Oliver, Jon L., De Ste Croix, Mark B ORCID logoORCID: https://orcid.org/0000-0001-9911-4355, Lloyd, Rhodri S. and Williams, Craig A. (2014) Altered neuromuscular control of leg stiffness following soccer-specific exercise. European Journal of Applied Physiology, 114 (11). pp. 2241-2249. doi:10.1007/s00421-014-2949-z

Title: Altered neuromuscular control of leg stiffness following soccer-specific exercise

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Abstract

Purpose: To examine changes to neuromuscular control of leg stiffness following 42-min of soccer-specific exercise. *Methods:* Ten youth soccer players aged 15.8 ± 0.4 hopped on a force plate at a self selected frequency before and after simulated soccer exercise performed on a non-motorised treadmill. During hopping muscle activity was measured using surface EMG from four lower limb muscles and analysed to determine feedforward and feedback mediated activity, as well as co-contraction. *Results:* There was no change in stiffness following the soccer-specific exercise (26.6 ± 10.6 versus 24.0 ± 7.0 kN·m^{-1}, $p > 0.05$), with half the group increasing and half decreasing their stiffness. Changes in stiffness were significantly related to changes in CoM displacement ($r = 0.90$, $p < 0.01$) but not changes in peak GRF ($r = 0.58$, $p > 0.05$). A number of significant relationships were observed between changes in stiffness and CoM displacement with changes in feedforward, feedback and eccentric muscle activity of the soleus and vastus lateralis muscles following the soccer exercise ($r = 0.64$-0.98, $p < 0.05$), but not with changes in co-contraction around the knee and ankle ($r = 0.11$-0.55, $p > 0.05$). *Conclusions:* Following soccer-specific exercise individual changes in extensor muscle activity modulate changes in CoM displacement and leg stiffness. Individuals who reduce preactivation, braking activity and consequently leg stiffness with fatigue may be at a greater risk of injury.

Keywords: fatigue; feedback; feedforward; adolescent boys; electromyography

Abbreviations

ANOVA analysis of variance

BF biceps femoris

BGA background muscle activity

CoM centre of mass

EMG electromyography

HR heart rate

M_1 short-latency stretch-reflex

M_2 medium-latency stretch-reflex

M_3 long-latency stretch-reflex

GRF ground reaction force

SSIET soccer-specific intermittent exercise test

SOL soleus

TA tibalis anterior

VL vastus lateralis

Introduction

Soccer is characterised by the need for players to repeatedly utilise stretch-shortening cycle (SSC) contractions to provide a high rate of force development in rebounding activities, such as sprinting, turning and jumping. Leg stiffness describes the multi-joint response of the lower limbs to generate force and resist deformation during rebounding activities (Komi 2000; Padua et al. 2005). Increased leg stiffness is suggested to enhance rate of force development, locomotor kinematics and energy storage and utilisation (Brughelli and Cronin 2008), providing performance benefits of increased force output, movement speed and running economy (Butler et al. 2003; Wilson and Flanagan 2008). Furthermore, it has been suggested that lower limb stiffness is an important injury protection mechanism (Alentorn-Geli et al. 2009), with low levels of stiffness associated with soft tissue injuries (Hobara et al. 2008).

Despite implications for performance and injury there is a limited amount of research that has examined leg stiffness in soccer players. Repeated SSC exercise performed over a prolonged period of time is likely to lead to modified musculotendon unit behaviour, altered stiffness regulation, impaired function and reduced dynamic knee stability (McLean et al. 2007; Nicol et al. 2006). Fatigue during soccer has been associated with increased injury risk in adult (Hawkins et al. 2001) and youth football (Price et al. 2004). It has been speculated that altered leg stiffness and movement control during a soccer-match contributes to the increased injury risk associated with fatigue (Cone et al. 2012). While previous research has demonstrated both adults (Andersson et al. 2008) and youths (Oliver et al. 2008) have impaired SSC performance and function following soccer exercise, these studies have only considered slow SSC movements not associated with high levels of leg stiffness.

