Journal of Science and Medicine in Sport xxx (2015) xxx–xxx

Contents lists available at ScienceDirect

Journal of Science and Medicine in Sport

journal homepage: www.elsevier.com/locate/jsams

Original research

Plyometric training improves voluntary activation and strength during isometric, concentric and eccentric contractions

Martin Behrens[a,*], Anett Mau-Moeller[b], Karoline Mueller[c], Sandra Heise[a], Martin Gube[a], Nico Beuster[a], Philipp K.E. Herlyn[d], Dagmar-C. Fischer[c], Sven Bruhn[a]

[a] *Department of Exercise Science, University of Rostock, Germany*
[b] *Department of Orthopaedics, University Medicine Rostock, Germany*
[c] *Department of Pediatrics, University Medicine Rostock, Germany*
[d] *Department of Traumatology, Hand and Reconstructive Surgery, University Medicine Rostock, Germany*

ARTICLE INFO

Article history:
Received 16 September 2014
Received in revised form 16 January 2015
Accepted 28 January 2015
Available online xxx

Keywords:
Quadriceps
Interpolated twitch technique
Twitch torque
M-wave
Stretch-shortening cycle

ABSTRACT

Objectives: This study investigated effects of plyometric training (6 weeks, 3 sessions/week) on maximum voluntary contraction (MVC) strength and neural activation of the knee extensors during isometric, concentric and eccentric contractions.
Design: Twenty-seven participants were randomly assigned to the intervention or control group.
Methods: Maximum voluntary torques (MVT) during the different types of contraction were measured at 110° knee flexion (180° = full extension). The interpolated twitch technique was applied at the same knee joint angle during isometric, concentric and eccentric contractions to measure voluntary activation. In addition, normalized root mean square of the EMG signal at MVT was calculated. The twitch torque signal induced by electrical nerve stimulation at rest was used to evaluate training-related changes at the muscle level. In addition, jump height in countermovement jump was measured.
Results: After training, MVT increased by 20 N m (95% CI: 5–36 N m, $P = 0.012$), 24 N m (95% CI: 9–40 N m, $P = 0.004$) and 27 N m (95% CI: 7–48 N m, $P = 0.013$) for isometric, concentric and eccentric MVCs compared to controls, respectively. The strength enhancements were associated with increases in voluntary activation during isometric, concentric and eccentric MVCs by 7.8% (95% CI: 1.8–13.9%, $P = 0.013$), 7.0% (95% CI: 0.4–13.5%, $P = 0.039$) and 8.6% (95% CI: 3.0–14.2%, $P = 0.005$), respectively. Changes in the twitch torque signal of the resting muscle, induced by supramaximal electrical stimulation of the femoral nerve, were not observed, indicating no alterations at the muscle level, whereas jump height was increased.
Conclusions: Given the fact that the training exercises consisted of eccentric muscle actions followed by concentric contractions, it is in particular relevant that the plyometric training increased MVC strength and neural activation of the quadriceps muscle regardless of the contraction mode.

1. Introduction

Several studies have shown that plyometric training has a positive effect on isometric maximum voluntary contraction (MVC) strength.[1–3] However, only few studies focused on the underlying neuromuscular adaptations.[2,4,5] Studies have revealed that increases in isometric MVC strength of the plantar flexors following plyometric training were due to an improved activation of the agonistic muscles[2,4] and in part due to muscular adaptations.[4] With regard to the effect of plyometric training on isometric MVC strength of the knee extensors, studies yielded different results. While some studies observed an increase in MVC strength after 8 weeks of training,[5,6] another experiment failed to show strength enhancements following a 15-week training period.[2] The strength gains of the knee extensors in the first studies mentioned were due to neural and muscular adaptations, i.e. an improved voluntary activation of the quadriceps, assessed with the interpolated twitch technique,[5] as well as an increased single-fiber cross-sectional area and contractile function of chemically skinned single muscle fibers.[6]

Previous research in quantifying the ability to voluntarily activate a muscle after a period of plyometric training using the interpolated twitch technique has been performed under isometric testing conditions.[4,5] Therefore, hardly anything is known about changes in MVC strength and voluntary activation of the quadriceps during concentric and eccentric contractions after a

---

[*] Corresponding author.
E-mail address: martin.behrens@uni-rostock.de (M. Behrens).

http://dx.doi.org/10.1016/j.jsams.2015.01.011
1440-2440/

plyometric training regimen. Because plyometric exercises consist of eccentric contractions followed by concentric muscle actions (stretch-shortening cycle), it is of interest whether or not this kind of training influences MVC strength and voluntary activation more during dynamic contractions than during isometric contractions.

Therefore, we investigated the effects of a 6-week plyometric training on neuromuscular function of the quadriceps during isometric, concentric and eccentric MVCs. In particular, the neural drive to the knee extensors during static and dynamic MVCs was measured by using the interpolated twitch technique and the root mean square of the EMG signal normalized to the maximal M-wave (M_{max}). Putative training-related changes at the muscle level were assessed by analyzing the twitch torque signal induced by transcutaneous electrical stimulation of the femoral nerve. Furthermore, jump height in countermovement jump (CMJ) was measured.

