Motor cortical representations before and after four weeks of heavy ballistic or non-ballistic strength training.

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Motor cortical representations before and after four weeks of heavy ballistic or non-ballistic strength training.

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Abstract

***Objectives*:** The aim of this pilot study was to examine how four weeks of equal volume squat training with different speeds of execution affected the organization of the primary motor cortex (M1).

***Methods*:** Fifteen healthy untrained participants participated in the study and were divided into three groups, ballistic training, conventional training and a control group. Each participant performed a total of twelve training sessions. Transcranial magnetic stimulation was used to obtain motor cortical maps (MAP) of vastus lateralis. Further, measures of maximal voluntary contraction (MVC) and 10 repetition maximum (10RM) strength were obtained.

***Results*:** No significant differences were found between any of the groups (p>0.05) for MAP size, MVC or 10RM.

***Conclusion*:** Our results imply that differences in execution speed of the squat does not significantly change the MAP size.

Introduction

Strength training leads to significant increases in muscular strength without noticeable muscle hypertrophy (Carroll, Riek, & Carson, 2002; Duchateau & Enoka, 2002; Gabriel, Kamen, & Frost, 2006; Moritani, 1993; Moritani & DeVries, 1979; Aagaard, Simonsen, Andersen, Magnusson, & Dyhre-Poulsen, 2002). Increases in protein synthesis have been observed after a single bout of resistance training (Phillips, 2000), however, changes in muscle hypertrophy are not evident until after eight weeks of resistance training (Akima, Takahashi, Kuno, Masuda, Masuda, Shimojo, Anno, Itai, Katsuta, 1999; Hickson, Hidaka, Foster, Falduto, & Chatterton, 1994; Moritani & DeVries, 1979; Narici, Roi, Landoni, Minetti, & Cerretelli, 1989). Strength gains have been reported following 14 and 19 weeks of training, respectively, for quadriceps (Sale, Martin, & Moroz, 1992; Aagaard et al., 2002), and have been attributed to changes in the neural drive (Akima et al., 1999; Chilibeck, Calder, Sale, & Webber, 1998; Enoka, 1997; Sale et al., 1992). Some of the neural changes that occur after resistance training are, among others, motor unit synchronization (Dowling, Konert, Ljucovic, & Andrews, 1994; Milner-Brown & Lee, 1975; Patten, Kamen, & Rowland, 2001; Semmler & Nordstrom, 1998), doublet firing (van Cutsem, Duchateau, & Hainaut, 1998), and improved intra-muscular coordination (Carolan & Cafarelli, 1992).

The exact mechanisms of the adaptations remain unclear, although several studies have proposed a reorganization of the primary motor cortex (M1) (Carroll et al., 2002; Pascual-Leone et al., 1995), which likely leads to a more optimal recruitment pattern of the muscles (agonists, antagonists and synergists) involved in strength-training. The neural adaptations that occur as a result of strength training (i.e. supraspinal and spinal) are similar to those affected when a complex movement is learned, which could lead to the assumption that motor learning and increases in strength are very similar (Rutherford & Jones, 1986). The acquisition of a new skill leads to reorganization of the M1 in healthy humans (Classen, Liepert, Wise, Hallett, & Cohen, 1998; Karni et al., 1995; Pascual-leone, Grafman, & Hallett, 1994). Transcranial magnetic stimulation (TMS) and neuroimaging techniques have demonstrated that motor skill training induced changes in the organization of M1 in the form of expansion of the cortical representation of specific muscles involved in the task (Classen et al., 1998; Elbert, Pantev, Wienbruch, Rockstroh, & Taub, 1995; Karni et al., 1995; Lotze, Braun, Birbaumer, Anders, & Cohen, 2003; Pascual-Leone et al., 1995; Pascual-leone et al., 1994). Pascual-Leone and colleagues (1995) investigated the effects of learning a fine motor skill (piano sequence) on M1 reorganization and found that the cortical representation increased following training. However, Carroll et al. (2002) found that strength training did not affect the organization of M1. Carroll et al. (2002) used isolated finger abduction as the strength training exercise. Thus, the isolated finger abductions' relevance to conventional strength training can be considered to be small since conventional strength training often involves complex movements with large proximal muscles and multiple joints (Kraemer & Ratamess, 2004), such as the squat. A coordinated movement, such as the squat, probably requires overlapping zones in the M1 for specifying functional synergies between distal and proximal muscles (Tyč & Boyadjian, 2011; Tyč, Boyadjian, & Devanne, 2005), which implies that M1 plays an important role in strength increases for complex movements. Further, evidence of the role of M1 on strength increase was shown in a study by Hortobágyi and colleagues (2008). They showed, that when repetitive (r)TMS delivered at 1Hz between training sets of the first dorsal interosseous to the M1, compared with sham rTMS and no rTMS appeared to hamper strength increase (Hortobagyi et al., 2008).

Considering that initial gains in strength also can be considered a motor skill, it is reasonable to assume that similar plastic changes in M1 would occur with complex strength training (Carroll, Riek, & Carson, 2001). Data acquired with TMS are task and training specific (Beck et al., 2007; Schubert et al., 2008). TMS has previously been used to map the cortical representations of muscles either at rest (Jensen, Marstrand, & Nielsen, 2005; Wassermann, McShane, Hallett, & Cohen, 1992) or during a low-intensity tonic muscle contraction (Wilson, Thickbroom, & Mastaglia, 1993). A low-intensity contraction provides more specific information of the organization of M1 following training because of task-dependent modifications of corticomotor output (Wilson et al., 1993). Weier et al. (2012) reported an 87% increase in strength and an increase in corticospinal excitability after four weeks of heavy squat training. Furthermore, an increase in strength and cortical excitability was observed for a four-week training period of the tibialis anterior (Griffin & Cafarelli, 2007).

Motor and/or strength training can be performed in numerous ways (i.e. ballistic, non-ballistic and sensorimotor training) and Gruber and colleagues (2007) compared ballistic to sensorimotor training and found that different training regimes affected the neural drive differently. In our previous study it was showed that the cortical representation of the vastus lateralis (VL) was significant larger in ballistically-trained athletes than non-ballistically-trained athletes (8447.8 mV compared to 3350.18 mV) (Jørgensen et al. 2017).

