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Changes in normalized mutual information in response to strength training: An ancillary analysis of a quasi-randomized controlled trial

Mathias Kristiansen[1] | **Ernst Albin Hansen**[1,2] | **Afshin Samani**[1] | **Pascal Madeleine**[1]

[1]Sport Sciences—Performance and Technology, Department of Health Science and Technology, Aalborg University, Aalborg, Denmark

[2]Centre for Health and Rehabilitation, University College Absalon, Slagelse, Denmark

Correspondence
Mathias Kristiansen, Sport Sciences—Performance and Technology, Department of Health Science and Technology, Aalborg University, Niels Jernes Vej 12, 9220, Aalborg, Denmark.
E mail:
Email: mvk@hst.aau.dk

Abstract

The aim of the present investigation was twofold. (1) to assess test–retest reliability of normalized mutual information (NMI) values extracted from the surface electromyography (sEMG) signal of muscles pairs of the upper body during dynamic bench press at a high load, and (2) to assess changes in NMI values from before to after a five-week quasi-randomized controlled bench press training intervention. For test–retest reliability, 20 strength trained males (age 25 ± 2 years, height 1.81 ± 0.07 m) performed two three-repetition maximum (3RM) tests in bench press, while sEMG was recorded from six upper body muscles. Tests were separated by 8.2 ± 2.9 days. For the training intervention, 17 male participants (age 26 ± 5 years, height 1.80 ± 0.07 m) trained bench press specific strength training for 5 weeks (TRA), while 13 male participants (age 23 ± 3 years, height 1.80 ± 0.08 m) constituted a control group (CON). 3RM bench press test and sEMG recordings were carried out before and after the intervention period. The NMI values ranged from poor to almost perfect reliability, with the majority displaying substantial reliability. TRA displayed a significant decrease in NMI values during the concentric phase for two agonist–agonist muscle pairs, while one agonist–agonist and two agonist–antagonist muscle pairs increased the NMI values during the eccentric phase. The observed changes did not exceed the minimal detectable threshold, and we therefore cannot surely ascertain that the changes observed in NMI values reflect genuine neural adaptations.

KEYWORDS

co-contraction, intermuscular coordination, motor control, motor strategy, neural adaptations

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1 | INTRODUCTION

The neural adaptations commonly observed following a strength training program may be divided in two distinct categories. Firstly, a set of intramuscular adaptations cause the force output and/or rate of force development of a single muscle to increase, such adaptation could for example be an increase of neural drive,[1] an increase of motor unit firing frequency,[2] or an increase of motor unit synchronization.[3] Secondly, intermuscular adaptations cause an increase of the force generated in the intended direction of a movement by optimizing the neural control and contribution of all task relevant muscles. The latter can be termed intermuscular coordination and involves optimization of the timing and activation level of all agonists, antagonists as well as synergist muscles for a specific movement.[4]

Rutherford and Jones (1986) were among the first to show that increases in dynamic leg extension strength far exceeded increases in isometric leg extensor strength, following a 12-week training intervention consisting of dynamic unilateral leg extension. This indicated that intermuscular coordination of all task relevant muscles were contributing to the ability to exert force in the intended direction.[5] Other studies have used surface electromyography (sEMG) recordings to study the activation ratio between the agonist and antagonist muscles during a forceful contraction, to assess intermuscular coordination. While some have shown that this ratio increases,[6,7] indicating either more agonist or less antagonist activation following strength training, others have failed to show this.[8,9] Furthermore, a common feature in almost all these studies is that they investigate the activation ratio in single joint, unilateral, isometric, machine-based exercises, where the neural control demands are low compared to multi-joint, bilateral, dynamic, free weight exercises. Furthermore, the agonist–antagonist relationship may be too gross a measure to effectively reveal information on intermuscular neural adaptations following strength training of multi-joint movements, as it is often difficult to identify the exact opposing muscles around joints due to anatomical (i.e., biarticular muscle) and neurophysiological reasons (i.e., muscle redundancy). Similarly, the agonist–antagonist ratio may change throughout the range of motion during dynamic movements because of different muscles being active in various phases of a single movement.

In our laboratory, we have previously investigated changes in intermuscular coordination during a multi-joint, bilateral, dynamic, free weight exercise, using a nonnegative matrix factorization algorithm for extraction of muscle synergies. Although, we have been able to discriminate intermuscular coordination between elite powerlifters and untrained participants using nonnegative matrix factorization,[10] the method was not sensitive enough to discover any changes in intermuscular coordination in bench press following 5 weeks of strength training and a concomitant significant increase in strength.[11] Consequently, our knowledge is still sparse when it comes to changes in intermuscular coordination following strength training.

Another approach for elucidation of changes in intermuscular coordination is the measure of normalized mutual information (NMI). NMI originates from information theory and is essentially a measure of the shared information delineating both linear and nonlinear dependencies in two sEMG signals.[12] Changes in functional connectivity among muscle pairs can mostly be interpreted as altered muscles interplay due to shared mono- or polysynaptic input.[13] NMI may therefore be more sensitive to subtle changes in motor control than extraction of muscle synergies or agonist–antagonist relationships. As such, NMI has previously been shown to discriminate functional connectivity in muscles in the presence of pain,[14] following fatiguing exercise,[12,15] due to ageing,[16] and between sexes.[17] The approach may therefore also be able to discriminate on changes of functional connectivity due to neural adaptations induced by strength training. A prerequisite for that is that the NMI measurement is reliable across measurements. However, to the best of our knowledge, no study has investigated test–retest reliability of NMI.

The present investigation comprised two experiments, with two distinct aims. The first experiment assessed the test–retest reliability of NMI computed across muscles of the upper body during dynamic bench press at a high load. The second experiment assessed changes in NMI between muscle pairs of the upper body, before and after a five-week quasi-randomized controlled bench press training intervention. We hypothesized that NMI values of upper body muscles during bench press would display substantial test–retest reliability. Due to the exploratory nature of the second experiment, no hypothesis was stated. For that purpose, we conducted an ancillary analysis of data from two previous studies investigating the reliability of bench press and effects of 5 weeks of strength training on muscle synergies.[11,18] The data set used in the present study consists of unpublished sEMG data from the three-repetition maximum (3RM) tests of the two previously mentioned studies.