We hypothesized that there would be a training-related increase in quadriceps MVC strength during isometric, concentric and eccentric contractions and an association between these changes and muscle activation. In view of the length of the training period, it was thought that contractile function of the knee extensors would not change. Furthermore, we expected training-related effects on the jump height in CMJ.

2. Methods

Based on the effect size for MVC strength of a previously published study,[5] a given two-sided significance level of 0.05 and a power of 0.80 sample size calculation indicated that a total of 27 persons would be required. Therefore, 27 recreational active participants without neurological disorders or injuries were recruited from our university. The participants were randomly assigned to an intervention group and a control group using randomization by a computer-generated table of random numbers. The intervention group consisted of 14 participants (10 males, 4 females, age: 24.4 ± 2.4 years, height: 180.5 ± 9.5 cm, body mass: 77.7 ± 16.4 kg), while 13 participants were assigned to the control group (10 males, 3 females, age: 25.3 ± 4.6 years, height: 182.0 ± 6.6 cm, body mass: 76.5 ± 8.0 kg). All study participants were recreational active (moderate exercise ~3 times per week, activities included running, swimming, strength training of the upper extremities and different sport games) and none of them had ever performed a systematic plyometric training program before. The participants were asked to avoid caffeine and alcohol consumption in the 24 h and strenuous exercise in the 48 h prior to the measurements. The study was approved by the university ethics committee and was in line with the declaration of Helsinki. All participants gave written informed consent prior to enrollment.

The intervention group trained 3 times a week for 6 weeks. The plyometric training consisted of CMJs in different variants, e.g. vertical CMJs, jump and reach tasks, standing long jumps, CMJs over different obstacles. The jump and reach tasks were performed next to a whiteboard where the individual jump heights were marked. These marks served as minimum target for the next jump and should motivate the participants. During long jumping, subjects jumped as far as they could and the distance was marked on the ground to motivate the subjects for the next jump. In order to adjust training intensity for each participant during the CMJs over obstacles, boxes of varying heights were used. In addition, Airex® balance pads, consisting of foam material, were used to enhance the height of the obstacles without increasing injury risk. During the first week, participants had to perform 4 sets of different CMJ exercises with 10 repetitions per set. In the following 3 weeks participants performed 12 repetitions per set. After 4 weeks of training, participants had to perform 5 sets with 15 repetitions per set. The rest interval between the CMJs was 10 s so that the participants could concentrate on every single jump and the rest interval between sets was 3 min. The participants were instructed to perform the CMJs with maximal effort in order to achieve explosive force production and maximal jump performance. In every training session, the individual jump height was measured during 1 set of the different exercises using a force plate (9290AD, Kistler, Winterthur, Switzerland) or a light barrier system (OptoGait, Microgate, Bolzano-Bozen, Italy). The results were immediately transmitted to the participants. The control group was asked to maintain their individual level of physical activities.

Neuromuscular function of the knee extensors of the right leg and jump height in CMJ were assessed prior to and after the 6-week plyometric training. Throughout the testing sessions, participants were comfortably seated in a standardized position on a CYBEX NORM dynamometer (Computer Sports Medicine®, Inc., Stoughton, MA). Neuromuscular tests consisted of supramaximal electrical stimulations of the femoral nerve at rest and during isometric, concentric and eccentric MVCs (Fig. 1). The contraction sequences were randomized. In addition, jump height was estimated on a separate day. All participants underwent a standardized warm-up on a cycle ergometer for 5 min at 60 W prior to the jump tests.

Transcutaneous electrical stimulation of the femoral nerve in the femoral triangle was used to assess neuromuscular function of the quadriceps as described previously.[7] Briefly, the femoral nerve was stimulated using a cathode ball electrode. The anode was a self-adhesive electrode (35 mm × 45 mm, Spes Medica, Genova, Italy) fixed over the greater trochanter. The electrical stimuli were single and paired rectangular pulses (1 ms duration and 1 ms duration, 10 ms apart, 400 V, respectively) delivered by a Digitimer® stimulator (DS7A, Hertfordshire, UK). The inter stimulus intervals (ISI) were provided by a LABVIEW® based program (Stimuli, Pfitec, Endingen, Germany). The testing procedure included electrical stimulation (ISI was randomized between 6 and 7 s) with increasing current intensity until identification of M_{max} of the vastus medialis (VM) muscle. M_{max} responses were elicited with supramaximal stimulation intensity (140%).[8,9] Resting twitch torques were evoked prior to the MVCs using supramaximal single and doublet stimuli.

Voluntary activation during isometric, concentric and eccentric MVCs was assessed by using the interpolated twitch technique.[10] All measurements were performed at 110° knee flexion (180° = full extension). For the isometric condition, the supramaximal electrical stimuli (doublet) were delivered to the femoral nerve 2 s after torque onset, during the plateau phase, and 2 s after MVC. Concentric and eccentric MVC testing was done at a velocity of 25°/s.[11,12] During dynamic contractions, the supramaximal doublet was triggered automatically and delivered at a knee angle of 110°. After every single contraction, participants had to relax their knee extensors immediately and the lever arm moved again through the same range of motion with the same velocity. During this passive trial, supramaximal electrical stimuli were applied at 110° knee flexion as well. The time between the active trial (concentric or eccentric MVC) and the electrical stimulation during the passive trial was 6 s. The stimuli were triggered by a LABVIEW® based software program (Stimuli, Pfitec, Endingen, Germany).

