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ORIGINAL ARTICLE

Unilateral hamstrings static stretching can impair the affected and contralateral knee extension force but improve unilateral drop jump height

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Abstract

Purpose Prolonged static stretching (SS) in isolation (no dynamic warm-up) can impair muscle performance. There are conflicting reports whether impairments are present in antagonist and contralateral muscles. The objective of this study was to assess the effect of unilateral hamstrings SS on ipsilateral stretched and contralateral limbs' strength and jump power.

Methods The SS (four repetitions of 30-s) and control sessions involved unilateral testing of the stretched leg and contralateral leg for knee extension (KE) maximum voluntary isometric contraction (MVIC) force and electromyography (EMG), drop jump (DJ) height and contact time at 1-min post-stretching.

Results There were significant KE MVIC force impairments for both the SS ($p=0.006$, $d=0.3$, -8.1%) and contralateral ($p=0.02$, $d=0.20$, -4.2%) leg. With normalized data, there was a near-significant ($p=0.1$), small magnitude ($d=0.29$), greater force impairment with the ipsilateral ($93.0\pm12.8\%$ of pre-test) versus the contralateral ($96.2\pm9.1\%$ of pre-test) KE MVIC force. DJ height significantly improved for the stretched leg ($p=0.03$, $d=0.18$, $+9.2\%$) with near-significant, improvements for the contralateral leg ($p=0.06$, $d=0.22$, $+12.1\%$). For the stretched leg, DJ contact time was significantly ($p=0.04$, $d=0.18$, $+3.4\%$) prolonged, but there was no significant change with the contralateral leg.

Conclusions Unilateral hamstrings SS induced strength deficits in the ipsilateral and contralateral knee extension MVIC and a prolongation of the stretched leg DJ contact period. In anticipation of maximal force outputs, prolonged SS in isolation (no dynamic warm-up included) can have negative consequences on antagonist and contralateral muscle performance.

Keywords Flexibility · Strength · Power · Range of motion · Crossover

Abbreviations

EMG	Electromyography
MVIC	Maximal voluntary isometric contraction
PAR-Q	Physical Activity Participation Questionnaire
RMS	Root mean square
ROM	Range of motion
RPM	Revolutions per minute
SS	Static stretching

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Introduction

There are a litany of studies espousing that prolonged static stretching (SS) in isolation (not included within a full dynamic warm-up) can impair subsequent strength, power, endurance, sprint, balance and other performance measures (Behm 2018; Behm et al. 2004; Behm and Chaouachi 2011; Kay and Blazevich 2012). In the vast majority of these studies, the muscle impairments are observed with the targeted SS muscles. There are only a few studies that have shown SS global effects whereby SS of a specific muscle can increase the range of motion (ROM) of contralateral, distant or non-local muscles. For example, unilateral SS of the hamstrings improved ROM of the contralateral hamstrings (hip flexion) (Chaouachi et al. 2017), while SS or dynamic stretching of the hip adductors improved shoulder horizontal abduction ROM and stretching the shoulders increased hip flexion ROM (Behm et al. 2016b).

SS-induced effects on strength have also demonstrated crossover or global effects. Some studies have reported no significant non-local SS-induced deficits after SS of the plantar flexors (measured contralateral balance) (Lima et al. 2014), a lack of deficits in contralateral homologous (quadriceps) isokinetic torque or power (Chaouachi et al. 2017), and no significant loss in knee extension maximum voluntary isometric contraction (MVIC) force output following SS of the contralateral quadriceps and hamstrings (Behm et al. 2019). In contrast, other studies demonstrated increased lower body propulsion duration (unfavorable for performance), decreased force after SS of the shoulders (Marchetti et al. 2014) and decreased contralateral jump height and impulse following unilateral plantar flexor SS (da Silva et al. 2015). The hamstrings muscle group is the most common muscle group used in stretching studies, with testing typically involving the tested muscle (Behm 2018; Behm et al. 2016a; Behm and Chaouachi 2011). There are only two studies investigating the effects of stretching on antagonist muscle performance (McBride et al. 2007; Sandberg et al. 2012) and one study examining contralateral heterologous (antagonist) muscle performance (Behm et al. 2019). As there are few studies examining the non-local SS effects and with the conflicting findings in the literature regarding global SS-induced strength impairments, further investigations are imperative.