Cone et al. (2012) recently examined changes in leg stiffness following a soccer match. Those authors reported no significant change in the group stiffness response post soccer-match, however individual responses or potential changes in neuromuscular control with fatigue were not considered. Following exhaustive running, leg stiffness is known to decrease (Dutto and Smith 2002), whereas, following non-exhaustive prolonged running changes to stiffness have been reported to be individualised (Hunter and Smith 2007). Given the non-exhaustive nature of soccer it may be speculated that changes to leg stiffness during a match will be player-specific, with players who exhibit fatigue-induced decrements in stiffness at risk of impaired joint stability (Hughes and Watkins 2008) and increased stress on passive structures resulting in increased injury risk (Dutto and Smith, 2002).

Leg stiffness is modulated by feedforward and feedback neural activity immediately prior to and proceeding ground contact (Komi 2000). Manipulating stiffness by adjusting movement speed or ground contact time has been shown to cause significant changes to the preactivation and stretch-reflex response in lower limb muscles (Hobara et al. 2007; Kuitenen et al. 2011).

Similarly, up to 97% of the variance in leg stiffness has been explained by the magnitude of the feedforward and stretch-reflex response of lower limb extensor muscles in boys and men (Oliver and Smith 2010). Consequently, we hypothesised that changes in leg stiffness following soccer-specific exercise would be player specific, and that changes in stiffness would be mediated by alterations in feedforward and feedback control.

Methods

Ten youth soccer players, who all played football for their school and a local football club, volunteered to participate in the study. The mean age of the players was 15.8 ± 0.4 y, stature 1.73 ± 0.06 m, body mass 59.8 ± 9.7 kg and sum of triceps and subscapular skinfold thickness 16.0 ± 3.9 mm. The Institutional Ethics Committee approved the project and written informed assent and consent was obtained from the boys and their parents/guardians respectively.

Experimental Design Summary

Participants were required to report to the laboratory on two occasions, separated by 7 d. The first occasion was used to familiarise participants to the test equipment and procedures, with all data then collected in the second session. Participants were instructed to refrain from vigorous exercise in the 24 h prior to data collection. Participants were required to perform two-legged hopping at their freely chosen preferred frequency on a force plate to measure leg stiffness, with hopping trials performed immediately before and after participants completed a 42 min soccer-specific intermittent exercise test on a non-motorised treadmill. Two legged hopping has been described as a highly controlled and well documented functional task (Padua et al. 2005) and enables movement representative of the spring-mass model. During hopping trials muscle activity was monitored around the ankle and knee using bipolar surface electromyography. A warm-up of 5 min of jogging at 8 km.h^{-1} on the non-motorised treadmill, including two brief sprints (<4 s), was performed prior to the initial hopping trial.

Soccer-Specific Intermittent Exercise Test (SSIET)

The SSIET is designed to simulate the demands of competing in one-half of a soccer match. The test has previously been shown to be valid and reliable when assessing youth male soccer players (Oliver et al. 2007) and has previously been employed to identify decrements in jump performance in a youth population (Oliver et al. 2008). During the test players cover approximately 5 km, with mean physiological load previously reported to be 70 ± 3 % of $\dot{V}O_2$ max (Oliver et al. 2007). The SSEIT consisted of three bouts of 14 min of intermittent exercise with 3 min recovery between bouts. Exercise was organised into repetitive 2 min periods of activity as follows; 45 s walking (4 km.h^{-1}), 15 s cruising (12 km.h^{-1}), 15 s stationary, 40 s jogging (8 km.h^{-1}) and a 5 s maximal sprint. The SSIET was performed on a Woodway Tramp non-motorised treadmill (Woodway GmbH, Germany) as per procedures described elsewhere (Oliver et al. 2007; Oliver et al. 2008). A visual display monitor placed in front of the treadmill allowed participants to monitor their velocity, with verbal feedback given by the instructor whenever a change in velocity was necessary. The distance covered in each sprint was calculated from the mean velocity of each sprint, with a custom software application developed using LabVIEW (National Instruments, Newbury, UK) used to sample the signal voltages at 100 Hz and then averaged over each sprint effort. Heart rate was recorded throughout the SSIET (Polar Electro, Finland).