2 | MATERIALS AND METHODS

2.1 | Experimental approach to the problem

To assess functional connectivity between muscles in the upper body using NMI, we chose the widely applied strength training exercise of bench press. Bench press is a multi-joint, dynamic, free weight barbell exercise and is categorized as utilizing most muscles of the upper body. It requires coordination of both the shoulder, elbow, and wrist joint to be performed effectively. To assess reliability in experiment 1, trained participants visited the laboratory for one familiarization session and two test sessions separated by on average 8.2 ± 2.9 days. To assess the effect of strength training in experiment 2, a quasi-randomized controlled trial was carried out in which previously untrained participants performed one familiarization session, one pre- and one posttest session, and either 5 weeks of bench press specific strength training (TRA) or 5 weeks as control (CON) participants. All test sessions comprised a warmup procedure and a 3RM test in the bench press.

2.2 | Participants

Participants for experiment 1 were healthy males with at least 2 years' experience of performing strength training, two to three times per week ($n = 20$, age 25 ± 2 years (mean ± standard deviation (SD), height 1.81 ± 0.07 m, body mass at first and second test session 88.5 ± 13.1 kg and 89.0 ± 12.8 kg, 3RM in bench press at first and second test session 109.2 ± 26.1 kg and 109.4 ± 25.9 kg). Participants in experiment 2 were also healthy males. They were between 18 and 40 years of age. None of them had participated in regular strength training in the past 2 years leading up to the start of the study. In addition, none of them had undergone surgery or suffered serious injuries to the upper extremities in the past. To account for a possible dropout, which is commonly observed in training studies, 17 participants were allocated to TRA (age of 26 ± 5 years, height of 180.0 ± 6.6 cm, and body mass of 77.2 ± 16.2 kg) and 13 participants to CON (age of 23 ± 3 years, height of 180.4 ± 7.9 cm, and body mass of 77.2 ± 11.1 kg). See publications[11,18] for more details. Prior to the commencement of the study, all participants gave their written informed consent, after having been explained the experimental methods and potential risks of the study. The experiments were approved by the local ethics committee of North Jutland Region (N-20120036) and experiment 2 has been registered as a randomized controlled trial (ISRCTN10375612). All experiments were carried out at Aalborg University, Department of Health Science and Technology.

2.3 | Familiarization and test sessions

The familiarization procedures and test sessions were identical for experiment 1 and 2. The purpose of the familiarization procedure was to familiarize the participants with the test protocol, test equipment, and laboratory environment, to minimize any learning effects in the subsequent test sessions. Moreover, the familiarization test was used as an initial screening of the strength of the participants. Based on the initial strength, participants were matched in pairs and then randomly allocated to either TRA or CON in experiment 2, using a computer-generated randomization process. This process was carried out by M. Kristiansen.

In the test sessions, the objective was to record sEMG during a repetition performed at a relatively high load, but at the same time with a minimum risk of fatigue development. For this purpose, a 3RM load was determined in a 3RM test. The test began with each participant performing 8–10 repetitions with a 20 kg barbell. Then the load was increased 10–40 kg depending on the strength level of the individual and five repetitions were performed. The load was then increased again with approximately 5–30 kg, and this time three repetitions were performed. From here on the load was incrementally increased until the 3RM was determined. All sets were separated by a rest pause of 4 min.

2.4 | Training intervention

As mentioned earlier, the training intervention has been described in detail previously.[11] Briefly, the participants allocated to TRA completed 5 weeks of bench press specific strength training following the completion of the pretest. Three training sessions were performed per week on Mondays, Wednesdays, and Fridays. Each session always started with the bench press exercise where three sets of increasing loads were completed with 12, 10, and 8 repetitions as a warmup. Following this, three sets of six repetitions, three sets of five repetitions, and four sets of three repetitions were completed in weeks 1–2, 3–4, and 5, respectively. All sets were completed with a lifting intensity corresponding to having one repetition in reserve.[19] Three minutes of rest separated the sets. The load was adjusted after each set if it was deemed either too heavy or too light. Six assistance exercises were performed each week to prevent injuries. All training sessions were supervised by educated trainers. CON performed no training in the 5 weeks between pre and posttest.

2.5 | Data recording and processing

Before mounting the sEMG electrodes (Ambu Neuroline 720 01-K/12, Ag/AgCl, interelectrode distance 20 mm;

Ambu A/S, Ballerup, Denmark), the skin was shaved, abraded, and cleaned with alcohol. Electrodes were placed over the following muscles on the right side of the body along the muscle fiber direction in relation to anatomical landmarks using a bipolar configuration: pectoralis major (PM), anterior deltoideus (AD), biceps brachii (BB), lateral head of triceps brachii (TBL), medial head of triceps brachii (TBM), and latissimus dorsi (LD). AD, BB, TBL, and TBM were mounted according to SENIAM recommendations.[20] PM and LD were mounted in accordance with Lehman et al. (2006),[21] as these muscles are not listed by SENIAM. The reference electrode was mounted over the skin of the lateral malleolus on the right ankle as the original data collection also recorded sEMG from lower limb muscles. The same researcher mounted all electrodes in both experiment 1 and 2.