It is unknown whether the possibility of SS-induced changes is more predominant with ipsilateral (local) antagonist muscle groups versus more distant, contralateral muscle groups. Marchetti (2017) reported that six sets (45 s per set) of shoulder SS diminished the EMG activity of auxiliary muscles such as pectoralis major and triceps brachii. The force output of an ipsilateral antagonist muscle could be adversely affected by SS of the agonist through the effects of reciprocal inhibition (Crone and Nielson 1989). As the reciprocal inhibition reflex to the ipsilateral antagonist muscle involves a disynaptic pathway, there may be greater inhibitory responses than with the more complex neural pathways to the contralateral muscle groups. McBride et al. (2007) stretched the hamstrings and found decreased knee extension MVIC force in the same leg but no difference in isometric squat force output. They suggested that SS appears to decrease muscle force output with a uni-articular isometric contraction as well as rate of force development with a multi-articular (squat) isometric contraction. Conversely, Sandberg et al. (2012) reported increased knee extension isokinetic torque at 300° s^{-1} and improved vertical jump height and power after hamstrings SS. With the conflicts in the literature regarding the effects of SS on antagonist and contralateral muscle groups, more research is needed to clarify these responses. Hence, unilateral static stretching of a single muscle group may have global consequences on performance (strength and power), which would be important information for researchers and practitioners.

Thus, the objective of the present study was to examine the responses of ipsilateral and contralateral knee extension (quadriceps) MVIC force (uni-articular strength measure) and drop jump characteristics (multi-articular power measure) following unilateral hamstrings SS. It was hypothesized that SS-induced deficits would be observed both ipsilaterally and contralaterally.

Methods

Participants

An "a priori" statistical power analysis (software package, G * Power 3.1.9.2), based on related articles (Behm et al. 2016b; Chaouachi et al. 2017; Marchetti et al. 2014; Marchetti 2017) revealed that approximately 28–36 participants were necessary to achieve an alpha of 0.05 and a power of 0.8. Hence, 40 participants consisting of male ($n=22$) and female ($n=18$) resistance-trained (2 or more sessions per week over the last 6 months) and recreationally active participants between the ages of 20 and 47 (22.47 ± 5.10) were recruited using a snowball sampling technique (Table 1). All participants regularly used static stretching as a component of their warm-up prior to training or activity. The recruitment process consisted of attaining both verbal and written consent from individuals willing to volunteer for the study. To ensure healthy, ethically informed participants, each participant read and signed a Physical Activity Participation Questionnaire (PAR-Q: Canadian Society for Exercise Physiology) and an approved informed consent form. The study adhered to the approval process of the institution's Interdisciplinary Committee on Ethics in Human Research (20190627-HK) and was conducted according to the Declaration of Helsinki.

Experimental protocol

The objective was to assess how unilateral stretching of the dominant hamstrings impacted knee extension maximum voluntary isometric contraction (MVIC) force and electromyographic (EMG) activity as well as drop jump height and contact time in both the target (dominant) stretched and unstretched contralateral limb. Participants attended two sessions, which included an experimental static stretching session and a control, no-stretch session. The initial warm-up

Table 1 Anthropometric characteristics

	Age (years)	Height (cm)	Mass (kg)
Males $n=22$	23.6 ± 7.5	175.8 ± 5.9	83.1 ± 15.1
Females $n=18$	21.7 ± 2.5	164.4 ± 7.28	75.05 ± 21.3

involved a 5-min warm-up on cycle ergometer at 70 revolutions per minute (RPM) and 1 kPa. The pre-test involved unilateral testing for knee extension MVIC force and EMG, drop jump height and contact time of the leg to be stretched and the contralateral leg. Self-administered unilateral stretching of the hamstrings (supine hip flexion) involved four sets of 30 s static stretching. Post-stretching testing was conducted within 1 min of the intervention. The duration of the testing was approximately 2-min and therefore testing was completed approximately 3-min post-stretching. Testing order was randomized. Participants were allowed to hydrate ad libitum.

The MVIC and drop jump tests provided proxies of strength and power. In addition, EMG was monitored as an indicator of changes in neuromuscular activation. Furthermore, rather than just testing for drop jump height (measure of power), contact time was monitored to determine if there were changes in the transition or amortization period of the stretch–shortening cycle. This aspect would be very important in activities such as sprinting which necessitate a brief contact or landing period.