Leg stiffness was calculated from double integration of force-time data during two-legged hopping performed at the freely chosen preferred frequency on a force plate (OR6-5, AMTI, Massachusetts, USA), with data sampled at 1000 Hz. The use of a preferred frequency is similar to other studies in adults (Hobara et al. 2007; Padua et al. 2005) and children (Oliver and Smith 2010). Participants were instructed to hop with hands placed on the hips and with an upright torso. Participants were also instructed to minimise ground contact while hopping as this has been shown to increase leg stiffness and muscle activity at a preferred frequency (Hobara et al. 2007), allowing observation of how rapid SSC movement is self-regulated following soccer-specific exercise. Hopping was performed for 10 s, with the 10 consecutive hops with most consistent frequency used for further analysis (Oliver and Smith 2010). Double-integration of the force-time data allowed calculation of CoM displacement during ground contact, leg stiffness was then calculated as peak ground reaction force (GRF) divided by peak CoM discplacment (Farley and Morgenroth, 1999). Spring-like behaviour was confirmed where the relationship between CoM displacement and GRF were $r > 0.8$ (Padua et al. 2005). The moment of ground contact was taken to have occurred when force data became >10 N, and take-off occurred when force data became < 10 N (Voigt et al. 1998).

Muscle activity

Activity from the vastus lateralis (VL), biceps femoris (BF), tibialis anterior (TA) and soleus (SOL) muscles of the dominant lower limb were monitored using bipolar surface electrodes (Neonatal ECG electrodes, Unomedical Ltd, Stonehouse, UK). Electrodes were placed over the middle of the muscle belly with an inter-electrode distance of 30 mm. Specifically, electrodes were placed on the area of greatest muscle bulk lateral to the rectus femoris on the distal half of the thigh for the VL; midway on the line between the ischial tuberosity and lateral epicondyle of the femur for the BF; on the lateral edge of the protruding muscle below the gastrocnemius for the SOL; on the area of greatest muscle bulk between the lateral condyle of the tibia and first metatarsal for the TA. Prior to electrode placement fine sandpaper was used as a skin abrasive, the skin was then vigorously cleaned using an alcohol wipe and alcohol on the skin was left to vaporise. An elastic bandage was used to secure electrodes in place and minimise any movement artefacts. The electrodes were left in place throughout the entire test session so that the same set of electrodes were used in jumps both pre and post the soccer-specific intermittent exercise test. The EMG signal was sampled simultaneous to ground reaction force data at a rate of 1000 Hz with a common mode rejection ratio of 110 dB. The EMG signals were preamplified (x375) close to the electrodes, band-pass filtered (8-500 Hz) and stored in a special measurement unit (ME3000P, Mega Electronics Ltd, Finland), with a total gain of 412. The raw EMG data were then transferred to a desktop PC and digitally processed using Labview 7.0 (National Instruments, Newbury, England). Filters were applied using a digital Butterworth 4^{th} order zero lag filter. Firstly, a 20 Hz high-pass filter was applied to minimise any movement artefacts. The EMG signal was then rectified and low-pass filtered at a frequency of 50 Hz to produce a linear envelope.

Muscle activity at each hopping frequency was averaged over 10 consecutive hops, with each hop aligned to the moment of ground contact. Muscle activity was quantified using procedures previously described by Oliver and Smith (2010); processed EMG data were integrated over the total ground contact period and for four periods associated with feedforward and feedback activity; 0-30, 31-60, 61-90 and 91-120 ms post-ground contact. The initial 30 ms is termed background muscle activity (BGA) and is an extension of preactivation prior to landing, the periods 31-60, 61-90 and 91-120 ms approximate short (M_1), medium (M_2) and long (M_3) latency stretch-reflex mediated responses, respectively (Oliver and Smith, 2010). Additionally, muscle activity was quantified during the braking and propulsive phases, which were determined from CoM displacement during ground contact.

Activity during each period was normalised by expressing activity as a percentage of the total muscle activity during the entire ground contact period (Oliver and Smith 2010; Lloyd et al. 2012). Co-contraction indices were calculated around the ankle (TA:SOL) and the knee (BF:VL) with the amount of antagonist activity divided by the amount of agonist (extensor muscle) activity during the 60-ms immediately proceeding ground contact (Padua et al. 2005).