All surface EMG signals were applied a subject-specific gain factor (500–2000), band-pass filtered (10–750 Hz), and sampled at 2048 Hz using a 128-channel sEMG amplifier (EMG-USB, LISiN—OT Bioelectronica). Following acquisition, all sEMG data were processed using a digital band-pass filter (Butterworth, 4th order, 5–500 Hz). In the 3RM set, only the first repetition was used for data analysis, as this repetition reflected muscle coordination during high external force output, but without the same amount of fatigue as present in repetition two and three. The first repetition was divided into the eccentric phase and the concentric phase using data from a potentiometer (Model KS60, NTT Nordic Transducer) mounted to the middle of the barbell during data collection to measure vertical barbell position. This was done as muscle activation profiles are affected by the type of muscle action.[22] Next, the sEMG data for each muscle was normalized to its own maximum activity in the eccentric phase and the concentric phase, respectively. Then, each phase was split in the middle, creating two time series equal in length (approx. 500 ms) for each muscle, reflecting the first and second part of the phase, respectively. This splitting was done to reflect the fact that muscles may differ in their contribution during the different parts of range of motion in bench press. To assess functional connectivity between muscles, NMI was then computed using the same methods as described in Madeleine et al. (2011).[12] Briefly, the amount of information contained in one of the EMG's in a pair was computed as an entropy using equation (1):

$$H(X) = -\sum_{i} p_x(x_i)\, log(p_x(x_i))$$

In the equation, H is the entropy, X is a random variable which in our case, assuming ergodicity, is the EMG signal used as a realization of a random variable, $p_x(x)$ is obtained from a histogram estimating the probability density function of the random variable, an i refers to i-th bin of the histogram. To produce the histogram that estimates the probability density function, the number of bins was set to 19, using the same approach as Bingham et al. (2017) to determine number of bins.[15] Mutual information of two sEMG measurements (X and Y) can then be computed using equation (2):

$$Mutual\_Information_{XY} = \sum_{i,j} p_{XY}(x_i, y_i)\, log\frac{p_{XY}(x_i, y_i)}{p_X(x_i)\, p_Y(y_i)}$$

where $p_{XY}(x_i, y_i)$ is the joint probability density function of X and Y. The upper bound of mutual information is the result of the minimum of the X and Y entropy involved. To set a common measurable quantity across subjects, the mutual information was normalized using the approach applied by Madeleine et al., 2011[12] in equation (3):

$$Normalized\_Mutual\_Information_{XY} = \frac{MI_{XY}}{\min(H(X), H(Y))}$$

The NMI can take values between 0 and 1, indicating either zero or maximal functional connectivity, respectively. Computations of NMI were done for the first and second part of the eccentric phase as well as for the first and second part of the concentric phase for muscle pairs of agonist muscles (PM/DA, PM/TBM, PM/TBL, DA/TBM, DA/TBL, and TBM/TBL) and muscle pairs of agonist–antagonist muscles (PM/LD, DA/LD, BB/TBM, and BB/TBL). Lastly, the average of the two NMI values for either the eccentric or the concentric phase was computed to have only one NMI value representing either the eccentric or concentric phase.

A subsequent analysis was performed to test if observed changes in NMI values could be the results of some carryover effect between the first repetition of the 3RM set, the second repetition of the 3RM set, and the average of the first and second repetition of the 3RM set. Further, NMI values were calculated from the first two repetitions of the first three warmup sets, carried out at 20 kg for the first set, and approximately ~40% and ~60% of the estimated 3RM for the second and third warmup sets, respectively. This was done to assess the effect of lifting intensity on NMI values. The data used for these two subsequent analyses were from session 1 in experiment 1.

2.6 | Statistical analysis

To assess relative reliability of NMI values from session one and two in experiment 1, a two-way mixed effects intra-class correlation coefficient ($ICC_{3,1}$) was calculated, as this is the recommended ICC model for test–retest reliability studies.[23] To assess the absolute reliability, the Standard Error of Measurement (SEM) was computed. Minimal Detectable Change (MDC) was computed as proposed by Weir., 2005.[24] 95% limits of agreement were calculated by taking the mean and standard deviation (SD) of the difference between session 1 and 2 for each muscle pair. The lower and upper limit were then computed as mean ± 1.96 * SD. $ICC_{3,1}$-values were interpreted according to the categories proposed by Landis and Koch, 1977[25] in which an $ICC_{3,1}$ of 0.00–0.20 is considered poor, 0.21–0.40 is fair, 0.41–0.60 is moderate, 0.61–0.80 is substantial, and 0.81–1.00 is almost perfect.

In experiment 2, a Shapiro-Wilks test combined with visual inspection of histograms and QQ-plots were used to assess normality of the data. As some variables were not normally distributed, a non-parametric statistical approach was applied. To test for changes in 3RM test results and NMI values of all muscle pairs following the training intervention, the pretest was compared to the posttest using a Wilcoxon signed ranks test in each group. Multiple test adjustments were not performed due to the exploratory nature of the present study, in accordance with Bender and Lange, 2001.[26]

To test the carryover effect and effect of lifting intensity on NMI values, a one-way ANOVA test was conducted with the independent variable being NMI value, and the independent variable having six levels (1 = 1. Warmup set, 2 = 2. Warmup set. 3 = 3. Warmup set. 4 = 1. Repetition in the 3RM set. 5 = 2. Repetition in the 3RM set. 6 = 1. and 2. Repetition in the 3RM set. The one-way ANOVA test was conducted for all muscle pairs in both the eccentric and concentric lifting phase. Data are presented as mean ± SD. Statistical significance was accepted at $p \leq 0.05$. All calculations were performed in SPSS Version 28.0 (IBM Corp.).

3 | RESULTS

In experiment 1, the 3RM was 109.2 ± 26.1 kg and 109.4 ± 25.9 kg in the pre and posttest, respectively. The muscle pairs of PM/TBM, TBL/TBM, and PM/LD exhibited poor reliability in the concentric lifting phase. PM// TBL exhibited fair reliability in the concentric lifting phase, while DA/TBL, DA/TBM, and BB/TBL exhibited moderate reliability in the eccentric lifting phase as well as the concentric lifting phase for DA/TBM. The remaining muscle pairs all exhibited substantial reliability, except for BB/TBL and BB/TB which showed almost perfect reliability in the concentric lifting phase (Table 1). All SEM and MDC values are included in Table 1.

In experiment 2, all participants completed the training intervention with 100% compliance. A significant increase, constituting on average 19% ($p \leq 0.001$), was observed in 3RM bench press from pre to posttest in TRA, while no statistically significant change occurred in CON (on average −0.3%). In TRA, significantly decreased NMI values were observed from pretest to posttest in the concentric phase for muscle pairs PM/TBM ($p = 0.035$) and TBL/TBM ($p = 0.028$) (Figure 1). In contrast, NMI for TRA significantly increased in the eccentric phase for muscle pairs PM/TBM ($p = 0.017$), PM/LD ($p = 0.004$), and DA/LD ($p = 0.010$) (Figure 2 and Figure 3).