Surface EMG electrodes (EMG Ambu® Blue Sensor N) were used to record muscle activity of VM, rectus femoris (RF) and vastus lateralis (VL) muscles of the right leg as described previously.[5,7,13] Signals were amplified (2500×), band-pass filtered (10–450 Hz) and digitized with a sampling frequency of 3 kHz through an analog-to-digital converter (NI PCI-6229, National Instruments, Austin, USA). Both, the EMG and torque signals were sampled at 3 kHz and stored on a hard drive for later analysis with a custom built LABVIEW® based program (Imago, Pfitec, Endingen, Germany).

Torque signals were measured using a CYBEX NORM dynamometer (Computer Sports Medicine®, Inc., Stoughton, MA). The participants were seated with a hip joint angle of 80°. The

Please cite this article in press as: Behrens M, et al. Plyometric training improves voluntary activation and strength during isometric, concentric and eccentric contractions. *J Sci Med Sport* (2015), http://dx.doi.org/10.1016/j.jsams.2015.01.011

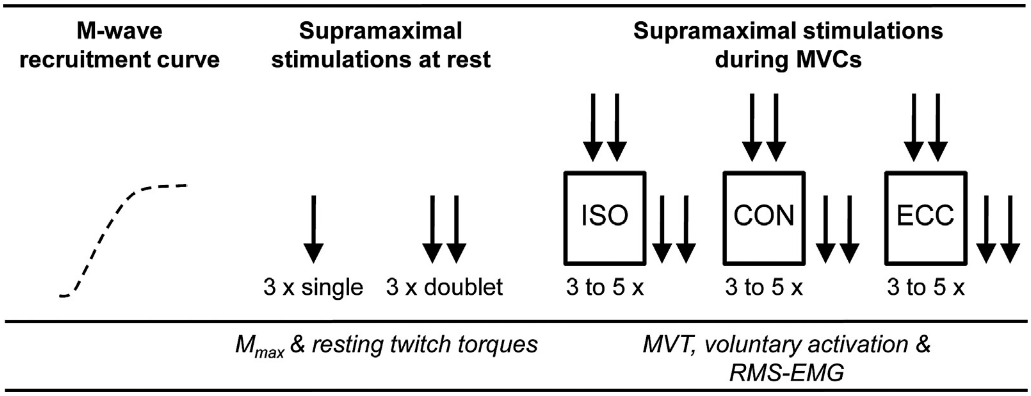

Fig. 1. An overview of the procedures carried out during neuromuscular testing and the extracted parameters. The arrows indicate stimulation at supramaximal intensity. M_{max}: maximal M-wave, MVT: maximum voluntary torque, RMS-EMG: root mean square of the EMG signal, ISO: isometric, CON: concentric, ECC: eccentric.

measurements during the isometric condition were performed at 110° knee flexion. In the concentric and eccentric MVC trials, testing was performed between 90° and 175° knee flexion at a velocity of 25°/s, while the electrical stimuli were delivered at 110°. The participants' knee joints were aligned with the axis of the dynamometer. The lever arm of the dynamometer was attached to the anterior aspect of the shank 2–3 cm above the lateral malleolus. Straps across the waist and chest prevented excessive movements.

During isometric, concentric and eccentric MVC strength testing, participants were instructed to exert maximal voluntary knee extensions against the lever arm of the dynamometer. Participants were thoroughly instructed to act as forcefully and as fast as possible. They were motivated by strong verbal encouragement and online visual feedback about the instantaneous dynamometer torque provided on a digital oscilloscope (HM1508, HAMEG Instruments, Mainhausen, Germany). A rest period of at least 1 min was allowed between the trials. Before each isometric, concentric and eccentric MVC, participants performed MVC familiarization trials. The participants performed three to five MVCs for each contraction mode (isometric, concentric and eccentric). The maximal attempts were recorded until the coefficient of variation of the best three trials was below 5%.[13]

CMJ jump height was measured with a light barrier system (OptoGait, Microgate, Bolzano-Bozen, Italy). CMJs were performed with hands akimbo. For familiarization purposes, participants performed up to four CMJs. When the coefficient of variation of three subsequent jumps was below 5%, CMJ testing was started. The participants were instructed to perform the jumps with maximal effort to achieve explosive force production and maximal jump height. Care was taken that the participants did not bend their knee and hip joints actively before landing in order to avoid artificial prolongation of flight time. A rest period of at least 1 min was allowed between the jumps. The three highest jumps were taken for further analysis.