Statistical Analyses

Descriptive data were calculated for all variables and reported as the mean ± sd. A repeated measures ANOVA was employed to determine if there were any significant changes in sprint performance across the three bouts of the SSIET. To examine whether completing the soccer-specific intermittent exercise test led to significant changes in leg stiffness and muscle activity, paired Students t-tests were used to analyse data collected pre and post the SSIET. Additionally, the sample was split to examine differences between sub-groups who either increased or decreased stiffness following soccer-exercise, with differences analysed using an independent t-test. A Pearsons correlation coefficient was calculated to confirm spring-like behaviour and to examine the relationship between pre-to-post SSIET induced changes in variables associated with leg stiffness (stiffness, peak GRF, CoM displacement, contact time) and changes in muscle activity. Significance for all tests was set at the $P < 0.05$ level. All analyses were performed using SPSS for Windows version 10 (SPSS Inc., Chicago, USA).

9

Results

Participants covered a total distance of 4745 ± 102 m during the SSIET, with a mean HR of 173 ± 12 $b \cdot min^{-1}$. Total sprint distance did not differ between bouts one, two or three (187.8 ± 22.8, 187.8 ± 22.7 and 185.0 ± 21.9 m, respectively, $p > 0.05$). Leg stiffness did not change significantly before and after the SSIET, nor did its constituent parts of peak GRF or CoM displacement (Table 1). This was a result of individual responses to the intervention, with half of the group displaying a decrease in leg stiffness and the other half an increase in leg stiffness post the prolonged exercise. When comparing sub-groups who either increased or decreased stiffness following exercise there were no between-group differences in stature (173.8 ± 7.4 versus 170.2 ± 4.9 cm, $p > 0.05$), body mass (60.8 ± 8.2 versus 55.0 ± 7.0 kg, $p > 0.05$), pre-exercise leg stiffness (23.5 ± 5.1 versus 29.6 ± 14.8 $kN.m^{-1}$, $p > 0.05$) or total distance covered (4759 ± 101 versus 4731 ± 113 m, $p > 0.05$), although total sprint distance was significant greater in those who increased stiffness compared to those that decreased stiffness (618.1 ± 33.4 versus 503.1 ± 23.5 m, $p < 0.05$). Across all trials the relationship between the change in GRF and change in CoM was r = 0.97 ± 0.01, indicating spring-like behaviour.

The contribution of extensor muscle activity during different phases of ground contact is shown in Table 2. The medium-latency reflex of the SOL was the only variable to show a significant change from pre- to post-SSIET. Approximately two thirds of muscle activity occurred during the braking phase for both extensor muscles pre- and post -SSIET (Table 2). Following 42 min of exercise co-contraction remained unchanged around the knee ($\triangle$0.14 ± 0.35, $p > 0.05$) and the ankle ($\triangle$-0.07 ± 0.17, $p > 0.05$). There were a number of significant relationships between pre-to-post changes in variables associated with leg stiffness and pre-to-post changes in muscle activity (Table 3). Additionally changes in stiffness were significantly related to changes in CoM displacement (r = 0.90, $p < 0.01$) but not changes in peak GRF (r = 0.58, $p > 0.05$).

Relationships between the change in BGA and leg stiffness for both the SOL and VL are shown in figure 1. For both extensor muscles there is a subgroup (n = 3) who experience the largest reductions in both leg stiffness and BGA compared with all other participants. However, such a distinct pattern of change in muscle activity for this subgroup is not obvious for other phases of activity in either the SOL of VL. Removal of this subgroup alters the strength of relationships between changes in stiffness and changes in BGA to $r = 0.63$ and $r = 0.72$ (both $p < 0.05$) for the SOL and VL, respectively. Figure 2 shows the highly linear relationship between changes in SOL braking activity and CoM displacement following the SSIET, where inclusion or exclusion of the subgroup has negligible impact on the strength of relationship ($r = -0.96$ versus $r = -0.97$, respectively)

Discussion

The major findings from this study revealed that following 42-min of soccer-specific exercercise changes in leg stiffness were player specific. Supporting our hypothesis, changes in leg stiffness regulation following exercise were strongly related to changes in feedforward and feedback strategies. A Sub-group may exist within the data set, with participants who exhibited large reductions in BGA of the extensor muscles experiencing considerable reductions in leg stiffness. However, the integration of feedforward and feedback activity to control changes in eccentric activity in the SOL provides a consistent explanation of changes in movement patterns and leg stiffness across all participants.