Therefore, this Master's thesis aimed to investigate whether the significantly larger VL cortical representation could be due to the speed of the execution of the squat. In the present study, TMS was used to investigate how four weeks of equal volume squat training with different speeds of execution affected the organization of M1.

Materials and Methods

Participants

Fifteen participants were recruited to participate in the study. Due to one participant not adhering to the training regimen and another participant's pre-test data was lost, two participants were excluded. Thirteen healthy, untrained individuals (seven males and six females, 27.3 ± 6.8 years, mean ± standard deviation (SD)) participated in the study. The participants had no known neurological illnesses and were injury free in the beginning of the study. The untrained participants were randomly divided into three groups; a ballistic training group (BAL) (*n*=4), a conventional (non-ballistic) training group (CON) (*n*=4) and a control group (CTL) (*n*=5), *see table 1*. All participants received written and verbal information of the experimental protocol, completed a TMS safety-screening questionnaire (Keel, Smith, & Wassermann, 2000) and provided written informed consent.

Experimental overview

The purpose of the following paragraph is to provide the reader with a brief chronological overview of the study.

All participants attended twelve training sessions during the four-week training period, *see figure 1 for graphical representation*. Before initiating the training intervention, and after, the participants attended a session in the laboratory where experimental measures were obtained. The experimental measures included 1) an assessment of the participants maximal voluntary contraction (MVC) for knee extension using a strain gauge, 2) assessment of M_{max} using peripheral nerve stimulation, 3) TMS measures to obtain the participants resting motor threshold (rMT), active motor threshold (aMT) and motor cortical map (MAP) size. The training intervention consisted of 12 sessions during the four-week intervention and the assessment of the participants' 10 repetition maximum (10RM) was performed at the first and last day of training.

All participants were familiarized with all the procedures before commencing the testing.

Electrode placement

To collect surface electromyography (sEMG) data, two individual systems were used; one system for measuring the M-wave and MVC for VL, and another for acquiring the TMS measurements, *see figure 2 for electrode placement*.

sEMG electrodes (AMBU® Neuroline 720) were placed on VL in accordance with the SENIAM guidelines (SENIAM) and anatomical landmarks at the sites of the electrodes was noted and used for placement at the post-test. Prior to the electrode placement, the skin was thoroughly shaved, abraded and cleaned with alcohol. The sEMG electrodes were placed on VL with an inter-electrode distance of 20mm from center to center.

For M_{max} and MVC, the sampling frequency was 2000Hz and was butterworth filtered between 5Hz and 1000Hz and was collected with Mr. Kick (Mr. Kick© v3.0, University of Aalborg, Aalborg, Denmark). For the TMS procedures, Brainsight (Rogue Research Inc. V. 2.2.14) was used to sample motor evoked potentials (MEP). sEMG data from Brainsight was amplified 2500 times, bandpass filtered between 16 Hz and 470 Hz and sampled at 3000 Hz.

Peripheral nerve stimulation

A cathode was placed in the gluteal fold of the participants' right leg and an anode was placed at the inguinal ligament where the largest M-wave, peak-to-peak amplitude, for an intensity of 1mA was elicited (Weier, Pearce, & Kidgell, 2012). After locating the optimal position, three stimuli were applied at 5mA and increased by 5mA until the M-wave amplitude plateaued.

Strength measurements

Measures of MVC were assessed with the participants sitting in a chair whilst maintaining a 90-degree hip and knee angle. A strain gauge was attached to the participants' right ankle just above the lateral malleolus. Three submaximal MVCs was performed at 50, 75 and 85% of the participants perceived MVC, followed by three MVCs (Hortobagyi et al., 2008). All MVCs, both submaximal and maximal, was separated by a one-minute rest period.

The peak MVC obtained for each participant were used to calculate a contraction level of 10% of MVC, which the participants had to maintain during the TMS measurements.

Before initiating the training protocol, the participants' 10 repetition maximum (RM) (a weight that could only be lifted 10 times) for the squat was evaluated. The participants first performed a standardized warm-up consisting of ten minutes of low-intensity cycling followed by an assessment of the participants' 10RM. This was preferably done within 3-5 sets. The 10RM test was performed again following the completion of the four-week intervention period.

If the participants successfully completed ten repetitions they were asked to report their rate of perceived exertion. If the participant was able to perform all 10 repetitions, the weight was increased by 2.5 – 5 kilos until the participant was no longer able to do 10 repetitions (Willardson & Bressel, 2004) or the participant experienced their perceived exertion as being maximal. If the participant was not able to perform all ten repetitions, the 10RM was noted as the last weight the participant was able to lift ten times.

Electrophysiological measurements

Single-pulse TMS was delivered using a Magstim 200 stimulator (Magstim Co. LtD) through a coned figure of eight coil (70mm diameter). Due to technical problems, a different coil (coned figure of eight batwing coil, 70mm diameter) was used for post-testing. The coil was placed perpendicular to the skull near the vertex and the optimal site position (“hotspot”) was located as the site, which elicited the highest peak-to-peak MEP amplitude for a given intensity. The hotspot was found for VL during a contraction of 10% of MVC. The active motor threshold (aMT) was defined as the minimum stimulator intensity that evoked 5 out of 10 peak-to-peak amplitudes of at least 200µV (Kidgell, Stokes, Castricum, & Pearce, 2010; Leung, Rantalainen, Teo, & Kidgell, 2015; Schabrun, Christensen, Mrachacz-Kersting, & Graven-Nielsen, 2015; Tyč et al., 2005) while VL was contracted at 10% of MVC. The resting motor threshold (rMT) was defined as the minimum stimulator intensity that evoked 5 out of 10 peak-to-peak amplitudes of at least 50µV (Rossini et al. 1994). Corticospinal excitability was evaluated using TMS to generate an input/output curve (I/O-curve) of VL in the resting musculature, if the participants’ rMT could be obtained (rMT<90% of maximal stimulator output). The participants whose rMT could be found (n=5) received a maximum of 33 randomized stimulations with an inter-stimulus interval (ISI) of 4-6 seconds. Three stimulations were performed at 60, 70, 80, 90, 100, 110, 120, 130, 140, 150 and 160% of rMT or to an upper limit of 100% of maximal stimulator output.