The torque signals were corrected for the effect of gravity. Resting twitch torques were analyzed regarding their peak torque, i.e. the highest value of twitch torque signal. M_{max} amplitudes were measured peak-to-peak and averaged. The three best isometric, concentric and eccentric MVCs, respectively, were retained for analysis. On the basis of the torque-time curves of the MVC trials, maximum voluntary torque (MVT) was determined, i.e. the highest torque value for the isometric contraction and the torque values immediately before the application of the electrical stimuli for the concentric and eccentric contractions. Muscle activation during MVC was analyzed by calculating the root mean square of the amplitude of the EMG signal (RMS-EMG) over a time interval of 200 ms at MVT, i.e. 200 ms around the MVT for the isometric contraction and 200 ms prior to the electrical stimuli for dynamic contractions. Muscle activity of VM, RF and VL was normalized to the corresponding M_{max} values (RMS-EMG/M_{max}). Furthermore, RMS-EMG/M_{max} was averaged across VM, RF and VL to calculate quadriceps activation at MVT (Q RMS-EMG$_{MVT}$/M_{max}). The calculation of voluntary activation for the isometric contraction was done with the formula $\%VA = (1 - (\text{superimposed twitch} \times (T_b/\text{MVT}) \times \text{control twitch}^{-1})) \times 100$.[5,7] T_b is the torque level immediately before the superimposed twitch. This formula counteracts the problem that, in some cases, the instant the superimposed doublet is delivered does not represent the maximal torque level. For the concentric and eccentric contractions, voluntary activation was calculated with the standard formula $\%VA = (1 - (\text{superimposed twitch}/\text{control twitch})) \times 100$.[10]

Twenty seven participants volunteered to participate. Unfortunately, two participants dropped out due to illness unrelated to the study. Thus, data from 25 participants are presented. Data were checked for normal distribution using the Shapiro–Wilk test. The statistical approach comprised the analysis of covariance (ANCOVA) with baseline measurement and gender entered as covariates.[14] This approach provides an estimate for the difference between groups which is the variable of interest in randomized controlled trials.[15] In addition, it has been proposed that ANCOVA with baseline adjustment remains the optimum statistical method for the analysis of continuous outcomes in randomized controlled trials.[16] The level of significance was established at $P \le 0.05$. SPSS 20.0 (SPSS Inc., Chicago, IL, USA) was used for statistical analysis. Data obtained at baseline are presented as mean values ± standard deviation and those obtained after 6 weeks of training are given as baseline-adjusted mean ± baseline-adjusted standard deviation. If appropriate, data are presented as difference between mean (95% confidence interval).

Sample size and effect size (f) were calculated with the statistical software package G*Power (version 3.1.4.).

3. Results

Findings of the neuromuscular and strength tests at baseline are given in Table 1. The training attendance rate of the participating individuals was 91.1%.

After 6 weeks of training, isometric, concentric and eccentric MVTs were significantly increased by 20 N m (5 to 36 N m, $P = 0.012$, $\eta_p^2 = 0.267$, $f = 0.604$), 24 N m (9 to 40 N m, $P = 0.004$, $\eta_p^2 = 0.338$, $f = 0.715$) and 27 N m (7 to 48 N m, $P = 0.013$, $\eta_p^2 = 0.299$, $f = 0.653$), respectively, compared to the controls (Fig. 2A). The strength

Please cite this article in press as: Behrens M, et al. Plyometric training improves voluntary activation and strength during isometric, concentric and eccentric contractions. *J Sci Med Sport* (2015), http://dx.doi.org/10.1016/j.jsams.2015.01.011