In CON, only one significant finding was observed as the muscle pair BB/TBL ($p = 0.011$) increased from pre to post during the eccentric phase (Figure 2).

With regards to carryover effect on NMI values, no significant difference was observed between the first repetition of the 3RM set, the second repetition of the 3RM set, or the average of the first and second repetition of the 3RM set for any of the muscle pairs in the eccentric nor the concentric lifting phase.

However, for lifting intensity the NMI values differed significantly in the concentric phase. For all muscle pairs, except BB/TBM and BB/TBL, the NMI values from the 3RM set were significantly lower compared to the NMI values of the first, second, and third warmup set ($p \leq 0.05$) (Table 2). Likewise, NMI values of the third warmup set were significantly lower than NMI values of the first and second warmup sets. For the eccentric phase only, a few significant results were obtained. The NMI value of BB/TBM were significantly higher during the second repetition of the 3RM set compared to the first warmup set. And the NMI value of PM/LD was significantly higher for the second warm up set compared to the third warmup set, the first repetition of the 3RM set and the average of the first and second repetition of the 3RM set, respectively.

4 | DISCUSSION

The aims of our study were (i) to assess test–retest reliability of the NMI values extracted from sEMG of upper body muscle pairs during high load bench press and (ii) to assess changes in the NMI values following 5 weeks of bench press specific strength training using a quasi-randomized controlled approach. It was shown that NMI values ranged from poor to almost perfect reliability, with the majority displaying substantial reliability. Following 5 weeks of bench press specific strength training, TRA displayed a significant decrease in NMI values during the concentric phase for two agonist–agonist muscle pairs, while one agonist–agonist and two agonist–antagonist muscle pairs increased in NMI values during the eccentric

TABLE 1 Mean ± standard deviation of the normalized mutual information values during dynamic bench press at a high load obtained at session 1 and 2 for assessment of test-retest reliability ($N=20$).

Eccentric phase	Session 1	Session 2	$ICC_{3,1}$	SEM	MDC	LOA [lower; upper]
PM/DA	0.067±0.018	0.073±0.023	0.645 [0.138:0.857]	0.012	0.034	[-0.048;0.035]
PM/TBL	0.054±0.015	0.059±0.015	0.698 [0.262:0.879]	0.008	0.023	[-0.033;0.024]
PM/TBM	0.056±0.013	0.058±0.015	0.639 [0.077:0.858]	0.008	0.023	[-0.031;0.027]
DA/TBL	0.054±0.014	0.063±0.015	0.528 [-0.075:0.805]	0.011	0.029	[-0.041;0.022]
DA/TBM	0.056±0.014	0.066±0.019	0.508 [-0.242:0.805]	0.012	0.033	[-0.048;0.029]
TBL/TBM	0.083±0.024	0.090±0.043	0.652 [0.122:0.862]	0.021	0.057	[-0.077;0.065]
BB/TBL	0.075±0.024	0.074±0.027	0.477 [-0.320:0793]	0.019	0.051	[-0.059;0.062]
BB/TBM	0.078±0.028	0.076±0.023	0.792 [0.475:0.918]	0.012	0.052	[-0.041;0.044]
DA/LD	0.063±0.017	0.063±0.015	0.709 [0.265:0.885]	0.009	0.024	[-0.031;0.031]
PM/LD	0.057±0.014	0.060±0.014	0.627 [0.058:0.852]	0.009	0.024	[-0.032;0.026]
Concentric phase	**Session 1**	**Session 2**	**$ICC_{3,1}$**	**SEM**	**MDC**	**LOA [lower; upper]**
PM/DA	0.054±0.010	0.054±0.012	0.642 [0.071:0.860]	0.007	0.018	[-0.023;0.024]
PM/TBL	0.048±0.006	0.046±0.009	0.392 [-0.512:0.757]	0.006	0.017	[-0.017;0.022]
PM/TBM	0.050±0.008	0.047±0.008	-0.251[-2.210:0.507]	0.009	0.024	[-0.021;0.026]
DA/TBL	0.049±0.010	0.049±0.011	0.664 [0.190:0.865]	0.006	0.017	[-0.019;0.020]
DA/TBM	0.054±0.011	0.049±0.011	0.516 [-0.164:0.818]	0.008	0.021	[-0.019;0.029]
TBL/TBM	0.069±0.016	0.074±0.036	0.172 [-1.092:0.672]	0.026	0.071	[-0.019;0.029]
BB/TBL	0.091±0.050	0.086±0.035	0.808 [0.515:0.924]	0.019	0.052	[-0.064;0.075]
BB/TBM	0.096±0.046	0.096±0.056	0.925 [0.811:0.970]	0.014	0.038	[-0.053;0.054]
DA/LD	0.059±0.015	0.058±0.016	0.749 [0.367:0.901]	0.008	0.021	[-0.027;0.028]
PM/LD	0.051±0.010	0.050±0.007	0.107 [-1.257:0.646]	0.008	0.023	[-0.023;0.025]

Note: Session 1 and 2 were separated by 8.2 ± 2.9 days. ICC3,1-values were interpreted according to the following categories: $ICC_{3,1}$ of 0.00–0.20 indicates poor reliability, 0.21–0.40 indicates fair reliability, 0.41–0.60 indicates moderate reliability, 0.61–0.80 indicates substantial reliability, and 0.81–1.00 indicates almost perfect reliability.