Intervention

Four repetitions of self-administered static stretching of the dominant hamstrings (hip flexion with knee fully extended) were held for 30 s with 15 s of recovery between repetitions. Hamstrings stretches were performed while supine, using a band (TheraBand stretch band: Performance Health Inc., Akron Ohio) positioned over the arch of the foot. Stretches were held at the participant's perceived threshold of discomfort. Researchers provided feedback to ensure the knee was fully extended. The stretching protocol was chosen as it provided a lower volume of static stretching than prior similar stretching research (Behm et al. 2019; Chaouachi et al. 2017; da Silva et al. 2015; Lima et al. 2014; Marchetti et al. 2014).

Testing measures

Knee extension MVIC force

For knee extension peak MVIC force and EMG measures, a cuff with a non-extensible strap was attached to a strain gauge (Omega Engineering Inc., LCCA 250, Don Mills, Ontario) and placed around the ankle of the participant. Knee joint angles were measured using a goniometer ($89.4 \pm 3.6°$). Four second MVICs were performed with the participants' arms crossed over their chest. Each leg was tested twice in an alternating pattern and a third measure was obtained if more than a 5% difference was observed. Verbal encouragement was provided during MVIC trials to maximize participant motivation and subsequent force output. A study by Andreacci et al. (2002) used verbal encouragement for a maximal performance test and found that a maximal effort was more likely to occur with verbal encouragement rather than without. Participants were instructed to contract as quickly and powerfully as possible for the entire duration of the MVIC. Forces were amplified (×1000) (Biopac Systems Inc., DA150; analog–digital converter MP100WSW, Holliston, MA) and interfaced with a computer. The data were sampled at 2000 Hz and analyzed with a commercially designed software program (AcqKnowledge III, Biopac Systems Inc., Holliston, MA).

Knee extension MVIC EMG

EMG activity was collected from the mid-belly (midway between the anterior superior iliac spine to the superior edge of the patella) of the vastus lateralis. Self-adhesive, 3.2 cm diameter Ag/AgCl electrodes (Meditrace TM 130 ECG conductive adhesive electrodes) with an edge-to-edge inter-electrode spacing of 20 mm were used. A reference electrode was placed over the fibular head. Prior to electrode placement, the skin was shaved and cleansed with an isopropyl alcohol swab. The mean root mean square (RMS) EMG was collected and analyzed over a 1-second period consisting of 500 ms before and after the peak force. EMG activity was amplified (×1000) (Biopac Systems Inc., DA150; analog–digital converter MP100WSW, Holliston, MA) and interfaced with a computer. The data were sampled at 2000 Hz and analyzed with a commercially designed software program (AcqKnowledge III, Biopac Systems Inc., Holliston, MA).

Drop jump height and contact time

Vertical jump performance was assessed with a single leg drop jump from a height of 30 cm. Participants were encouraged to jump with the shortest possible contact time (i.e., explosively) and maximum jump height. The jump was performed with both hands on the hips (akimbo) and participants landed on a contact mat that provided measures of contact time and jump height (SmartJump, Fusion Sport, Chicago, Illinois). Each leg was tested twice in an alternating pattern, and peak values for height and shortest contact times were recorded for statistical analysis.

The mean amplitude of the RMS EMG activity was analyzed for a period of 300 ms from the start of the contact time. Since there was no video analysis available, there was no ability to differentiate between the eccentric and concentric phases of the landing phase. Signal amplification, sampling and analysis were the same as for the MVIC.

Statistical analysis

Statistical analyses were completed using the SPSS software (Version 23.0, SPSS, Inc. Chicago, IL). First, normality

(Kolmogorov–Smirnov) and homogeneity of variances (Levene) tests were conducted for all dependent variables. If the assumption of sphericity was violated, the Greenhouse–Geisser correction was employed. A repeated measures 2-way ANOVA involving two conditions (stretch vs. control) × two times (pre- and post-stretch training program) was performed for the stretched and contralateral, non-stretched legs. To compare the ipsilateral and contralateral knee extension MVIC, data were normalized ([post-/pre-test] × 100), and a two-way ANOVA with two conditions (stretch vs. control) and two tested legs (stretched vs. contralateral, non-stretched, leg) were employed. Paired *t* tests with Holm–Bonferroni corrections were used to decompose significant interactions, and Bonferroni post hoc tests were used if main effects were found. Significance was set at $p \leq 0.05$. Cohen's d effect sizes (ES) (Cohen 1988) were also calculated to compare all measures. Reliability was assessed using intraclass correlation coefficients (ICC). Data are reported as mean ± SD.