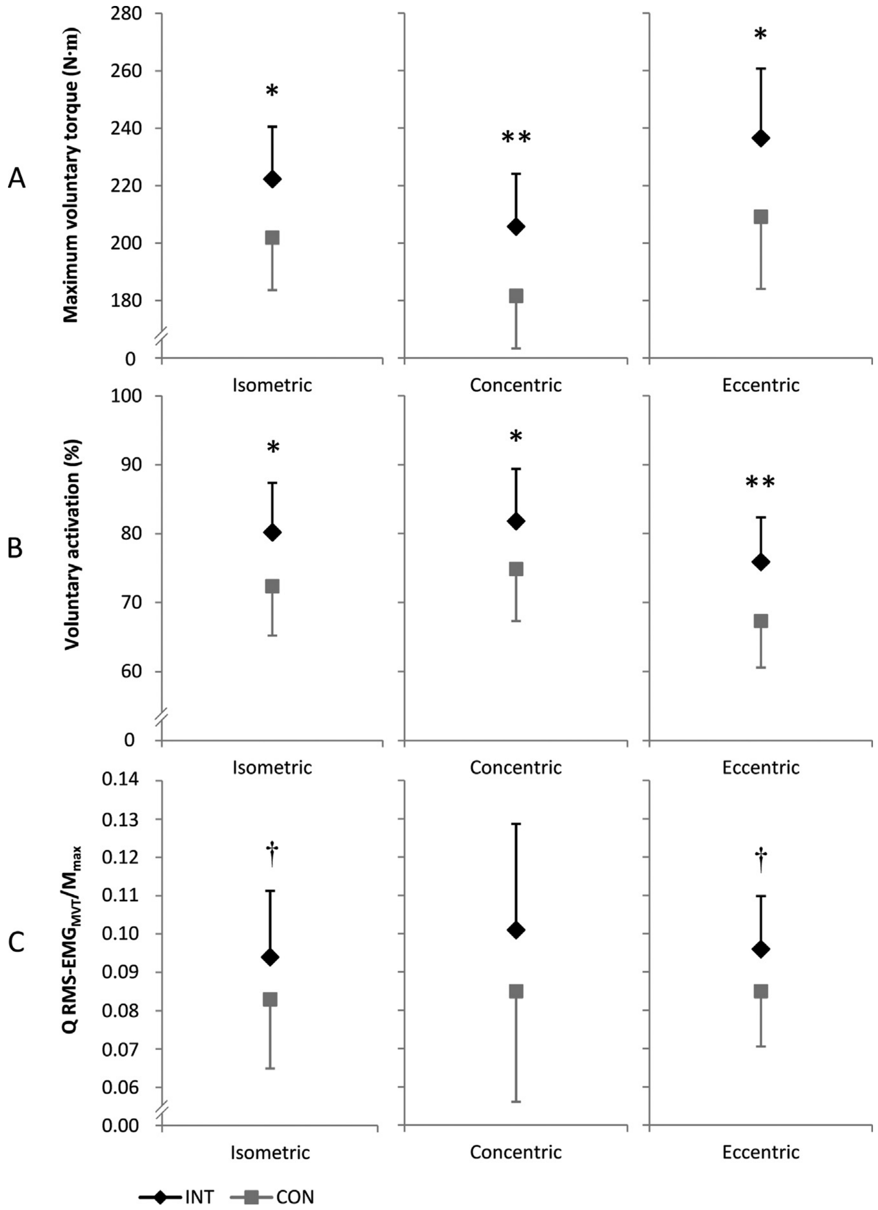

Fig. 2. Effect of the training intervention (INT) on maximum voluntary torque (A), voluntary activation (B) and normalized muscle activity of the quadriceps at MVT (Q RMS-EMG$_{MVT}$/M$_{max}$, C) during isometric, concentric and eccentric MVCs. * Denotes a significant difference between groups ($^*P \leq 0.05$; $^{**}P \leq 0.01$) and † Denotes a statistical tendency toward a significant difference between groups ($P \leq 0.10$). CON: control group.

enhancements were associated with increases in voluntary activation during isometric, concentric and eccentric MVCs by 7.8% (1.8 to 13.9%, $P = 0.013$, $\eta_p^2 = 0.257$, $f = 0.588$), 7.0% (0.4 to 13.5%, $P = 0.039$, $\eta_p^2 = 0.188$, $f = 0.481$) and 8.6% (3.0 to 14.2%, $P = 0.005$, $\eta_p^2 = 0.366$, $f = 0.759$), respectively (Fig. 2B). The training tended to increase the normalized muscle activity of the quadriceps during isometric and eccentric MVCs (Q RMS-EMG$_{MVT}$/M$_{max}$) by 0.012 (−0.002 to 0.026, $P = 0.094$, $\eta_p^2 = 0.128$, $f = 0.383$) and 0.011 (−0.002 to 0.024, $P = 0.090$, $\eta_p^2 = 0.152$, $f = 0.423$). No significant difference between groups in Q RMS-EMG$_{MVT}$/M$_{max}$ during concentric MVCs was found [0.016 (−0.008 to 0.040, $P = 0.171$, $\eta_p^2 = 0.088$, $f = 0.310$)] (Fig. 2C).

Twitch mechanical parameters did not change with training. An overview of the results for the peak twitch torques, M$_{max}$ values and normalized muscle activity of VM, RF and VL is given in Table 2.

Jump height in CMJ was 1.8 cm (0.14 to 3.53 cm, $P = 0.035$, $\eta_p^2 = 0.195$, $f = 0.492$) higher after the training for the intervention group compared with controls (Fig. 3).

4. Discussion

The present study analyzed the neuromuscular function of the knee extensors following a 6-week period of plyometric training. Data indicate that the training regimen increased isometric, concentric and eccentric MVC strength due to an increased neural drive to the quadriceps (each $f > 0.40$). The contractile function of the knee extensors, assessed by femoral nerve stimulation at rest, remained unchanged. In addition, jump height in CMJ was increased after the intervention.

To the best of our knowledge, this is the first study analyzing the effects of plyometric training on MVC strength and voluntary activation during isometric, concentric and eccentric contractions. Isometric MVC strength was significantly enhanced following the training (group difference 10.1%). This is in accordance with the results of previously published studies that reported increased isometric MVC strength after plyometric training.[2,4,5] Concentric and eccentric MVC strength was increased as well (group

Please cite this article in press as: Behrens M, et al. Plyometric training improves voluntary activation and strength during isometric, concentric and eccentric contractions. *J Sci Med Sport* (2015), http://dx.doi.org/10.1016/j.jsams.2015.01.011

Table 1
Peak twitch torques, maximal M-waves (M_{max}), maximum voluntary torques, voluntary activation, normalized muscle activity during MVT ($RMS\text{-}EMG_{MVT}/M_{max}$) and jump height in countermovement jump (CMJ) at baseline for the training (INT) and control group (CON).