Abbreviations: $ICC_{3,1}$, Two-way mixed effects intra-class correlation coefficient; LOA, 95% limits of agreement; MDC, minimal detectable change; SEM, standard error of measurement.

phase. In CON, only one NMI value changed significantly from pre to posttest.

sEMG measurements have previously been found to display high test–retest reliability in terms of normalized amplitude.[27,28] However, to the best of the authors knowledge, no study has assessed the reliability of computing NMI on sEMG data sets captured for test–retest reliability. Although most NMI values displayed substantial reliability, quite a few also had poor to moderate reliability, indicating that NMI is not in all cases reliable. One explanation for the low reliability measurements in some muscle pairs may be dependent on the fact that only one repetition was used for computation of NMI values. Furthermore, the repetition used was obtained during a multi-joint, dynamic, free weight barbell exercise performed at a high load, which could have added further variability to the movement execution, and thus the recorded sEMG data. Previous studies have found the amplitude of sEMG to be less reliable when recorded during maximal voluntary contractions compared to submaximal contractions.[29] It is therefore possible that reliability measures obtained during isometric, low load contractions with less requirements for motor control and force output may display different reliability measures. Still, the present results are valuable when assessing the effects of a training intervention on muscle pair coordination. Our hypothesis was partly verified as 12 muscle pairs displayed substantial to almost perfect reliability (Eccentric phase: PM/DA, PM/TBL, PM/TBM, TBL/TBM, BB/TBM, DA/LD, and PM/LD. Concentric phase: PM/DA, DA/TBL, BB/TBL, BB/TBM, and DA/LD), while the remaining eight muscle pairs did not.

In TRA, NMI values decreased in agonist–agonist muscle pairs PM/TBM and TBL/TBM during the concentric phase, thereby indicating less functional connectivity following 5 weeks of bench press specific strength training. One possible explanation is that the training intervention altered the intermuscular coordination of PM/TBM and TBL/TBM to fit the anthropometry and muscle architecture of the individual,[10] although this remains speculative.

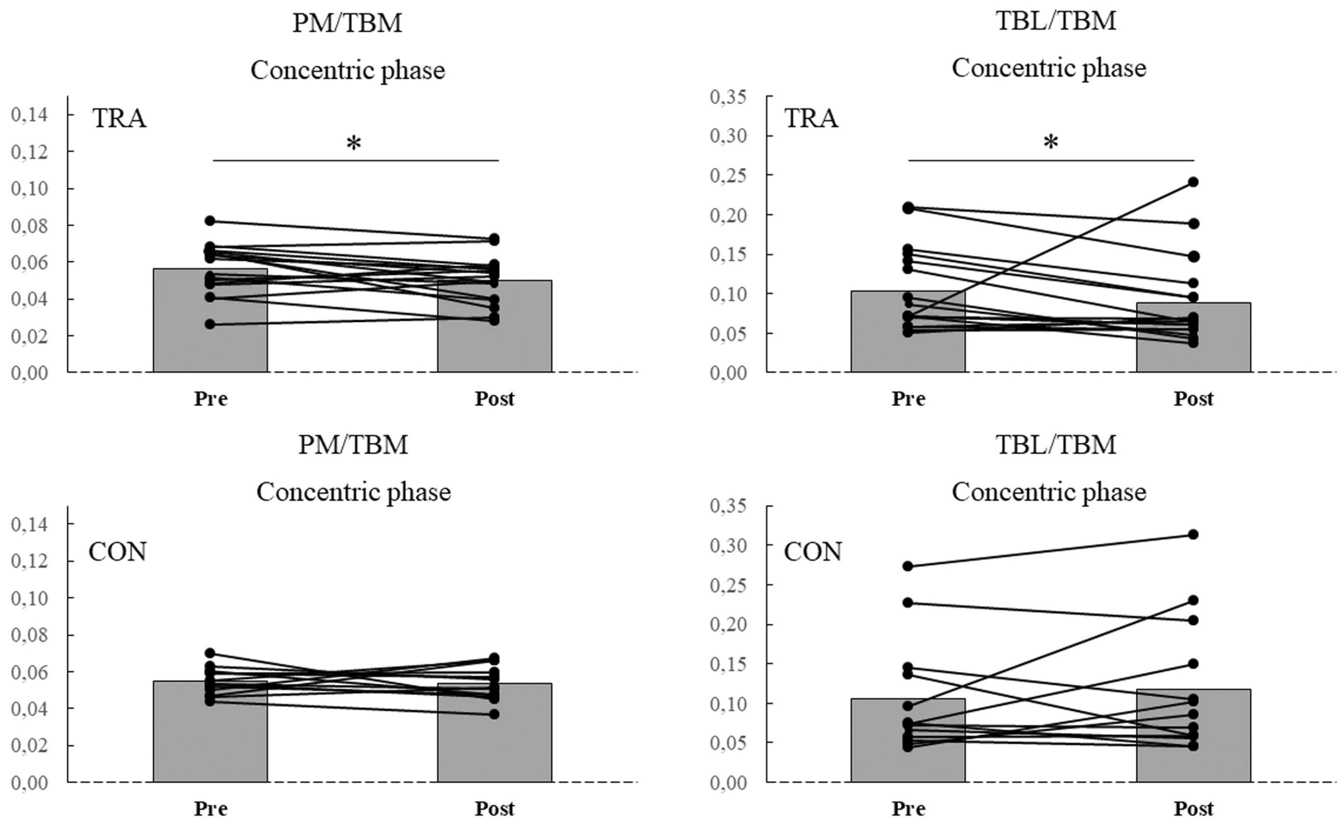

FIGURE 1 Normalized mutual information for the training (TRA) and control (CON) group during dynamic bench press at the pre and posttest, respectively. PM = pectoralis major. TBM = triceps brachii medial head. TBL = triceps brachii lateral head. Gray bars represent group mean. Solid black dots represent individual data points at pre and post test, respectively. * denotes $p \leq 0.05$. $N = 30$.