Motor cortical maps

The motor cortical map (MAP) was performed using a rectangular grid (15mm x 15mm) orientated to the vertex with a distance of 15 mm between each grid point. The stimulus intensity was set to 105% of aMT (Jørgensen et al., 2017). All MAPs were recorded with the participants seated with a 90-degree knee- and hip angle whilst maintaining a contraction of 10% of the MVC previously recorded. Visual feedback was provided on a monitor directly in front of the participants. The 10% MVC contraction was chosen because this intensity has previously been shown to be most sensitive to changes in MEP amplitude (Han, Kim, & Lim, 2001).

Each grid point was stimulated three times, and if one MEP had a peak-to-peak amplitude >200 µV, the site was considered active. TMS was applied at the grid point nearest the hotspot and pseudo-randomly expanded until no sites were considered active according to the MEP amplitude criteria.

Intracortical inhibition and facilitation

Paired-pulse TMS was delivered to VL at rest using two Magstim 200^2 stimulators connected via a bistim module (Magstim Co. LtD). If the participants' rMT could not be determined at a stimulation intensity ≤83% of maximal stimulator output, no measures of short interval intracortical inhibition (SICI) or intra cortical facilitation (ICF) were performed, as it would not be possible to perform the test stimuli of 120% of rMT. The rMT could be identified for a total of five participants.

The inter-stimulus intervals were set to 3 ms for SICI and 13 ms for ICF (Wagle-Shukla, Ni, Gunraj, Bahl, & Chen, 2009) and ten stimulations were performed at 70, 80 and 90% of rMT for both SICI and ICF. The test stimulus was set at 120% of the participants' rMT. Ten unconditioned test stimulus of 120% of rMT were recorded prior to the acquisition of SICI and ICF.

Training protocol

The training intervention had a duration of four weeks and consisted of three weekly sessions of three sets of 12 repetitions with a three-minute rest interval between sets (Latella, Kidgell, & Pearce, 2012; Munn, Herbert, Hancock, & Gandevia, 2005). The ballistic training group was instructed to perform the concentric phase as fast as possible (Duchateau & Hainaut, 1984; Aagaard, 2003), while the eccentric phase was ≈ 2 seconds. The conventional training group was instructed to perform the eccentric phase for 4 seconds and the concentric phase for 2 seconds (Willardson & Bressel, 2004). The speed of execution was controlled with a metronome and sessions were separated by at least one day when possible, due to logistic circumstances. All squats were performed to a knee angle of 90 degrees. All participants initiated the training protocol by lifting a weight with the equivalent of 60% of their 1RM (calculated by virtue of their 10RM[1]). A starting weight of 60% of 1RM was chosen because a position stand by ACSM (2009) concluded that novice lifters ought to implement a weight between 50-60% of 1RM to promote the largest strength gains, whilst being able to properly perform the lift with the correct technique (ACSM, 2009). The weight was progressively increased during the four-week training intervention (Kraemer & Ratamess, 2004) if the participant successfully completed all 12 repetitions.

Data analyses

Data were processed using Microsoft Excel 2011 and Matlab® 2016a.

The three corresponding MEP peak-to-peak amplitudes for each stimulated grid point were averaged and normalized to $_{peak}$MEP for either the pre- or post-test. A site was considered active, if the mean MEP peak-to-peak amplitude were ≥200 µV before normalization.

The MAP size was calculated as the sum of the normalized active sites. The discrete peaks were defined as the mean peak-to-peak amplitude being at least 90% of the normalized MEP amplitude, and if seven of the surrounding sites had a mean peak-to-peak amplitude of 5% below, or lower than the mean peak-to-peak amplitude of the participant.

The MAP center of gravity (CoG) was defined as the amplitude-weighted center of the MAP (Wassermann et al., 1992) and calculated by weighting the X and Y coordinates on the MAP of

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[1] 1-RM=100*repetition weight/(102.78 – 2.78*repetitions) (LeSuer, McCormick, Mayhew, Wasserstein, & Arnold, 1997)

each point according to the matching amplitude of the site and finding the average coordinate of all weighted sites.

Statistical analyses

Because of the low sample size (n=13), each data set was considered as being not normally distributed. Statistics were only carried out for 10RM, MVC, MAP size, discrete peaks, CoG. Because of the low sample size (n=5), statistics for M_{max} SICI, ICF and I/O-curve were not performed. A two-way ANOVA was used to compare within, between and the interaction of the groups. Where appropriate, a Wilcoxon signed rank-test or a Mann whitney U test was performed as the post HOC test. Significance was set at $p \leq 0.05$. All data in text are presented as mean ± SD.

Results

Change in dynamic and isometric strength

Only the two training groups, BAL and CON, participated in the 10RM test.

At the end of the training period a significant difference was found from the pre- to post-test in 10RM ($F_{(1, 12)}$=24.528 , *p=0.0002*), but not between groups ($F_{(1, 12)}$=0.024 , *p=0.88*) and interaction ($F_{(1, 12)}$=0.339 , *p=0.57*). Following the four-week intervention the BAL group increased their 10RM with 65% (48.8 ± 8.5 kg to 80.6 ± 19.6 kg), but this was not significant (Z=-1.841, *p=0.06*). The CON group increased their 10RM by 93% (43.4 ± 18.4 kg to 83,8 ± 7.5 kg), but this was not significant (Z=-1.826, *p=0.06*), *see graph 1*.

A power analysis (G*power v. 3.1.9.2) for sample size estimation was performed for the BAL and CON groups. Based on our data for the BAL group (*n*=4), comparing 48.75 ± 8.54 kg to 80.63 ± 19.62 kg the effect size in the BAL group was 1.870729, with an alpha = 0.05 and power = 0.95, the projected sample size needed with this effect size is *n*=7. For the CON group (*n*=4), comparing 43.38 ± 18.36 kg to 83.75 ± 7.5 kg for CON, the effect size in the CON group was 2.525216, with an alpha = 0.05 and power = 0.95, the projected sample size needed with this effect size is *n*=5.

The results imply that there is a strong tendency for the two trainings groups to have increased their 10RM.