Parameter	Pre		
	INT	CON	Diff.
Peak twitch torque (N m)			
Supramaximal single	25.2 ± 8.7	20.1 ± 8.8	5.1
Supramaximal doublet	55.5 ± 13.6	46.7 ± 14.0	8.8
Evoked potentials (mV)			
M_{max} vastus medialis	9.58 ± 3.08	9.73 ± 3.29	−0.15
M_{max} rectus femoris	3.97 ± 1.82	3.86 ± 2.07	0.11
M_{max} vastus lateralis	6.83 ± 4.18	6.83 ± 3.83	0.00
Maximum voluntary torque (N m)			
Isometric	226 ± 80	199 ± 62	27
Concentric	185 ± 63	172 ± 44	13
Eccentric	210 ± 39	203 ± 54	7
Voluntary activation (%)			
Isometric	72.3 ± 12.1	75.2 ± 10.4	−2.9
Concentric	69.2 ± 8.5	76.5 ± 9.8	−7.3
Eccentric	66.6 ± 7.7	69.4 ± 14.4	−2.8
$RMS\text{-}EMG_{MVT}/M_{max}$ ISO			
Quadriceps	0.090 ± 0.039	0.078 ± 0.022	0.012
Vastus medialis	0.067 ± 0.028	0.060 ± 0.018	0.007
Rectus femoris	0.118 ± 0.069	0.108 ± 0.049	0.010
Vastus lateralis	0.087 ± 0.038	0.067 ± 0.021	0.020
$RMS\text{-}EMG_{MVT}/M_{max}$ CON			
Quadriceps	0.089 ± 0.033	0.087 ± 0.019	0.002
Vastus medialis	0.069 ± 0.029	0.068 ± 0.015	0.001
Rectus femoris	0.114 ± 0.061	0.120 ± 0.047	−0.006
Vastus lateralis	0.082 ± 0.029	0.073 ± 0.017	0.009
$RMS\text{-}EMG_{MVT}/M_{max}$ ECC			
Quadriceps	0.083 ± 0.025	0.080 ± 0.017	0.003
Vastus medialis	0.063 ± 0.027	0.060 ± 0.012	0.003
Rectus femoris	0.100 ± 0.041	0.114 ± 0.052	−0.014
Vastus lateralis	0.086 ± 0.035	0.068 ± 0.018	0.018
Jump height CMJ (cm)	36.0 ± 4.8	34.7 ± 8.4	1.3

Diff.: difference between means, ISO: isometric, CON: concentric, ECC: eccentric. Data are mean ± standard deviation.

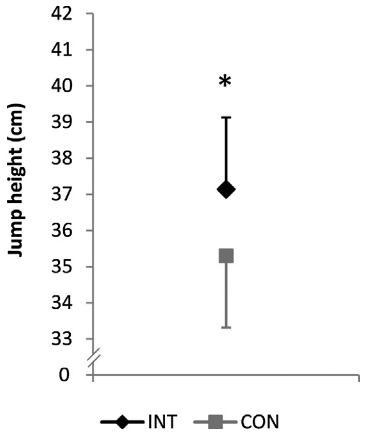

Fig. 3. Effect of the training intervention (INT) on jump height in countermovement jump. * Denotes a significant difference between groups ($^{*}P \leq 0.05$). CON: control group.

difference 13.3% and 13.1%, respectively), indicating that the training increased strength regardless of the type of contraction.

Our data on voluntary activation demonstrate that plyometric training increased isometric, concentric and eccentric MVT of the quadriceps due to an increased neural drive to the agonistic muscles. The voluntary activation during the different types of contraction seems to be relatively low in the present study, but is comparable to those observed during isometric MVCs of the knee extensors at a similar knee angle.[17] The normalized muscle activity tended to increase following the training and supports the findings for voluntary activation. These data and the unchanged peak twitch torque of the quadriceps indicate that the training regimen induced mainly neural adaptations. Similar results were obtained by Kyrolainen et al.[2] and Behrens et al.[5] The authors have shown that 15 and 8 weeks of plyometric training improved isometric MVC strength of the plantar flexors and knee extensors, respectively. These training-related changes were accompanied by increased muscle activation. Neither studies found measurable changes at

Table 2
Peak twitch torques, maximal M-waves (M_{max}) and normalized muscle activity during MVT ($RMS\text{-}EMG_{MVT}/M_{max}$) at post test for the training (INT) and control group (CON).

Parameter	Post			
	INT	CON	Diff. (95% CI)	*P*
Peak twitch torque (N m)				
Supramaximal single	20.3 ± 5.6	19.6 ± 5.6	0.7 (−4.0 to 5.4)	0.762
Supramaximal doublet	47.0 ± 10.2	47.2 ± 10.2	−0.2 (−8.8 to 8.4)	0.966
Evoked potentials (mV)				
M_{max} vastus medialis	8.87 ± 1.81	10.62 ± 1.81	−1.75 (−3.28 to −0.22)	0.027*
M_{max} rectus femoris	3.80 ± 0.90	4.09 ± 0.90	−0.29 (−1.05 to 0.47)	0.431
M_{max} vastus lateralis	6.10 ± 2.22	6.75 ± 2.22	−0.65 (−2.51 to 1.21)	0.476
$RMS\text{-}EMG_{MVT}/M_{max}$ ISO				
Vastus medialis	0.077 ± 0.014	0.058 ± 0.014	0.019 (0.005 to 0.032)	0.008**
Rectus femoris	0.120 ± 0.024	0.112 ± 0.024	0.008 (−0.011 to 0.027)	0.378
Vastus lateralis	0.085 ± 0.038	0.077 ± 0.038	0.008 (−0.025 to 0.042)	0.613
$RMS\text{-}EMG_{MVT}/M_{max}$ CON				
Vastus medialis	0.081 ± 0.017	0.061 ± 0.017	0.020 (0.005 to 0.036)	0.014*
Rectus femoris	0.128 ± 0.028	0.115 ± 0.028	0.013 (−0.010 to 0.036)	0.244
Vastus lateralis	0.097 ± 0.055	0.078 ± 0.055	0.019 (−0.027 to 0.066)	0.400
$RMS\text{-}EMG_{MVT}/M_{max}$ ECC				
Vastus medialis	0.069 ± 0.010	0.057 ± 0.010	0.012 (0.002 to 0.022)	0.019*
Rectus femoris	0.122 ± 0.021	0.111 ± 0.021	0.011 (−0.009 to 0.030)	0.257
Vastus lateralis	0.098 ± 0.042	0.089 ± 0.042	0.009 (−0.027 to 0.044)	0.607

Diff. (95% CI): difference between means (95% confidence interval), ISO: isometric, CON: concentric, ECC: eccentric. Data are baseline-adjusted mean ± baseline-adjusted standard deviation.