This in turn may have lowered the functional connectivity between these muscle pairs and helped facilitate an increase in 3RM. We have previously published evidence to suggest that expert powerlifters display specialized neural strategies compared to untrained counterparts during the execution of bench press.[10] More specifically, we showed that the agonist muscles of expert powerlifters are highly activated, but considerable inter-individual variability exists in the timing of this activation. The muscle pairs PM/TBM, PM/LD, and DA/LD, however, significantly increased in NMI values in TRA during the eccentric phase, thus indicating more functional connectivity. This goes along with the suggested downscaled inhibition seen for eccentric compared with concentric strength training component.[30] One explanation is, therefore, that participants in TRA are likely to have improved their ability to control the barbell during the eccentric phase of the bench press, through increased shared neural activity of the abovementioned muscles pairs and, thus, increased NMI values.[31,32] As an individual becomes stronger in the bench press, the intermuscular coordination associated with the eccentric phase becomes increasingly important. This is because the barbell trajectory must be precisely controlled during this phase to maintain optimal positioning and thereby allow enough force to be exerted on the barbell to lift it during the concentric phase. This is also referred to as lifting technique and signifies that the biomechanical characteristics of the lift must be optimized for heavier loads to be lifted. The fact that NMI decreased for two agonist–agonist muscle pairs during the concentric phase, while it increased for one agonist–agonist and two agonist–antagonist muscle pairs during the eccentric phase, may indicate that changes in functional connectivity between muscle pairs are specific to the contraction mode mostly due to differences in neural control.[33] The decrease in NMI values during the concentric phase may thus represent a strategy, whereby co-contraction of the agonist muscles is reduced to ensure a more efficient use of these muscles, similar to what has been suggested for muscle endurance.[31,32] During the eccentric phase, however, the increase in NMI may be interpreted as a strategy whereby the need for co-contraction is higher, to control the barbell during the descent.[31,32] Based on the authors interpretation, the present results thereby seem to indicate that some changes in intermuscular coordination did in fact occur in TRA and may in fact be related to their respective increase in 3RM. It should be noted, however, that the changes observed in TRA were below the MDC computed from the reliability measurements in experiment 1. Thus, the present study cannot surely ascertain

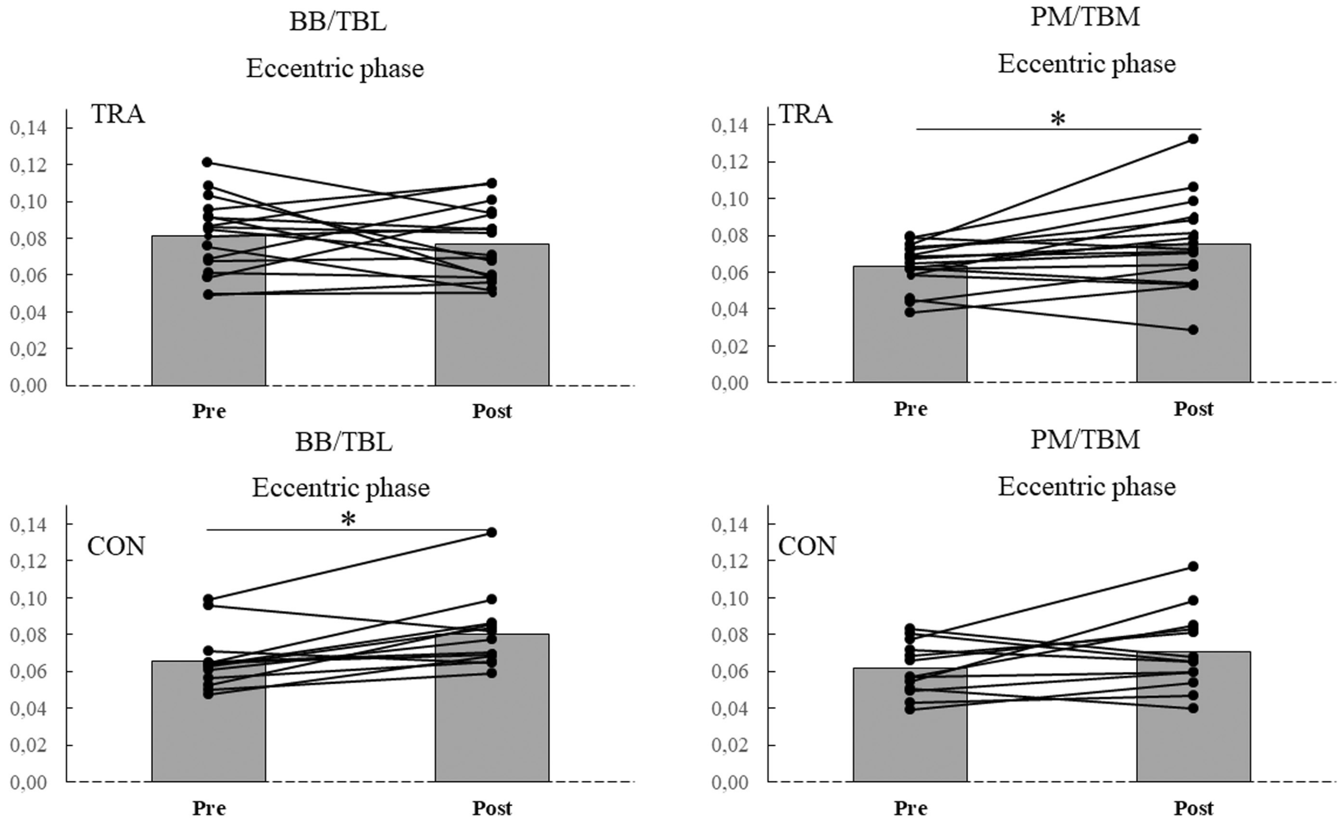

FIGURE 2 Normalized mutual information for the training (TRA) and control (CON) group during dynamic bench press at the pre and posttest, respectively. Only muscle pairs displaying a significant change are displayed. PM = pectoralis major. TBM = triceps brachii medial head. TBL = triceps brachii lateral head. BB = biceps brachii. Gray bars represent group mean. Solid black dots represent individual data points at pre and post test, respectively. * denotes $p \leq 0.05$. $N = 30$.

that the observed changes in muscle pairs reflect functionally relevant adaptations of intermuscular coordination. The same holds true for the observed significant change in CON for BB/TBL during the eccentric phase. Here, the NMI value was shown to increase from pre to posttest in CON but was also far below MDC suggesting a coincidental finding.