None of the groups (BAL, CON and CTL) displayed a significant difference in MVC from the pre- to post-test ($F_{(1, 20)}$=0.675 , *p=0.42*), between the groups ($F_{(2, 20)}$=2.680 , *p=0.09*) or interaction ($F_{(2, 20)}$= , *p=0.88*). The BAL, CON and CTL groups experienced an increase in MVC following the four-week intervention of 9,1%, 1,5% and 2,7%, respectively, *see graph 2*.

Cortical representations

The TMS mapping procedure aimed to measure the structural changes of M1. The mapping data showed a decrease in overall MAP size for the BAL group (pre-test: 10.47 ± 9.47, post-test: 8.28 ± 6.01), the CON group (pre-test: 8.76 ± 3.49, post-test: 4.23 ± 2.54), and CTL group (pre-test: 5.42 ± 4.62, post-test: 4.36 ± 2.68), *see graph 3*. However no significant difference from pre- to post-test was found ($F_{(1, 20)}$=1.582 , *p=0.22*), between groups ($F_{(2, 20)}$=1.643 , *p=0.218*) or interaction ($F_{(2, 20)}$=0.250 , *p=0.78*). *See figure 3 for examples of MAP for each group before and after training.* Based on our data and its partial eta squared for the group comparison (0.141), the effect size for groups was 0.4051473, with an alpha = 0.05 and power = 0.95, the projected sample size needed with this effect size is n=158. For the time comparison the partial eta squared was 0.073, the effect size was 0.2806219, with an alpha = 0.05 and power = 0.95, the projected sample size needed is n=319. For the interaction the partial eta squared was 0.022, the effect size was 0.1568125, with an alpha = 0.05 and power = 0.95, the projected sample size needed is n=1001.

There were no differences observed between the numbers of peaks from the pre-test to post-test within groups ($F_{(1, 20)}$=2.046 , *p=0.17*), between groups ($F_{(2, 20)}$=3.083, *p=0.07*) or interaction ($F_{(2, 20)}$=0.476 , *p=0.63*), *see table 2*.

A significant difference was observed between the groups in the center of gravity (CoG) latitude coordinate ($F_{(2, 20)}$=8.287 , *p=0.002*), but not within the groups ($F_{(1, 20)}$=0.000007, *p=0.998*) or interaction ($F_{(2, 20)}$=0.185 , *p=0.83*, *see table 2*. Further investigation was conducted with a Mann Whitney U test for the pre-test data for the BAL and CON groups (U=0.000 , *p=0.02*), pre data for the BAL and CTL groups (U=4.000 , *p=0.14*) and pre data for the CON and CTL groups (U=6.000 , *p=0.33*). For post data comparison of the BAL and CON groups (U=2.000 , *p=0.08*), for the BAL and CTL groups (U=6.000 , *p=0.33*) and for the CON and CTL groups (U=5.000 , *p=0.22*).

There were no significant differences in the CoG longitude coordinate within the groups ($F_{(1, 20)}$=1.018 , *p=0.33*), between the groups ($F_{(2, 20)}$=2.294, *p=0.13*) or interaction ($F_{(2, 20)}$=0.311, *p=0.74*).

rMT, SICI, ICF, I/O-curve, M-wave and H-reflex

rMT could only be obtained from five participants for both the pre- and post-tests. For the remaining participants, the rMT could not be obtained at either the pre- or post-test. One of the participant's M_{max} data for the pre-test is missing due to failed saving of the data file and three other M_{max} –values from the pre-test seems to have hit a upper limit before M_{max} was attained, thus not providing a valid result, so M_{max} data were not analyzed. Further, only five of the participants' rMT were found, because it was not possible to elicit a MEP ≥ 50μV below 90% of maximal stimulator output for the remaining participants, and therefore the rMT, SICI, ICF, I/O-curve were not further analyzed.

Discussion

The aim of this study was to investigate how four weeks of equal volume squat training with different speeds of execution, affected the reorganization of M1 assessed by TMS.

No significant difference in 10RM, knee extensor MVC or MAP size was found between any of the groups (BAL, CON and CTL).

Changes in dynamic and isometric strength

No significant difference was observed in 10RM strength from the pre- to post-test, the CTL group did not participate in the 10RM tests. The CON group experienced a 93% increase in 10RM, which is similar to the increment of 87% showed by Weier and colleagues (2012). The participants in the study by Weier and colleagues (2012) also performed four weeks of heavy squat training, as done in the present study. Other studies report of an increase in strength of approximately 20%, although these studies examined less complex exercises; unilateral and bilateral seated leg extension, respectively (Bruhn, Kullmann, & Gollhofer, 2006; Latella et al., 2012). The reason for that might be contributed to the complexity, with the opportunity for a larger inter-muscular coordination, of the movement performed in the current study.

The tendency toward an increase for both the BAL and CON group in 10RM strength could also be attributed to the participants becoming more familiar with the squat movement (Rutherford & Jones, 1986; Weier et al., 2012). Externally paced movements result in a greater use-dependent plasticity due to the added element of skill of the movement by taking longer to complete each repetition (Kidgell et al., 2010). Although not being subject to investigation in the present study, lower MU recruitment threshold (van Cutsem et al., 1998) and a decreased agonist/antagonist coactivation (Carolan & Cafarelli, 1992; Häkkinen et al., 1998), might also have influenced the increase in 10RM.

In the present study, no differences were found between the BAL, CON or CTL groups in MVC leg extensor strength for VL. This can be attributed to the fact that the MVC was not included in the training protocol. Adaptations to training are rather specific to the performed task (Voigt, Chelli, & Frigo, 1998; Aagaard et al., 2002), which could explain the lack of increase for the BAL, CON and CTL groups. The BAL and CON group experienced a non-significant increase in MVC of 9.1% and 1.5%, respectively. A significant increase in MVC by 15-18% has previously been observed following four weeks of resistance training of the tibialis anterior (Cannon & Cafarelli, 1987; Christie & Kamen, 2014). An increase in MVC knee extensor strength of 20% was observed following 14 weeks of dynamic and isometric strength training (Aagaard et al., 2002). The above-mentioned studies have in common that MVCs were performed as part of their training program, which was not done in the present study.

Cortical representations

No significant difference in overall MAP size was observed between any of the groups.