Results

ICC reliability values were excellent for all measures with coefficients of 0.96, 0.95, and 0.91 for MVIC force, drop jump height and contact time, respectively. Table 2 illustrates all pre- and post-test interaction values and identifies the *p* values, effect sizes (*d*) and percentages for significant changes in MVIC and drop jump data. There were significant, small magnitude, pre- to post-stretch impairments in knee extension MVIC force for both the stretched hamstrings leg and the contralateral, non-stretched leg; however, there were no significant changes in quadriceps MVIC EMG activity for either leg. With the normalized data, there was a near significant ($p = 0.1$), small magnitude ($d = 0.29$), greater force impairment with the ipsilateral (93.0 ± 12.8% of pre-test) versus the contralateral (96.2 ± 9.1% of pre-test) knee extension MVIC force. There were no significant relative control differences.

Drop jump height significantly (trivial magnitude) improved pre- to post-stretch for the stretched leg with near-significant, small magnitude, improvements for the contralateral leg (Table 2). There was no significant difference in the relative (normalized) ipsilateral to contralateral drop jump height changes following SS nor with the control conditions.

For the stretched leg, drop jump contact time was significantly (trivial magnitude) prolonged, but there was no significant change with the contralateral leg (Table 2). The ipsilateral drop jump contact time (104.2 ± 8.0% of pre-test) demonstrated a near significant ($p = 0.1$; $d = 0.49$), small magnitude, greater relative increase in contact time

Table 2 Pre- and post-test results for the stretched hamstrings leg and contralateral leg

	Pre-stretch stretched hamstrings	Post-stretch stretched hamstrings	***P* value ES (*d*)**	Pre-stretch contral-leg	Post-stretch contral-leg	***P* value ES (*d*)**	Pre-control Dom leg	Post-control Dom leg	*P* value ES (*d*)
Knee extension MVIC force (N)	514.1 ± 147.9	472.2 ± 132.4	**$p = 0.0006$ $d = 0.3$ −8.1%**	512.1 ± 119.5	490.4 ± 113.7	**$p = 0.02$ $d = 0.20$ −4.2%**	576.4 ± 121.9	565.8 ± 132.3	NS
Quadriceps MVIC EMG (mV)	0.55 ± 0.42	0.52 ± 0.48	NS	0.58 ± 0.39	0.56 ± 0.44	NS	0.59 ± 0.41	0.57 ± 0.39	NS
Unilateral drop jump height (cm)	9.8 ± 5.1	10.7 ± 5.3	**$p = 0.03$ $d = 0.18$ +9.2%**	9.9 ± 4.3	11.1 ± 5.5	**$p = 0.06$ $d = 0.22$ +12.1%**	10.2 ± 4.8	10.3 ± 4.1	NS
Drop jump contact time (ms)	326.2 ± 64.1	337.4 ± 61.1	**$p = 0.04$ $d = 0.18$ +3.4%**	324.05 ± 72.02	322.05 ± 61.5	NS	331.8 ± 66.4	329.7 ± 58.7	NS

Values include means ± standard deviations, *p* values, effect sizes (*d*) and percentage changes. Bold cells highlight the significant changes

Contral contralateral, *ES* effect size, *Dom Leg* dominant leg compared to the contralateral leg (100.3 ± 7.8% of pre-test). There was no significant difference with the control condition. There were no significant changes with drop jump contact time EMG.

Significant main effects for time were evident for knee extension MVIC force ($p < 0.0001$; pre-test: 652.2 ± 138.6 vs. post-test: 581.2 ± 142.6 N), drop jump height ($p = 0.04$: pre-test: 12.1 ± 4.7 vs. post-test: 13.6 ± 5.3 cm) and contact time ($p = 0.05$; pre-test: 326.8 ± 64.7 vs. post-test: 330.3 ± 58.9 ms).