* Significant difference between groups $P \leq 0.05$.

** Significant difference between groups $P \leq 0.01$.

Please cite this article in press as: Behrens M, et al. Plyometric training improves voluntary activation and strength during isometric, concentric and eccentric contractions. *J Sci Med Sport* (2015), http://dx.doi.org/10.1016/j.jsams.2015.01.011

the muscle level. In contrast, studies have found that neural and muscular changes contribute to increased strength after plyometric training.[4,6] The inconsistent results might be due to the different exercises performed during the training and the dissimilar durations of the training periods. However, the cited studies have not analyzed the effect of the training regimen on dynamic MVC strength. The results of the present study reveal that plyometric training is able to modulate MVC strength via an increased voluntary activation during concentric and eccentric contractions as well. Voluntary activation of muscles by the central nervous system generally depends on the excitability of cortical neurons and spinal α-motoneurons. However, the contribution of cortical and spinal centers to the neural drive differs depending on the type of contraction.[18] It has been shown that motor evoked potentials and H-reflexes evoked during eccentric voluntary contractions are smaller than those obtained during isometric and concentric voluntary contractions.[19–21] Therefore, it may be that the training induced specific adaptations at the supraspinal and/or spinal level depending on the contraction mode. In addition, the sensitivity of the muscle spindles as well as the extent of presynaptic inhibition of Ia afferents might have changed in response to the training regime as shown previously.[22] Because contractile properties provide only a crude estimation of changes at the muscle level,[23] adaptations within the muscle cannot be completely ruled out.

It has been shown that neural adaptations mainly contribute to the early strength gains during a training period.[24–26] In view of the length of the training intervention in this study, it is most likely that primarily neural adaptations were responsible for the increased MVC strength during isometric, concentric and eccentric contractions. Based on the results of studies that have analyzed the effects of concentric and eccentric training on muscle strength, it is known that concentric training increases mainly concentric strength, and eccentric training leads to a more pronounced increase in eccentric strength.[27,28] In the present study, CMJ exercises performed during the training consisted of an eccentric phase rapidly followed by a concentric muscle action. This type of training led to similar gains in strength and neural activation during isometric, concentric and eccentric contractions.

Jump height in CMJ was increased following the training. This is in accordance with the results of previously published studies that reported increased jump heights after plyometric training.[5,29,30]

5. Conclusion

Our data indicate that plyometric training is able to increase isometric, concentric and eccentric MVC strength of the knee extensors due to enhanced neural drive to the muscles. Peak twitch torque data indicate that no training-related changes at the muscle level occurred.

The mechanisms for an improved voluntary activation after the training may involve an increase in α-motoneuron firing frequency and/or recruitment during MVC. Because voluntary activation of muscles by the nervous system depends on the excitability of cortical neurons and spinal α-motoneurons, it may be that the training induced specific adaptations at the supraspinal and/or spinal level.

6. Practical implications

- plyometric training increased MVC strength during isometric, concentric and eccentric contractions;
- the strength gains were mainly due to an increased neural activation of the quadriceps;
- plyometric training can be used to improve neuromuscular function during dynamic and static contractions.

Conflict of interest

None.

Acknowledgements

The authors would like to thank Detlef Werner for technical support. The study was funded by the Federal Institute of Sport Science (BISp, IIA1-070504/13-14).