This could be due to the low power, however the power analysis shows that 1001 participants are required to find a significant interaction. It is more likely, that the outcome of the results, in part, can be due to the change of TMS coils because of a technical error. Both coils were designed as coned figure-of-eight coils. The coil used at the post-test was slightly less coned (batwing design) compared to the coil used at the pre-test (coned) (Magstim LtD). A study by Deng and colleagues (2013) investigated the different effects on electric field depth and focality of 50 unique coil designs. Among these 50 coil designs were two coils that matched the coil types used in the present study. Further, they report that the two different coil types used in the present study produce similar electric field distributions over the scalp (Deng, Lisanby, & Peterchev, 2013). By close examination of their results it is clear that the two coil types are not exact replicas, although the focality of the two coils does not differ. The parameter in which the coils do differ is in the extent of the spread of the electric field (Deng et al 2013). The coil used at the pre-test allowed for a more widespread current compared the one used at the post-test, which might have lead to the activation of surrounding sites. This might have affected the post-test data, as the resulting MAP size might not have been as large as it would have been using the same coil from the pretest.

The complexity of the squats performed in the present study might be more similar to the thumb-tapping, or finger abduction-adduction, movement than first assumed, as the squat, to a 90-degree knee angle, is commonly performed as a normal sitting-down and standing-up motion. The observation of no significant differences in MAP size are in line with the observations in a study on squirrel monkeys training a simple finger flexion movement for three weeks (Plautz, Milliken, & Nudo, 2000). They concluded that following 12,000 finger flexions, no significant difference was observed in any of the investigated monkeys. Although not significant, their results showed a tendency towards a decrease in overall MAP size for two out of four monkeys in all investigated hand and finger muscles (Plautz et al., 2000). The trained groups of monkeys experienced a decrease of 8% in MAP size compared to the non-significant 18% decrease observed for the BAL group in this study. Plautz and colleagues (2000) further speculate on whether a change in the speed of a movement is enough to classify as skill learning, and that skill learning has to be related to a change in the movement pattern. The skill learning part of a movement, and not strength, has been attributed to the increase in MAP size in rats using a fairly simple task (Remple, Bruneau, VandenBerg, Goertzen, & Kleim, 2001). It is important to remain vigilant in drawing conclusion from studies performed in non-human participants, as it is not a given that the occurring changes are comparable between species.

A single bout of repetitive thumb movements in humans showed an increase in M1 representation, although this increase returned to baseline a few minutes after task completion (Classen et al., 1998). Previously, the effects of four weeks of finger abduction and adduction on corticospinal properties were investigated and no differences was found (Carroll et al., 2002). During the training intervention, all squats were performed to a knee angle of 90-degrees, which might have affected our results as it has previously been shown that performing a movement with full range of motion is superior in eliciting gains in strength and hypertrophy (Pinto et al., 2012).

The complexity of the movement might not have been great enough to elicit skill acquisition and therefore not being able to induce a functional reorganization of the M1 (Adkins et al., 2006), or the squat might have been too complex, because it requires over 300 muscles to perform (Schoenfeld, 2010). Therefore, the squat could require a longer period than four weeks to 'learn'. It is uncertain as to how the cortical representation behaved in weeks one through three, as no measurements were performed during the four-week intervention. Following this notion, the participants might have learned the squatting movement by week one, two or three already (followed by a subsequent increase in M1 representation), after which the M1 representation returned to the baseline level. This has previously been revealed following three and four days of training, where M1 representation had significantly increased (Nudo, Milliken, Jenkins, & Merzenich, 1996).

It is uncertain as to how the cortical representation behaved in weeks one through three, as no measurements were performed during the four-week intervention. Following this notion, the participants might have learned the squatting movement by week one, two or three already (followed by a subsequent increase in M1 representation), after which the M1 representation returned to baseline. This has previously been revealed following three and four days of training, where M1 representation had significantly increased (Nudo, Milliken, Jenkins, & Merzenich, 1996).

The low-intensity contraction was performed as a knee extension exercise, whereas the implication of an isometric squat MVC, instead of a knee extensor MVC, could have yielded better results, as the specificity would have been greater (Rutherford & Jones, 1986; Voigt et al., 1998; Aagaard et al., 2002). Although a percentage increase of 93% in 10RM was observed for the CON group, this does not guarantee a subsequent increase in M1 representation as the strength gains observed in one type of movement, does not necessarily transfer onto different movements performed by the same muscle (Adkins et al., 2006). Subsequently, the mapping procedure would have been performed by implementing the 10% contraction of a squat MVC instead of the knee extension MVC.

Other neural adaptations might occur prior to the cortical reorganization of M1, such as MU firing rate (Hortobagyi et al., 2008), MU synchronization (Dowling et al., 1994; Milner-Brown & Lee, 1975; Patten et al., 2001; Semmler & Nordstrom, 1998), intra- and inter-muscular coordination (Carolan & Cafarelli, 1992).

The lack of difference between the CON and BAL groups might be due to the fact that both groups performed the movement with a predefined speed of execution and not self-paced (Ackerley, Stinear, & Byblow, 2011; Weier et al., 2012). In our previous study (Jørgensen et al., 2017) a significant difference was found between a group of weightlifters and conventionally trained lifters, using a similar pace as the groups in the present study. The weightlifters performed a movement with an added element of skill (i.e. the snatch and clean & jerk movements) and had been training for more than two years and trained their legs more frequently than the conventionally trained lifters. This might have caused the larger MAP size observed in our previous study (Jørgensen et al., 2017).

Methods discussion

The mapping procedure was performed during a 10% contraction, as it has previously been shown that training-induced adaptations are rather specific for the trained task (Beck et al., 2007; Voigt et al., 1998; Aagaard et al., 2002). Further, a contraction size of 10% MVC was chosen as this intensity has previously been shown to be most sensitive to changes in MEP amplitude (Han et al., 2001).

A grid size of 15 x 15, with a distance of 1.5mm between grid points, instead of an often implemented grid size of 6 x 6cm (Thordstein, Saar, Pegenius, & Elam, 2013; Van De Ruit, Perenboom, & Grey, 2015), as the map area exceeded the grid size (Thordstein et al., 2013; Wilson, Thickbroom, & Mastaglia, 1995).