In agreement with previous research of group responses to one hour of continuous running (Hunter and Smith 2007) and exercise replicating a soccer match (Cone et al. 2012), leg stiffness was found not to significantly change following the soccer-specific exercise. In the present study half of the participants increased, while the other half decreased, their leg stiffness following exercise. The sample was split to examine possible explanatory factors for this response, although it is acknowledged this creates small sample sizes. Comparison of sub-groups revealed no differences in physical characteristics, total distance covered or pre-exercise leg stiffness. However, participants who decreased stiffness covered significantly less distance while sprinting during the SSIET. This may not be surprising given the established relationship between leg stiffness and sprint performance (Bret et al. 2002). Covering a lower total sprint distance in the simulated soccer exercise may identify those participants with lower fitness levels and a greater susceptibility to fatigue, which is also manifested in a reduction in leg stiffness.

Examining relationships between changes in variables pre to post exercise provides a greater insight into possible explanatory mechanisms for changes in leg stiffness. Individual changes in leg stiffness following exercise were due to changes in CoMd as opposed to alterations to peak GRF. For participants who decreased stiffness following exercise this would suggest more of a yielding action during the ground contact phase. Horita et al. (1999) demonstrated that short duration exhaustive SSC exercise (3 min) reduced stiffness, increased joint extension at touchdown, thus enabling a greater yielding action. The authors speculated that the observed changes in stiffness were the result of altered prelanding motor commands, which is substantiated by the relationship between changes in feedforward activity and stiffness observed in the present study. For those individuals reducing stiffness and yielding to a greater extent, this may reflect impaired joint stability and increased injury risk (Dutto and Smith 2002; Hughes and Watkins 2008; Nicol et al. 2006). In the current study injury risk may be a particular concern for the sub-group of three participants who exhibited large reductions in BGA and also substantial reductions in leg stiffness post-exercise.

Altered regulation of leg stiffness and SSC control following exercise is not a new concept. Preactivation levels have been shown to reduce in sprints performed after a 10 km run

(Paavolainen et al. 1999) and preactivation and the short-latency stretch-reflex are reduced during rebounds completed post marathon running (Avela and Komi 1998; Komi and Gollhofer 1997). In the present study changes in stiffness following exercise were strongly related to changes in feedforward activity and the short-latency stretch-reflex of the extensor muscles were strongly related to changes in CoMd. The influence of background muscle activity on changes in stiffness suggests some level of supraspinal control while the influence of the short-latency reflex reflects control at a spinal level (Avela and Komi 1998). Reductions in the stretch-reflex response have been speculated to be caused by disfacilitation of muscle spindles, presynaptic inhibition or other unidentified peripheral mechanisms (Avela and Komi 1998; Millet and Lepers 2004), although the potential recruitment strategies to adjust leg stiffness have been suggested to be limitless (Padua et al. 2005). However, the observation that leg stiffness increased post exercise for some individuals in the present study suggests the possibility of a potentiated state within the neuromuscular system. This is supported by the previous suggestion that the short-latency stretch reflex can be modulated in a positive way to increase leg stiffness (Hobara et al. 2007), which agrees with the present study and the finding that the short-latency stretch reflex of the SOL demonstrated a significant increase in contribution post-exercise.

Often it is difficult to gain meaning for an individual based on a group research design (Bouffard and Reid 2012). Observation of the raw data when considering changes in stiffness and muscle activity following exercise provide a means to examine individual responses within the current sample. Figure 1 shows three of the participants appear to have a differential response to other participants when examining changes in BGA of the extensor muscles. This might offer one approach to identify those at increased risk of injury; players who have substantially reduced leg stiffness and a disproportionate decrease in background muscleactivity may be at increased injury risk with fatigue. This is because reduced preactivation may cause greater yielding (Wilson and Flanagan 2008), decrease stability (Padua et al. 2005) and increase stress on ligaments (Hewett et al. 2005). The present findings may help to begin to explain the high incidence of ankle and knee injuries during match-play, with incidence known to increase towards the end of the first half of a match (Ekstrand et al. 2011). However, further research is needed to confirm the link between altered neuromuscular control and injury risk or incidence. The relationship between changes in eccentric muscle activity of the SOL and CoMd provided a more universal response across participants. This may be because eccentric activity reflects the integrated response of both feedforward and feedback activity to prepare for and absorb impact forces, providing a truer reflection of overall movement control. The strong relationship between changes in eccentric muscle activity of the SOL and CoMd and the observation that the short-latency stretch-reflex significantly increased in the SOL, support the suggestion that leg stiffness is primarily determined by stiffness of the ankle and not the knee (Farley and Morgenroth 1999; Kuitunen et al. 2011). Decreased maximal eccentric strength in the lower limbs following prolonged soccer-specific exercise has been suggested to reflect increased injury risk (Greig and Seigler 2009). However, soccer players will rarely have to produce a maximum voluntary contraction during match play and injury risk may be better reflected by reduced eccentric activity in a more functional task, such as hopping or similar movements requiring rapid recruitment of the SSC (Padua et al. 2005).