References

1. Cornu C, Almeida Silveira MI, Goubel F. Influence of plyometric training on the mechanical impedance of the human ankle joint. *Eur J Appl Physiol Occup Physiol* 1997; 76(3):282–288.
2. Kyrolainen H, Avela J, McBride JM et al. Effects of power training on muscle structure and neuromuscular performance. *Scand J Med Sci Sports* 2005; 15(1):58–64.
3. Spurrs RW, Murphy AJ, Watsford ML. The effect of plyometric training on distance running performance. *Eur J Appl Physiol* 2003; 89(1):1–7.
4. Kubo K, Morimoto M, Komuro T et al. Effects of plyometric and weight training on muscle-tendon complex and jump performance. *Med Sci Sports Exerc* 2007; 39(10):1801–1810.
5. Behrens M, Mau-Moeller A, Bruhn S. Effect of plyometric training on neural and mechanical properties of the knee extensor muscles. *Int J Sports Med* 2014; 35(2):101–109.
6. Malisoux L, Francaux M, Nielens H et al. Stretch-shortening cycle exercises: an effective training paradigm to enhance power output of human single muscle fibers. *J Appl Physiol* 2006; 100(3):771–779.
7. Behrens M, Mau-Moeller A, Bruhn S. Effect of exercise-induced muscle damage on neuromuscular function of the quadriceps muscle. *Int J Sports Med* 2012; 33(8):600–606.
8. Behrens M, Mau-Moeller A, Wassermann F et al. Effect of balance training on neuromuscular function at rest and during isometric maximum voluntary contraction. *Eur J Appl Physiol* 2015. http://dx.doi.org/10.1007/s00421-00014-03089-00421.
9. Behrens M, Mau-Moeller A, Heise S et al. Alteration in neuromuscular function of the plantar flexors following caffeine ingestion. *Scand J Med Sci Sports* 2014. http://dx.doi.org/10.1111/sms.12243.
10. Allen GM, Gandevia SC, McKenzie DK. Reliability of measurements of muscle strength and voluntary activation using twitch interpolation. *Muscle Nerve* 1995; 18(6):593–600.
11. Klass M, Baudry S, Duchateau J. Aging does not affect voluntary activation of the ankle dorsiflexors during isometric, concentric, and eccentric contractions. *J Appl Physiol* 2005; 99(1):31–38.
12. Wilder MR, Cannon J. Effect of age on muscle activation and twitch properties during static and dynamic actions. *Muscle Nerve* 2009; 39(5):683–691.
13. Mau-Moeller A, Behrens M, Lindner T et al. Age-related changes in neuromuscular function of the quadriceps muscle in physically active adults. *J Electromyogr Kinesiol* 2013; 23(3):640–648.
14. Vickers AJ, Altman DG. Statistics notes: analysing controlled trials with baseline and follow up measurements. *BMJ* 2001; 323(7321):1123–1124.
15. Vickers AJ. Analysis of variance is easily misapplied in the analysis of randomized trials: a critique and discussion of alternative statistical approaches. *Psychosom Med* 2005; 67(4):652–655.
16. Egbewale BE, Lewis M, Sim J. Bias, precision and statistical power of analysis of covariance in the analysis of randomized trials with baseline imbalance: a simulation study. *BMC Med Res Methodol* 2014; 14:49.
17. Kubo K, Tsunoda N, Kanehisa H et al. Activation of agonist and antagonist muscles at different joint angles during maximal isometric efforts. *Eur J Appl Physiol* 2004; 91(2–3):349–352.
18. Duchateau J, Baudry S. Insights into the neural control of eccentric contractions. *J Appl Physiol (1985)* 2014; 116(11):1418–1425.
19. Abbruzzese G, Morena M, Spadavecchia L et al. Response of arm flexor muscles to magnetic and electrical brain stimulation during shortening and lengthening tasks in man. *J Physiol* 1994; 481(Pt 2):499–507.
20. Gruber M, Linnamo V, Strojnik V et al. Excitability at the motoneuron pool and motor cortex is specifically modulated in lengthening compared to isometric contractions. *J Neurophysiol* 2009; 101(4):2030–2040.
21. Duclay J, Martin A. Evoked H-reflex and V-wave responses during maximal isometric, concentric, and eccentric muscle contraction. *J Neurophysiol* 2005; 94(5):3555–3562.
22. Voigt M, Chelli F, Frigo C. Changes in the excitability of soleus muscle short latency stretch reflexes during human hopping after 4 weeks of hopping training. *Eur J Appl Physiol Occup Physiol* 1998; 78(6):522–532.
23. Mau-Moeller A, Bader R, Bruhn S et al. The relationship between lean mass and contractile properties of the quadriceps in elderly and young adults. *Gerontology* 2014. http://dx.doi.org/10.1159/000368656.
24. Duchateau J, Semmler JG, Enoka RM. Training adaptations in the behavior of human motor units. *J Appl Physiol* 2006; 101(6):1766–1775.
25. Häkkinen K, Pakarinen A, Kyrolainen H et al. Neuromuscular adaptations and serum hormones in females during prolonged power training. *Int J Sports Med* 1990; 11(2):91–98.

Please cite this article in press as: Behrens M, et al. Plyometric training improves voluntary activation and strength during isometric, concentric and eccentric contractions. *J Sci Med Sport* (2015), http://dx.doi.org/10.1016/j.jsams.2015.01.011

26. Moritani T, deVries HA. Neural factors versus hypertrophy in the time course of muscle strength gain. *Am J Phys Med* 1979; 58(3):115–130.
27. Higbie EJ, Cureton KJ, Warren 3rd GL et al. Effects of concentric and eccentric training on muscle strength, cross-sectional area, and neural activation. *J Appl Physiol (1985)* 1996; 81(5):2173–2181.
28. Hortobagyi T, Hill JP, Houmard JA et al. Adaptive responses to muscle lengthening and shortening in humans. *J Appl Physiol (1985)* 1996; 80(3):765–772.
29. Markovic G. Does plyometric training improve vertical jump height? A meta-analytical review. *Br J Sports Med* 2007; 41(6):349–355.
30. de Villarreal ES, Kellis E, Kraemer WJ et al. Determining variables of plyometric training for improving vertical jump height performance: a meta-analysis. *J Strength Cond Res* 2009; 23(2):495–506.

Please cite this article in press as: Behrens M, et al. Plyometric training improves voluntary activation and strength during isometric, concentric and eccentric contractions. *J Sci Med Sport* (2015), http://dx.doi.org/10.1016/j.jsams.2015.01.011