Differences in the electrode placement from pre to post test, might have been a contributing factor to the change in sEMG amplitude. Although, placing the electrodes according to the SENIAM guidelines and anatomical landmarks, reduced the influence of this. Normalization of MEP to M_{max} is preferable because it would be easier to compare different participants to each other, and because M_{max} normally is a very stable measure (Aagaard et al., 2002).

Conclusion

In conclusion, this pilot study demonstrated that the speed of execution of a complex strength exercise (i.e. the squat) did not influence the reorganization of M1. Because of the low sample size and the different TMS coils used from the pre- to post-test, it is not possible to draw any conclusions. Further, this study shows a tendency towards, that both ballistic and conventional training increases the strength in the practiced movement, without a subsequent increase in MAP size and MVC for the knee extensors.

Perspectives

It is well known that ballistic training involves higher amounts of stress on an individual's body compared to non-ballistic training (Bruce-Low & Smith, 2007). Individuals performing ballistic exercises report of lower back pain more often than individuals performing slower movements. A study by Hall (1985) showed that shear forces on the lumbar region increased progressively with an increased lifting speed (Hall, 1985). Several participants in the BAL group reported of pain/discomfort in their lower back and hip. Although, we don't expect this to have influenced the results, as they were able to continue the training, it would be reasonable to consider whether or not ballistic training should be implemented this early in a training regimen. To prevent injuries of that kind, it would be preferable, when initiating a resistance-training regimen, to gradually improve overall strength before incorporating ballistic training as part of a training regimen. An improvement of overall strength before initiating ballistic training is beneficial in lowering the injury risk (Bruce-Low & Smith, 2007).

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Appendix

Table 1 – Shows the descriptive data (mean ± SD) for all participants in their respective groups.

	BAL (n=4)	CON (n=4)	CTL (n=5)
Age (yr)	32.5 ± 10.8	24.0 ± 1.4	25.8 ± 3.1
Height (cm)	174 ± 5.4	175 ± 7.0	181.6 ± 9.2
Weight (kg)	63.7 ± 2.9	78.1 ± 14.0	82.6 ± 14.7
Pre 10RM (kg)	43.38 ± 18.36	48.75 ± 8.54	-
Before training aMT (%)	56 ± 19	48 ± 7	50 ± 7
After training aMT(%)	57 ± 16	50 ± 8	56 ± 8