Co-contraction around the ankle and knee did not change following soccer-exercise, nor were changes in co-contraction indices significantly related to changes in stiffness. This may be because a greater variety of control mechanisms exist to modulate the activity of agonist extensor muscles compared to antagonist muscles. However, it is at least partly likely to be the result of the inter-individual variability associated with measures of co-contraction (Oliver and Smith 2010). Previous research has demonstrated that it is the activity of the extensor muscles of the lower limb and not co-contraction that modulate leg stiffness (Hobara et al. 2007; Oliver and Smith 2010).

Conclusions

Competing 42 min of soccer-specific exercise caused individualised changes in leg stiffness. Altered stiffness was mediated by modulating CoMd during ground contact, with both changes in stiffness and CoMd strongly related to changes in feedforward, feedback and total eccentric muscle activity of lower limb extensor muscles. Consequently, our original hypothesis was accepted. For some players this led to a potentiated response and increased stiffness. For other players the soccer-exercise led to reduced stiffness due to reduced pre-planned activity; alterations which have been implicated with increased injury risk due to impaired joint stability and increased stress on soft tissue (Dutto and Smith 2002; Hughes and Watkins 2008; Nicol et al. 2006; Padua et al. 2005). However, future research is needed to confirm if individuals who experience impaired neuromuscular control and reduced stiffness with soccer exercise are at

feedback and eccentric activity of lower limb extensor muscles modulate changes in CoM displacement and leg stiffness. It is speculated that those individuals who experience large reductions in feedforward and eccentric activity, leading to yielding and decreased leg stiffness following exercise, may be at increased risk of injury.

Acknowledgements

None

Conflicts of Interest

None

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Abbreviations

ANOVA analysis of variance

BF biceps femoris

BGA background muscle activity

CoM centre of mass

EMG electromyography

HR heart rate

M_1 short-latency stretch-reflex

M_2 medium-latency stretch-reflex

M_3 long-latency stretch-reflex

GRF ground reaction force

SSIET soccer-specific intermittent exercise test

SOL soleus

TA tibalis anterior

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Legends

Table 1 Changes in leg stiffness and associated variables pre and post the soccer-specific intermittent exercise test

Table 2 Changes in extensor muscle activity contribution during different phases of hopping pre and post the soccer-specific intermittent exercise test

Table 3 Relationships between changes in leg stiffness variables and changes in muscle activity following the soccer-specific intermittent endurance test

Figure 1 Relationship between changes in leg stiffness and changes in background muscle activity of A) the soleus and B) the vastus lateralis following prolonged soccer-specific exercise

Figure 2 Relationship between changes in SOL muscle activity during the braking phase and changes in CoM displacement following 42-min of prolonged soccer-specific exercise.

Table 1 Changes in leg stiffness and associated variables pre and post the soccer-specific intermittent exercise test

	Pre	**Post**
Stiffness ($kN.m^{-1}$)	26.6 ±10.6	24.0 ± 7.0
Peak GRF (N)	2406 ± 475	2449 ± 485
Average GRF (N)	1123 ± 218	1124 ± 220
Braking GRF (N)	1271 ± 231	1271 ± 263
Propulsive GRF (N)	1030 ± 197	988 ± 201
CoMd (cm)	10.3 ± 3.8	10.8 ± 2.3
Contact time (ms)	210 ± 35	216 ± 28
Flight time (ms)	216 ± 47	221 ± 39