The subsequent analysis on the effect of lifting intensity showed that for all muscle pairs except, BB/TBM and BB/TBL, the NMI values from the 3RM set were significantly lowered compared to the NMI values of the first, second and third warmup set in the concentric phase. This result supports the decrease in NMI values seen in the concentric phase for TRA in experiment 2 and thus seem to indicate that during the concentric phase functional connectivity is lowered both when the lifting intensity increases as well as when strength levels are increased over time. With regards to the carryover effect between repetition one and two in the 3RM set, our analysis showed no significant difference between the NMI values. This may indicate that there were no changes in the level of fatigue between the repetitions as previous studies have shown NMI values to be increased in the presence of fatigue.[15,34] However, these studies were done using isometric contractions, and may therefore not be comparable to dynamic contractions used in the present study, as differences in NMI values between isometric and dynamic contractions have previously been shown.[35]

The present study is limited by the fact that it uses only one repetition for collection of sEMG. In most sEMG studies, several repetitions or cycles are used, and an average sEMG pattern is then concatenated from these repetitions/cycles. This was, however, not possible in the current experiments as the aim was to record sEMG during a repetition at high load and at the same time with a target of limited amount of fatigue. Our subsequent analysis supported our decision to only include the first repetition as there were no significant differences between NMI values of the first or the second repetition of the 3RM set. Further, an inherent limitation associated with the use of sEMG is that it only captures the motor unit action potentials occurring directly beneath the electrodes. It is therefore possible that changes of muscle activation can occur, without being detected using the present sEMG setup. Similarly, the results of the present study must be viewed in the light of the normalization procedure used. In the

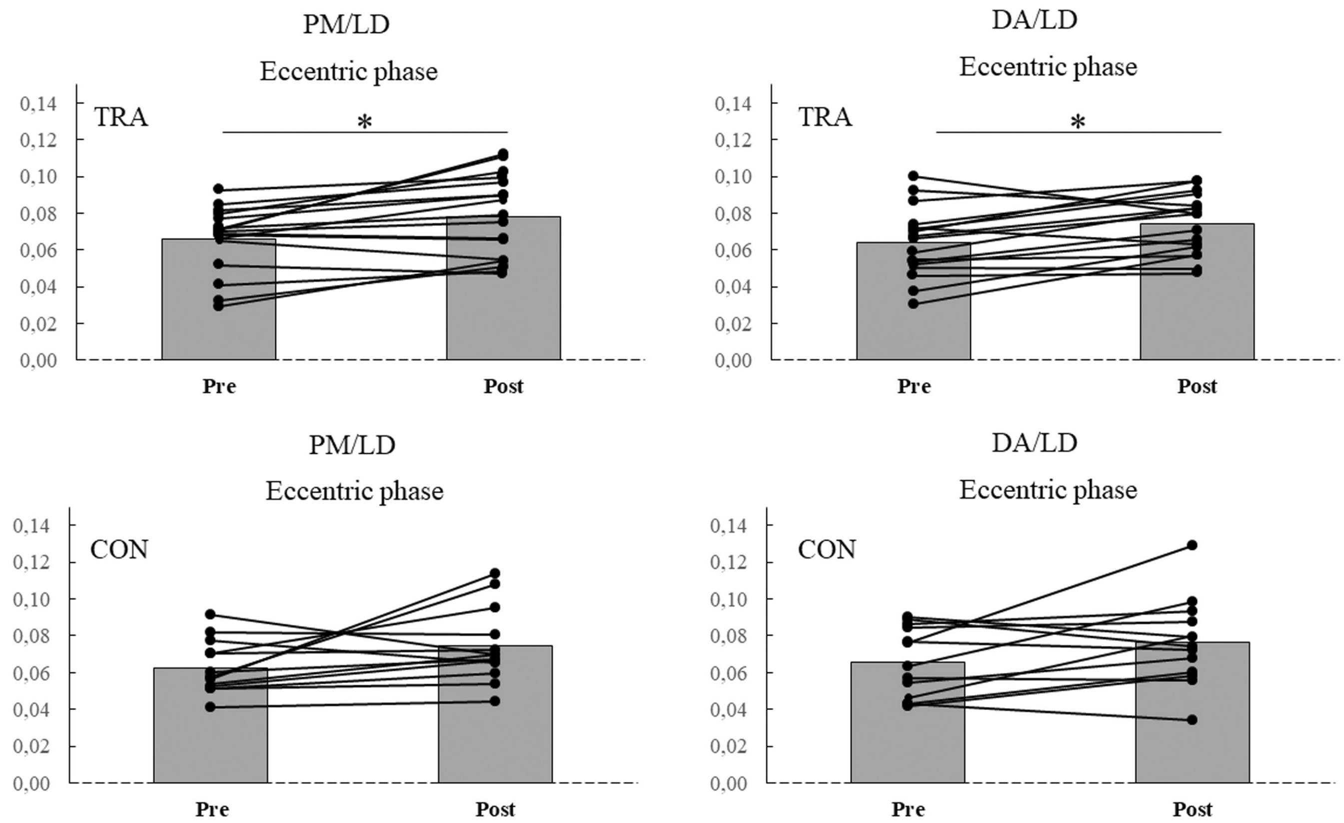

FIGURE 3 Normalized mutual information for the training (TRA) and control (CON) group during dynamic bench press at the pre and posttest, respectively. Only muscle pairs displaying a significant change are displayed. PM = pectoralis major. DA = deltoideus anterior. LD = latissimus dorsi. Gray bars represent group mean. Solid black dots represent individual data points at pre and post test, respectively. * denotes $p \leq 0.05$. $N = 30$.

present study sEMG data for each muscle was normalized to its own maximum activity in the eccentric phase and the concentric phase. The results may be markedly different if another normalization procedure had been applied, for example, normalizing to a reference task/contraction or to the maximum voluntary contraction of the specific muscle. Finally, crosstalk may influence the results of studies looking at functional connectivity. In our opinion, however, crosstalk has not had a significant influence on the results of the present study. This is due to the fact that cross talk primarily occurs when recording sEMG from adjacent and overlapping muscles,[36] while the muscles in the current study are for the most part, spatially well-apart. Secondly, there is no reason to believe that the effect of crosstalk would be systemically different between the subject groups and across the experimental sessions, as opposed to our results which shows changes across days and between groups.

In conclusion, an investigation of the reliability of NMI values extracted from sEMG of upper body muscle pairs during bench press at a high load showed poor to almost perfect ICC values, with most muscle pairs exhibiting substantial reliability. Five weeks of bench press specific strength training resulted in a decrease in NMI during the concentric phase for two agonist–agonist muscle pairs, and an increase for one agonist–agonist and two agonist–antagonist muscle pairs during the eccentric phase. The observed changes did not exceed the MDC threshold, and we therefore cannot surely ascertain that the changes observed in NMI values reflect genuine neural adaptations.