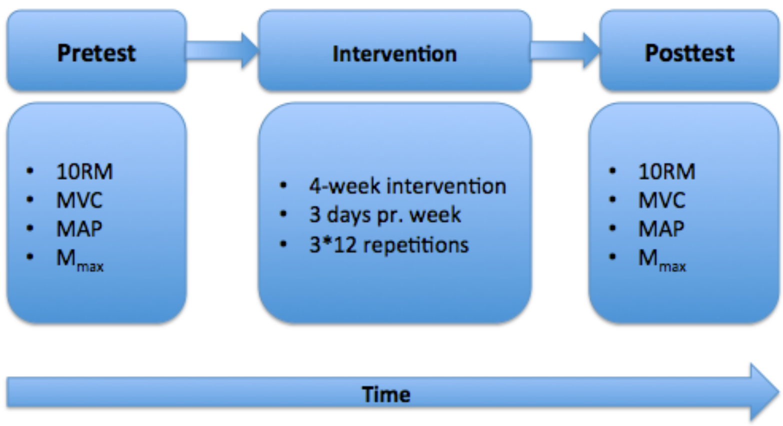


Figure 1 – Illustrates a graphical representation of the study period

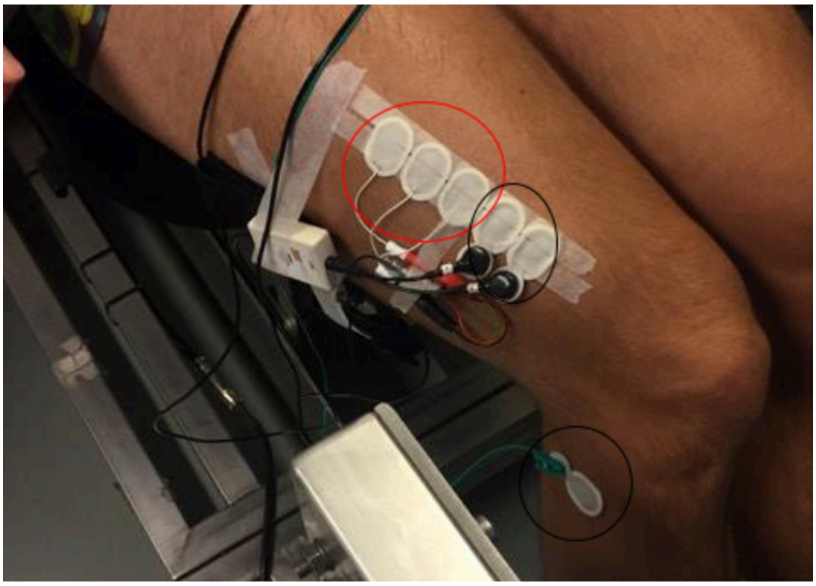
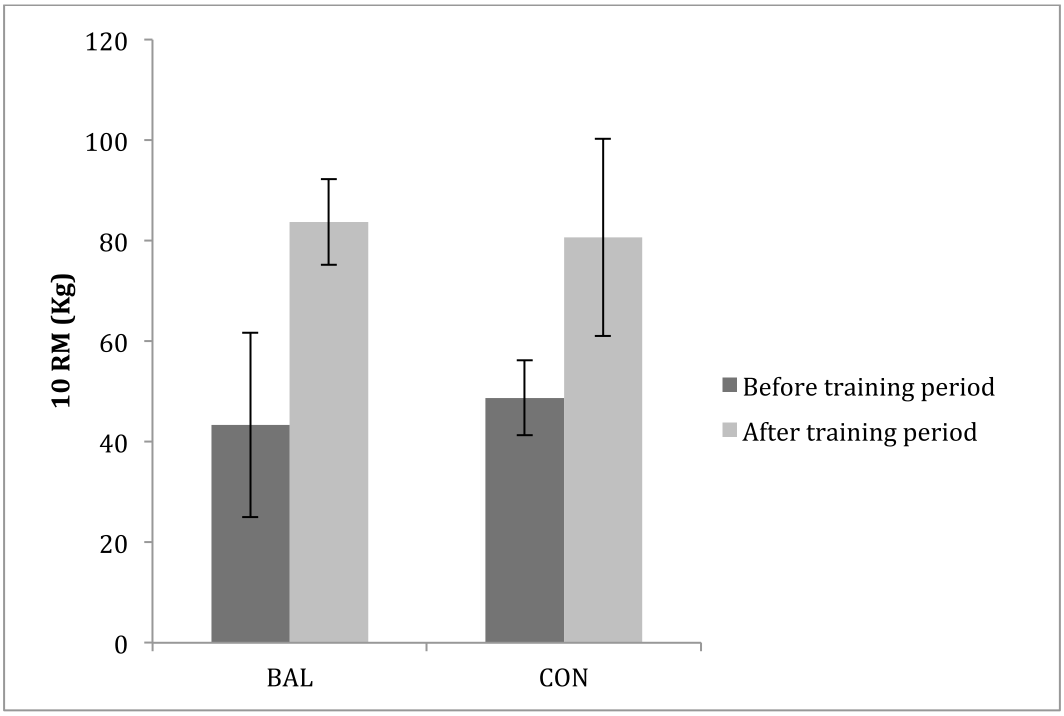
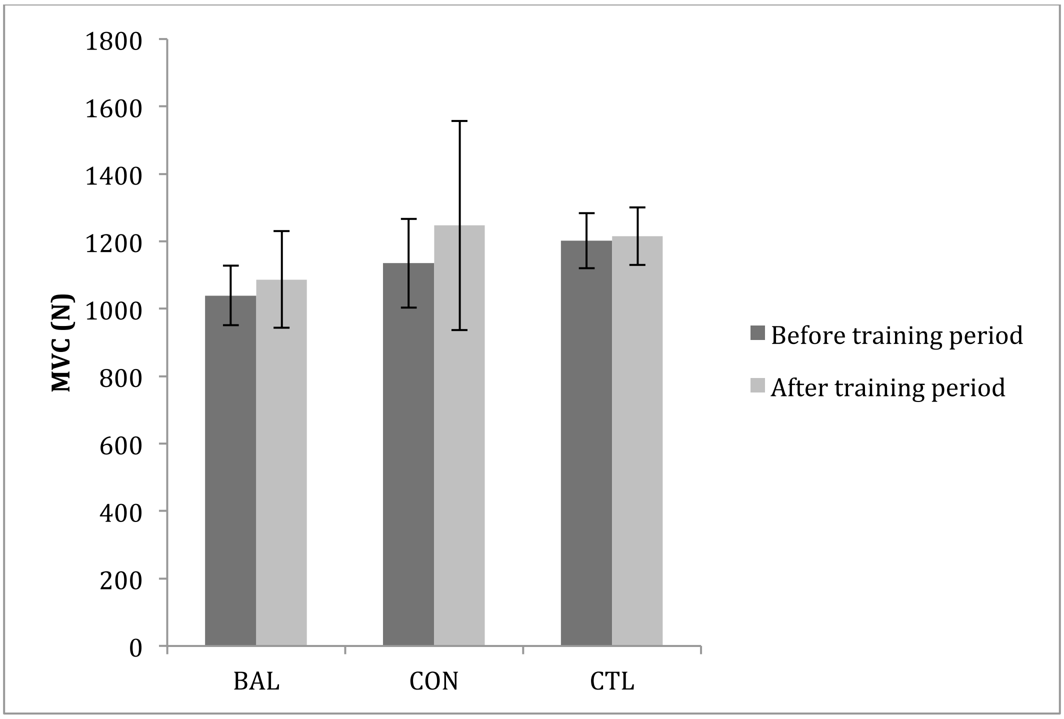


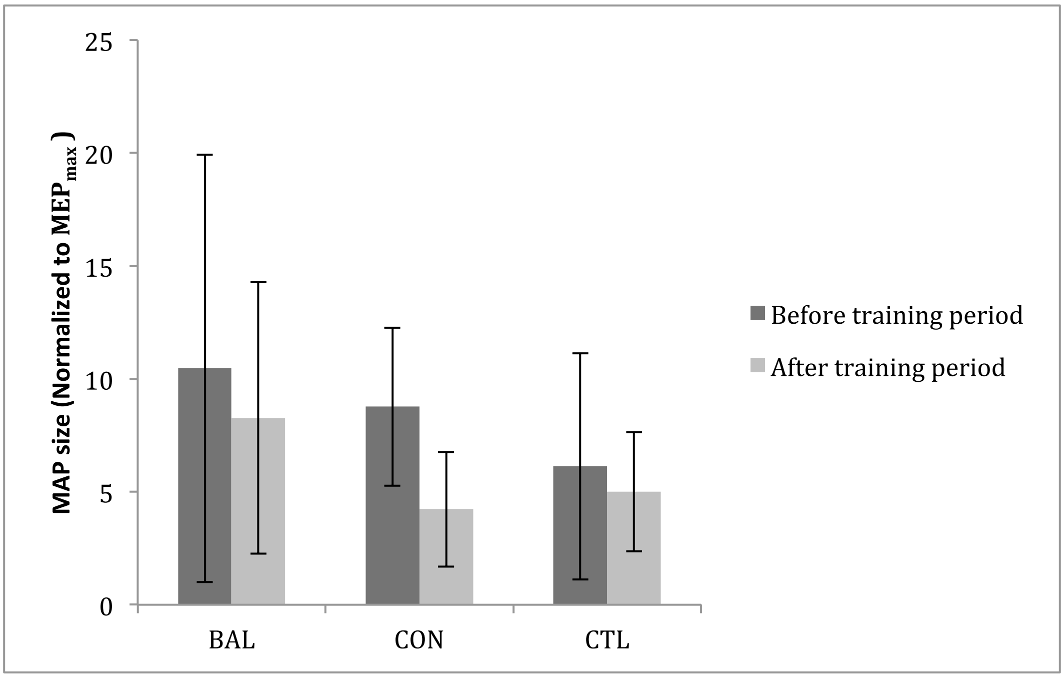
Figure 2 - Illustrates the sEMG electrode configuration on VL. The black circles indicate the electrodes used to sample data for Brainsight and the red circle shows the electrodes for measuring M_{max}.