Discussion

The most important findings in the present study were that unilateral SS of the dominant side hamstrings induced strength deficits in both the ipsilateral and contralateral knee extension (quadriceps) MVIC, with a near-significant, small-magnitude greater relative impairment with the ipsilateral versus the contralateral legs. In contrast, unilateral hamstrings SS significantly improved ipsilateral drop jump height and near significantly improved contralateral drop jump height. Although drop jump height was increased indicating improved performance, drop jump contact time was significantly (trivial magnitude) prolonged (detrimental for performance) for the stretched (ipsilateral) leg. There was no significant change with the contralateral leg drop jump contact time.

The MVIC strength deficits following unilateral SS are in accord with two studies that implemented SS of the plantar flexors (da Silva et al. 2015) and shoulders (Marchetti et al. 2014) and reported decrements with contralateral jump height and impulse and lower body drop jump propulsion duration, respectively. However, other studies have reported no significant non-local SS-induced deficits with balance (Lima et al. 2014), quadriceps isokinetic torque or power (Chaouachi et al. 2017), or knee extension MVIC force (Behm et al. 2019) following SS of the contralateral plantar flexors, quadriceps or quadriceps and hamstrings, respectively. It is difficult to explain the discordant results with the aforementioned three non-significant studies. Whereas the presents study incorporated the lowest volume of SS (4 × 30 s), the five prior studies (two with significant deficits and three without decrements) had SS volumes ranging from 6 × 45 s, 8 × 30 s, and 10 × 30 s. Similar to the present study, the SS intensity of all the other studies was to the point of discomfort or 70–90% of point of discomfort (Lima et al. 2014) and all studies stretched the dominant limb. There were a range of participants in these studies with resistance-trained participants in the studies with deficits compared to non-trained (Lima et al. 2014), national level rowing athletes (Chaouachi et al. 2017), recreationally active participants in the Behm et al. (2019) and present study. The only other methodological difference was that participants in the present study used a stretch band to self-administer the SS whereas all other studies had the researchers apply the SS. Thus an overview of the present study and other studies that experienced SS-induced deficits does not illustrate any common methodological themes that would differentiate the studies.

SS-induced performance impairments have been ascribed to both peripheral, mechanical, and central neural mechanisms. Although there are reported SS-induced increases in musculotendinous compliance, decreased visco-elasticity (thixotropic properties), fascicle angles and rotation (Behm 2018; Behm et al. 2004; Behm and Chaouachi 2011; Kay and Blazevich 2012), the decreased MVIC force of the ipsilateral and contralateral antagonist muscles could not be directly affected by mechanical alterations. Hamstrings SS could invoke reciprocal inhibition of the ipsilateral quadriceps (Crone and Nielson 1989) adversely affecting force output. Reciprocal inhibition would not be an adequate explanation for the contralateral knee extension MVIC force deficits. Hence, the unilateral SS may have induced a crossover spinal reflex inhibition and/or long loop reflexes for contributions from supraspinal inhibition. Prolonged SS can disfacilitate muscle spindle discharge frequency (Behm et al. 2001,2014,2016a; Behm and Chaouachi 2011). Spinal reflex inhibition might be facilitated through reflexes associated with the cross-extensor reflex (Sherrington 1910) or cross-education (Carroll et al. 2006). Small amplitude passive stretches have been shown to induce pre-synaptic inhibition (decreased H-reflex) (Delwaide et al. 1981; Behm et al. 2013).

The ability to activate a muscle depends not only on spinal motoneurone excitation but also supraspinal excitatory and inhibitory influences (Gandevia 2001). Although the 2 min of SS implemented in the present study should not have induced extensive fatigue, unilateral fatigue can inhibit motor cortex intracortical facilitation of the non-exercised contralateral muscle (Baumer et al. 2002). Stretching to the point of discomfort for 2 minutes could have approached or reached the individual's sensory tolerance limit inducing central drive inhibition (Amann 2012; Amann et al. 2013). However, the possibility of neural inhibition was not illustrated with any significant changes in MVIC or drop jump EMG activity. The EMG–force relationship exhibits a plateau at high forces (Perry and Bekey 1981; Behm and St-Pierre 1997) and thus the small magnitude ($d = 0.2$–0.3), 4–8% MVIC decrements may not have been apparent with the near -maximal force outputs.