5 | PERSPECTIVE

The present study showed that the reliability of computing NMI values ranged from poor to almost perfect. This has implications when using NMI to investigate changes in motor strategies as the magnitude of change needed to exceed the minimum detectable change threshold will differ between muscle pairs. Despite that significant changes were found for some muscle pairs in TRA following 5 weeks of strength training, it does not appear likely that these changes can solely explain the 19% strength increase in 3RM for this group.

TABLE 2 Mean ± standard deviation of the normalized mutual information values obtained during dynamic bench press at different intensities of lifting during 3RM testing at session 1 of experiment 1. ($N = 20$).

Eccentric phase	1. Warmup (20kg)	2. Warmup (~40%)	3. Warmup (~60%)	1. Rep 3RM	2. Rep 3RM	1. + 2. Rep 3RM
PM/DA	0.069±0.023	0.076±0.018	0.067±0.017	0.067±0.018	0.069±0.020	0.068±0.018
PM/TBM	0.061±0.013	0.063±0.013	0.055±0.009	0.056±0.013	0.064±0.014	0.060±0.012
PM/TBL	0.063±0.013	0.064±0.015	0.059±0.009	0.054±0.015	0.064±0.013	0.059±0.013
DA/TBL	0.061±0.013	0.064±0.012	0.058±0.010	0.056±0.014	0.059±0.015	0.056±0.013
DA/TBM	0.059±0.012	0.066±0.015	0.061±0.012	0.056±0.014	0.065±0.015	0.060±0.013
TBL/TBM	0.083±0.024	0.094±0.026	0.093±0.025	0.083±0.024	0.097±0.032	0.090±0.027
BB/TBM	0.062±0.018e	0.080±0.034	0.083±0.035	0.078±0.028	0.102±0.054 [a]	0.090±0.039
BB/TBL	0.063±0.013	0.079±0.032	0.080±0.027	0.075±0.025	0.086±0.025	0.080±0.024
DA/LD	0.062±0.017	0.066±0.014	0.062±0.017	0.063±0.017	0.067±0.019	0.065±0.017
PM/LD	0.064±0.017	0.072±0.018 [c,d,f]	0.058±0.011 [b]	0.057±0.014 [b]	0.061±0.009	0.059±0.011 [b]
Concentric phase	**1. Warmup (20kg)**	**2. Warmup (~40%)**	**3. Warmup (~60%)**	**1. Rep 3RM**	**2. Rep 3RM**	**1. + 2. Rep 3RM**
PM/DA	0.108±0.030 [c,d,e,f]	0.106±0.022 [c,d,e,f]	0.083±0.014 [a,b,d,e,f]	0.054±0.011 [a,b,c]	0.049±0.013 [a,b,c]	0.051±0.011 [a,b,c]
PM/TBM	0.097±0.026 [c,d,e,f]	0.102±0.025 [c,d,e,f]	0.074±0.014 [a,b,d,e,f]	0.050±0.008 [a,b,c]	0.043±0.008 [a,b,c]	0.046±0.007 [a,b,c]
PM/TBL	0.096±0.028 [c,d,e,f]	0.099±0.022 [c,d,e,f]	0.076±0.012 [a,b,d,e,f]	0.049±0.007 [a,b,c]	0.043±0.008 [a,b,c]	0.046±0.006 [a,b,c]
DA/TBL	0.098±0.010 [c,d,e,f]	0.098±0.021 [c,d,e,f]	0.078±0.012 [a,b,d,e,f]	0.050±0.010 [a,b,c]	0.044±0.011 [a,b,c]	0.047±0.010 [a,b,c]
DA/TBM	0.098±0.029 [c,d,e,f]	0.102±0.022 [c,d,e,f]	0.078±0.017 [a,b,d,e,f]	0.054±0.011 [a,b,c]	0.047±0.012 [a,b,c]	0.051±0.010 [a,b,c]
TBL/TBM	0.113±0.040 [d,e,f]	0.121±0.029 [c,d,e,f]	0.095±0.019 [b,d,e,f]	0.069±0.017 [a,b,c]	0.064±0.025 [a,b,c]	0.066±0.019 [a,b,c]
BB/TBM	0.109±0.043	0.126±0.052	0.108±0.044	0.096±0.047	0.091±0.033	0.094±0.038
BB/TBL	0.108±0.037	0.114±0.027	0.111±0.030	0.091±0.051	0.087±0.039	0.089±0.039
DA/LD	0.103±0.036 [c,d,e,f]	0.105±0.021 [c,d,e,f]	0.082±0.018 [a,b,d,e,f]	0.059±0.015 [a,b,c]	0.052±0.019 [a,b,c]	0.055±0.014 [a,b,c]
PM/LD	0.103±0.033 [c,d,e,f]	0.100±0.023 [c,d,e,f]	0.073±0.015 [a,b,d,e,f]	0.051±0.011 [a,b,c]	0.044±0.011 [a,b,c]	0.048±0.010 [a,b,c]

Note: 1. Rep 3RM = the first repetition in the 3 repetition maximum set. 2. Rep 3RM = the second repetition in the 3 repetition maximum set. 1.+2. Rep 3RM = the average of the first and second repetition in the 3 repetition maximum set. [a] = Significantly different from 1. Warmup. [b] = Significantly different from 2. Warmup. [c] = Significantly different from 3. Warmup. [d] = Significantly different from 1. Rep 3RM. [e] = Significantly different from 2. Rep 3RM. [f] = Significantly different from 1.+2. Rep 3RM.

Abbreviations: BB, biceps brachii; DA, anterior deltoideus; LD, latissimus dorsi; PM, Pectoralis major; TBL, lateral head of triceps brachii; TBM, medial head of triceps brachii.

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CONFLICT OF INTEREST STATEMENT

The authors report no conflict of interest.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Mathias Kristiansen https://orcid.org/0000-0003-2372-2543
Pascal Madeleine https://orcid.org/0000-0002-2164-234X

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