Graph 1 - Shows the measures of maximal dynamic muscle strength (10 RM) before (solid bars) and after (shaded bars) the 4-weeks training period (mean ± SD).



Graph 2 - Illustrates the measures of maximal isometric voluntary contraction (MVC) before (solid bars) and after (shaded bars) the 4-weeks training period (mean ± SD).



Graph 3 - Shows MAP size before (solid bars) and after (shaded bars) 4-weeks of training for the ballistic (BAL), conventional (CON) and control (CTL) group. Measurements were obtained with a tonic contraction of 10% of MVC for leg extension and normalized to MEP_{max} in either pre- or post-test for the individual and merged to calculate the area (mean ± SD).

Table 2 – Shows the neurophysiological measures: MAP size, MAP discrete peaks, CoG latitude and longitude (mean ± SD).

	BAL		CON		CTL		***F-value***	***P-value***
	Pre	Post	Pre	Post	Pre	Post	(Interaction)	(Interaction)
MAP size (norm. to MEPmax)	10.47± 9.47	8.28± 6.01	8.76± 3.49	4.23± 2.54	5.42± 4.62	4.36± 2.68	$F_{(2, 20)}$ =0.250	*p*=0.78
MAP discrete peaks (number)	1.75± 0.95	3 ± 2.71	1± 0	1.5± 0.58	1± 0	1.2± 0.5	$F_{(2, 20)}$=0.476	*p=0.63*
CoG latitude (cm)	-3.47± 1.29	-3.42± 1.55	-1.26± -0.87	-0.96± 1.60	-1.83± 0.85	-2.19± 0.40	$F_{(2, 20)}$=0.185	*p=0.83*
CoG longitude (cm)	-2.34± 2.49	-0.98± 2.66	-0.24± 1,99	0.64± 1,40	-1.32± 1,43	-1.32± 0.98	$F_{(2, 20)}$=0.311,	*p=0.74*

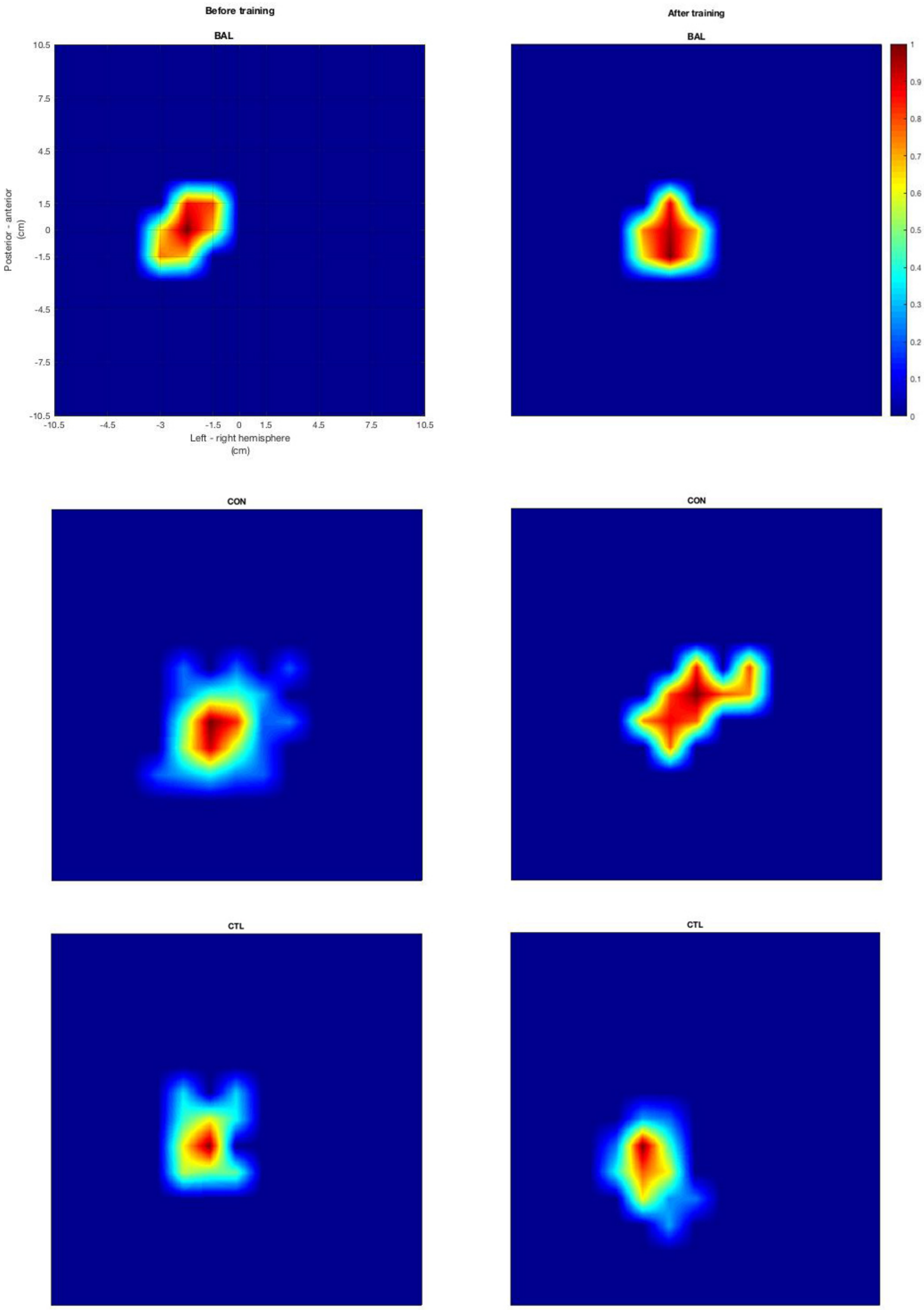


Figure 2 - An example of the MAP size for 1 subject for each group (BAL, CON and CTL) from the pre- to post-test normalized to the maximum MEP. The colored scale represents the proportion of MEP amplitude. The vertex is located at 0,0 and negative numbers indicate a placement left or posterior to the vertex and positive numbers to the right or anterior.