Frequency (Hz)	2.44 ± 0.44	2.32 ± 0.29

GRF = Ground reaction force, CoMd = Centre of mass displacement during ground contact

Table 3 Relationships between changes in leg stiffness variables and changes in muscle activity following the soccer-specific intermittent endurance test

	Soleus					
	△BGA	△M_1	△M_2	△M_3	△Braking	△Co-contraction
△Stiffness	0.94**	0.68*	0.26	-0.71*	0.88**	-0.55
△CoMd	-0.76*	-0.89**	-0.45	0.70*	-0.96**	0.46
△Peak GRF	-0.53	-0.76*	-0.08	0.77**	-0.71*	0.44
	Vastus Lateralis					
△Stiffness	0.86**	0.64*	-0.69*	-0.76*	0.48	-0.52
△CoMd	-0.94**	-0.86**	0.62	0.91**	-0.68*	0.34

△Peak GRF	-0.74*	-0.61	0.58	0.61	-0.76*	-0.11

CoMd = Centre of mass displacement during ground contact, GRF = Ground reaction force, BGA = Background muscle activity (0-30 ms), M_1 = Short-latency reflex (31-60 ms), M_2 = Medium-latency reflex (61-90 ms), M_3 = (91-120 ms)

*Significant relationship, p < 0.05

**Significant relationship, p < 0.01

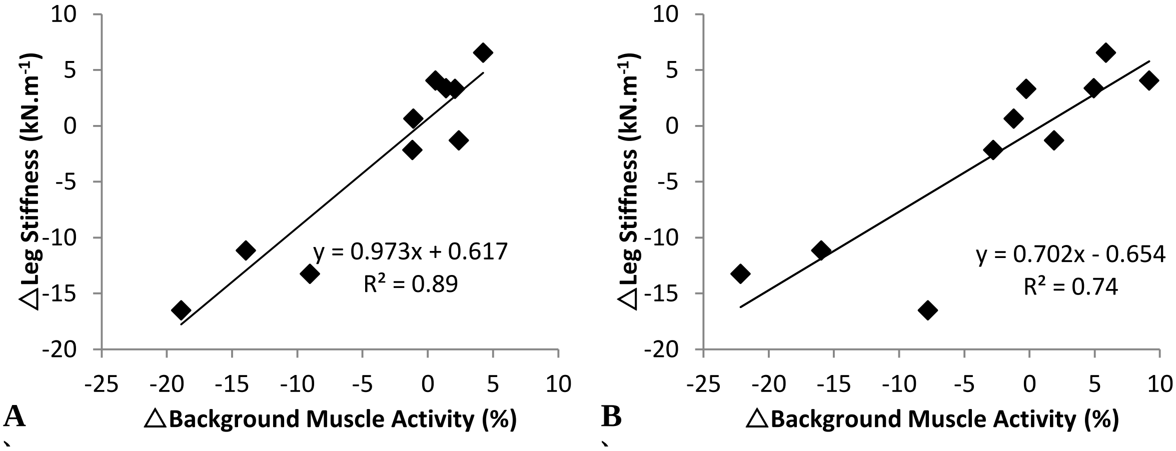

Figure 1 Relationship between changes in leg stiffness and changes in background muscle activity of A) the soleus and B) the vastus lateralis following prolonged soccer-specific exercise

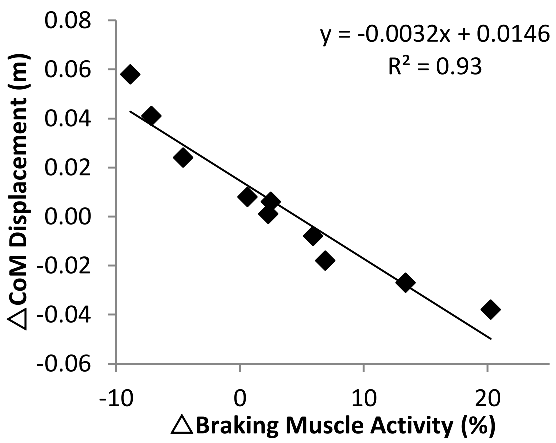

Figure 2 Relationship between changes in SOL muscle activity during the braking phase and changes in CoM displacement following 42-min of prolonged soccer-specific exercise.