It has also been postulated in studies examining crossover and non-local muscle fatigue, that a mental energy deficit may play a role (Halperin et al. 2015). The mental energy deficit suggests that the mental energy used to focus the attention on the initial task (i.e., fatiguing or stretching tasks) would result in less cortical energy to focus on the subsequent task (i.e., knee extension MVIC or drop jump contact time). With such prior mental activity, the activity can be perceived as more strenuous, and thus the individual may desist earlier (Pageaux et al. 2013; Marcora et al. 2009; Amann et al. 2013), impairing performance (Pageaux et al. 2013, 2014; Marcora et al. 2009), in the non-exercised muscle (Halperin et al. 2015). Hence, the reduced ipsilateral and contralateral KE MVIC and prolonged drop jump contact times (stretched leg only) with unilateral hamstrings SS may be influenced by supraspinal or spinal inhibition or psycho-physiological (mental energy deficit) factors.

The near significant, small magnitude, greater relative impairment with the ipsilateral versus the contralateral legs suggests that the local MVIC deficit was greater than the non-local, contralateral impairment. While the mental energy deficit theory and supraspinal inhibition would be expected to be global, this finding suggests that local reflexes such as reciprocal inhibition may have contributed an additional or contributed to a stronger reflex inhibition not experienced by the contralateral limb. An alternative explanation may be the self-administered (with stretch bands) hamstrings SS involved some active quadriceps contractions, which might have contributed to a small, local, fatigue effect.

In contrast, the ipsilateral (stretched limb) drop jump height was significantly facilitated. Greater SS-induced musculotendinous compliance (Behm 2018; Behm et al. 2004; Behm and Chaouachi 2011; Kay and Blazevich 2012), could have increased the duration of force absorption (deceleration or eccentric contraction phase) during landing and the electromechanical delay during propulsion. In this unilateral drop jump situation, a prolonged contact time may be a benefit rather than a disadvantage. Whereas, a short contact or transition time is essential for high stride frequencies when sprinting (Dintiman and Ward 2003), a prolonged contact time would increase the duration of the muscle force application resulting in a greater impulse (force × time) contributing to an augmented jump height. Another possible contributing factor could be that stretch-induced changes in compliance could have altered the force–length relationship changing the knee angle at which greatest forces are applied. However, the near-significant ($p = 0.06$) drop jump height increase of the contralateral non-stretched limb cannot be ascribed to changes in muscle compliance. With no significant change in contralateral drop jump contact time and a significant decrease in knee extension MVIC force, the near-significant improvement in jump height is difficult to rationalize. Although there was extensive familiarization with the test measures, unilateral drop jumps are not a common activity and thus it might be possible that improvements in balance or motor control with multiple attempts (practice) may have contributed to the increased jump height with both legs.

A limitation of this study was that testing was only conducted, starting at 1-min post-stretching intervention. The duration of the MVIC and drop jump testing was approximately 2-min. Hence, the results observed in this study cannot be applied to possible prolonged changes beyond approximately 3-min post-stretching. Torres et al. (2008) for example, did not find significant bench press or medicine ball throw impairments when post-testing began 5-min after stretching. On the other hand, unlike many other exercise science studies, the present research incorporated a relatively larger subject sample of both female ($n = 18$) and male ($n = 22$) participants with a wider than typical age range (20–47 years) encompassing both trained and recreationally active individuals. Hence, the results can be applied to a large spectrum of the population.

Conclusions

Unilateral SS of the dominant hamstrings induced strength deficits in both the ipsilateral and contralateral knee extension MVIC, with greater relative impairments of the ipsilateral quadriceps. The MVIC impairments are speculated to be associated with neural inhibition or a mental energy deficit. A prolongation of the stretched leg drop jump contact period may have provided a greater impulse with which to exert forces during the propulsion phase. When competing or training in activities that necessitate maximal force outputs, prolonged SS in isolation (no dynamic warm-up included) can have consequences on antagonist and contralateral muscle performance. Dynamic stretching and activities are strongly encouraged as part of the warm-up procedure to counterbalance possible SS-induced local and global impairments (Opplert and Babault 2018; Behm 2018; Behm et al. 2016a; Behm and Chaouachi 2011).

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Compliance with ethical standards

Conflict of interest The authors declare no conflict of interest with the contents of this.

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