol : Official Journal of the International Society of Electrophysiological Kinesiology*, 2010; 20(5): 947–52. http://doi.org/10.1016/j.jelekin.2009.09.006

Bizid R, Margnes E, François Y, Jully JL, Gonzalez G, Dupui P, Paillard T. Effects of knee and ankle muscle fatigue on postural control in the unipedal stance. *Eur J Appl Physiol*, 2009; 106(3): 375–80. http://doi.org/10.1007/s00421-009-1029-2

Boyas S, Remaud A, Bisson EJ, Cadieux S, Morel B, Bilodeau M. Impairment in postural control is greater when ankle plantarflexors and dorsiflexors are fatigued simultaneously than when fatigued separately. *Gait & Posture*, 2011; 34(2): 254–9. http://doi.org/10.1016/j.gaitpost.2011.05.009

Carroll TJ, Herbert RD, Munn J, Lee M, Gandevia SC. Contralateral effects of unilateral strength training: Evidence and possible mechanisms. *J Appl Physiol*, 2006; 101(5): 1514-22. http://doi.org/10.1152/japplphysiol.00531.2006

Chua MC, Hyngstrom AS, Ng AV, Schmit BD. Movement strategies for maintaining standing balance during arm tracking in people with multiple sclerosis. *J Neurophysiol*, 2014; 112(7): 1656–66. http://doi.org/10.1152/jn.00598.2013

Cynarski WJ, Kudlacz M. Injuries in martial arts and combat sports - a comparative study. *Arch Budo*, 2008; 4: 91-7

Ghram A, Damak M, Costa PB. Effect of acute contract-relax proprioceptive neuromuscular facilitation stretching on static balance in healthy men. *Science & Sports*, 2017; 32(1): e1–e7. http://doi.org/10.1016/j.scispo.2016.06.005

Ghram A, Damak M, Rhibi F, Marchetti PH. The contract-relax proprioceptive neuromuscular facilitation (PNF) stretching can affect the dynamic balance in healthy men. *Medical Express*, 2016; 3(4): M160404.

http://doi.org/10.5935/MedicalExpress.2016.04.04

Halperin I, Aboodarda SJ, Behm DG. Knee extension fatigue attenuates repeated force production of the elbow flexors. *Eur J Sport Sci*, 2014; 14(8): 823–9. http://doi.org/10.1080/17461391.2014.911355

Halperin I, Chapman DW, Behm DG. Non-local muscle fatigue: effects and possible mechanisms. *Eur J Appl Physiol*, 2015; 115(10): 2031–48. http://doi.org/10.1007/s00421-015-3249-y

Halperin I, Copithorne D, Behm DG. Unilateral isometric muscle fatigue decreases force production and activation of contralateral knee extensors but not elbow flexors. *Appl Physiol, Nutr Metabol*, 2014; 39(12): 1338–44. http://doi.org/10.1139/apnm-2014-0109

Hammami R, Behm DG, Chtara M, Ben Othman A, Chaouachi A. Comparison of static balance and the role of vision in elite athletes. *J Hum Kinet*, 2014; 41: 33–41. http://doi.org/10.2478/hukin-2014-0030

Han J, Anson J, Waddington G, Adams R, Liu Y. The Role of Ankle Proprioception for Balance Control in relation to Sports Performance and Injury. *BioMed Research International*, 2015, 24: 1–8. http://doi.org/10.1155/2015/842804

Kawamoto JE, Aboodarda SJ, Behm DG. Effect of differing intensities of fatiguing dynamic contractions on contralateral homologous muscle performance. *J Sports Sci Med*, 2014; 13(4): 836–45

Krabben KJ, van der Kamp J, Mann DL. Fight without sight: The contribution of vision to judo performance. *Psychology of Sport and Exercise*, 2018; 37: 157–63. http://doi.org/10.1016/j.psychsport.2017.08.004

Massion J. Postural control system. *Current Opinion in Neurobiology*, 1994; 4(6): 877–87. http://doi.org/10.1016/0959-4388(94)90137-6

Maszczyk A, Gołaś A, Pietraszewski P, Kowalczyk M, Cięszczyk P, Kochanowicz A, Smółka W, Zając A. Neurofeedback for the enhancement of dynamic balance of judokas. *Biol. Sport* 2018; 35: 99-102. http://doi.org/10.5114/biolsport.2018.71488

Morel B, Clémençon M, Rota S, Millet GY, Bishop DJ, Brosseau O, Rouffet DM, Hautier CA. Contraction velocity influence the magnitude and etiology of neuromuscular fatigue during repeated maximal contractions. *Scand J Med Sci Sports*, 2015; 25(5): e432-41. http://doi.org/10.1111/sms.12358

Paillard T, Borel L. Unilateral and bilateral fatiguing contractions similarly alter postural stability but differently modify postural position on bipedal stance. *Hum Mov Sci*, 2013; 32(2): 353–62. http://doi.org/10.1016/j.humov.2012.12.001

Paillard T, Costes-Salon C, Lafont C, Dupui P. Are there differences in postural regulation according to the level of competition in judoists? *Br J Sports Med*, 2002; 36(4): 304–5

Prieske O, Aboodarda SJ, Benitez Sierra JA, Behm DG, Granacher U. Slower but not faster unilateral fatiguing knee extensions alter contralateral limb performance without impairment of maximal torque output. *Eur J Appl Physiol*, 2017; 117(2): 323–34. http://doi.org/10.1007/s00421-016-3524-6

Šambaher N, Aboodarda SJ, Behm DG. Bilateral knee extensor fatigue modulates force and responsiveness of the corticospinal pathway in the non-fatigued, dominant elbow flexors. *Frontiers in Human Neuroscience*, 2016; 10: 18. http://doi.org/10.3389/fnhum.2016.00018

Soleimanifar M, Salavati M, Akhbari B, Moghadam M. The interaction between the location of lower extremity muscle fatigue and visual condition on unipedal postural stability. *Eur J Appl Physiol*, 2012; 112(10): 3495–502. http://doi.org/10.1007/s00421-012-2330-z

Vincent WJ. *Statistics in Kinesiology*. 1999; Champaign, IL: Human Kinetics

Vuillerme N, Boisgontier M. Changes in the relative contribution of each leg to the control of quiet two-legged stance following unilateral plantar-flexor muscles fatigue. *Eur J Appl Physiol*, 2011; 110(1): 207–13. http://doi.org/10.1007/s00421-010-1449-z

Vuillerme N, Sporbert C, Pinsault N. Postural adaptation to unilateral hip muscle fatigue during human bipedal standing. *Gait & Posture*, 2009; 30(1): 122–5. http://doi.org/10.1016/j.gaitpost.2009.03.004

Yahia A, Jribi S, Ghroubi S, Elleuch M, Baklouti S, Habib Elleuch M. Evaluation of the posture and muscular strength of the trunk and inferior members of patients with chronic lumbar pain. *Joint, Bone, Spine: Revue Du Rhumatisme*, 2011; 78(3): 291–7. http://doi.org/10.1016/j.jbspin.2010.09.008

Yard EE, Knox CL, Smith GA, Comstock RD. Pediatric martial arts injuries presenting to Emergency Departments, United States 1990–2003. *J Sci Med Sport*, 2007; 10(4): 219–26. http://doi.org/10.1016/j.jsams.2006.06.016

Corresponding author:

David G. Behm PhD
School of Human Kinetics and Recreation; Memorial University of Newfoundland
230 Elizabeth Ave. St. John’s, Newfoundland, Canada, A1C 5S7
Phone: 709-864-3408
Fax: 709-864-3979
E-mail: dbehm@mun.ca