Experimental Brain Research (2019) 237:2559–2571
https://doi.org/10.1007/s00221-019-05610-2

RESEARCH ARTICLE

Combination of jaw and tongue movement training influences neuroplasticity of corticomotor pathways in humans

Takashi Iida[1] · Yoshihiro Komoda[1,2] · Mohit Kothari[2,3] · Satoshi Sekihata[1] · Osamu Komiyama[1] · Barry Sessle[4,5] · Peter Svensson[2,6,7]

Received: 9 February 2019 / Accepted: 18 July 2019 / Published online: 25 July 2019

Abstract

Since humans in daily life perform multiple motor behaviors that often involve the simultaneous activation of both jaw and tongue muscles, it is essential to understand the effects of combined orofacial sensorimotor tasks on plasticity in corticomotor pathways. Moreover, to establish novel rehabilitation programs for patients, it is important to clarify the possible interrelationships in corticomotor excitability between jaw and tongue motor control. The aim of this study was to examine the effect of a combination of a repetitive tooth bite task (TBT) and a repetitive tongue lift task (TLT) on corticomotor excitability of the tongue and jaw muscles as assessed by transcranial magnetic stimulation (TMS). Sixteen healthy individuals participated in three kinds of training tasks consisting of 41-min TBT, 41-min TLT, and 82-min TBT + TLT. Motor-evoked potentials (MEPs) from the tongue muscle, masseter muscle, and first dorsal interosseous muscle were measured before and after the training tasks. The amplitude of tongue MEPs after training with TLT and TLT + TBT, and masseter MEPs after training with TBT and TLT + TBT, were significantly higher than before training ($P < 0.05$). Tongue MEPs and masseter MEPs were significantly higher after TLT + TBT than after TBT or TLT ($P < 0.05$). The present results suggest that a task combining both jaw and tongue movement training is associated with a greater degree of neuroplasticity in the corticomotor control of jaw and tongue muscles than either task alone.

Keywords Neuroplasticity · Corticomotor control · Tooth bite movement · Tongue lift movement · Transcranial magnetic stimulation

Introduction

Animal and human studies have both convincingly shown that cortical control of the jaw and tongue muscles allows for fine regulation and accurate coordination of jaw and tongue movements needed to execute fast and highly complex oral sensorimotor tasks, respectively (Murray et al. 1991; Lin et al. 1993; Yoshida et al. 2000; Shibukawa et al. 2004; Iida et al. 2007; Avivi-Arber and Sessle 2018). The motor cortex in animals indeed plays a significant role in the fine control of jaw and tongue movements such as those associated with tongue protrusion and the semiautomatic movements associated with chewing and swallowing (Murray and Sessle 1992; Martin et al. 1997, 1999; Yao et al. 2002; Arce-McShane et al. 2013, 2014). Like corticomotor control of other muscles in the body, this corticomotor control of jaw and tongue musculature is also subject to neuroplastic changes. Neuroplasticity has a role in several functions, including the capability to adapt to

✉ Takashi Iida
iida.takashi96@nihon-u.ac.jp

1 Division of Oral Function and Rehabilitation, Department of Oral Health Science, Nihon University School of Dentistry at Matsudo, 2-870-1, Sakaecho-nishi, Matsudo, Chiba 271-8587, Japan

2 Section of Orofacial Pain and Jaw Function, Department of Dentistry, Aarhus University, Aarhus, Denmark

3 Hammel Neurorehabilitation Centre and University Research Clinic, Aarhus, Denmark

4 Department of Oral Physiology, Faculty of Dentistry, University of Toronto, Toronto, Canada

5 Department of Physiology, Faculty of Medicine, University of Toronto, Toronto, Canada

6 Scandinavian Center for Orofacial Neurosciences (SCON), Huddinge, Sweden

7 Department of Dental Medicine, Karolinska Institutet, Huddinge, Sweden

changes in the environment and to store information in memory associated with learning (Johnston 2004). For example, training of a coordinated movement involving several muscles and joints requires an activity-dependent coupling of cortical networks (Tyc and Boyadjian 2011).

In the case of the corticomotor control of orofacial sensorimotor functions, several animal studies have demonstrated neuroplasticity in the motor cortex related to learning of novel sensorimotor functions in the orofacial region, and to tooth loss and other dental manipulations (Sessle et al. 2005; Avivi-Arber et al. 2011; Avivi-Arber and Sessle 2018; Arce-McShane et al. 2013, 2014). Although some studies have investigated the effects of short-term training in jaw or tongue movements on corticomotor excitability related to the control of the jaw and tongue, no study has yet investigated the effect of combined training in the orofacial area (e.g., jaw and tongue movements) on plasticity of corticomotor pathways in the same participants. Since in daily life, humans perform multiple orofacial sensorimotor tasks that involve both jaw and tongue muscles, it is essential to investigate the effects of combined orofacial sensorimotor tasks on the corticomotor excitability related to the control of jaw and tongue movements.

There are isolated activation areas in the dorsal aspects of the human sensorimotor cortex whose anatomical locations are at the border between the motor cortex related to tongue motor control and jaw motor control (Penfield and Boldrey 1937). Previous human studies have demonstrated the sensorimotor organization within the motor cortex (Ridding et al. 2000; Rosenkranz and Rothwell 2006). In the orofacial area, closely approximating and often overlapping motor cortical sites representing both tongue and jaw muscles have been shown in animals (Huang et al. 1988, 1989; Murray and Sessle 1992; Martin et al. 1997; Avivi-Arber et al. 2010, 2011, 2015). Our previous human studies have investigated the effects of repetitive tongue lift movements on corticomotor excitability related to the control of the jaw and tongue muscles, and have suggested that repetitive tongue lift movements trigger neuroplasticity in the corticomotor representation not only of the tongue musculature but also of jaw-closing muscles (Komoda et al. 2015). However, no studies have addressed the effects of combinations of repetitive tongue and jaw movements on corticomotor excitability related to the jaw and tongue musculatures. To establish novel rehabilitation programs for patients, it is important to clarify the possible interrelationships in corticomotor excitability between jaw and tongue motor control. Therefore, the aim of this study was to examine the effect of a combination of a repetitive tooth bite task (TBT) and a repetitive tongue lift task (TLT) on corticomotor excitability of the tongue and jaw muscles as assessed by transcranial magnetic stimulation (TMS).

Methods

Participants

Sixteen healthy volunteers (seven men and nine women) in the age range of 19–29 years [mean age ± standard deviation (SD); 22.9 ± 2.8 years] participated in the study. Before the experiment, participants were informed about the experimental procedures and informed consent was obtained from all participants. The ethics committee, Region Midtjylland, Denmark, approved the project based on the guidelines set forth in the Declaration of Helsinki II. Exclusion criteria were medical or psychological problems, epilepsy, metal implants in the head, a pacemaker, an implanted drug pump, and pregnancy.

Study design

The three training tasks were performed on separate days in a randomized order. To avoid any carry-over effects, an interval of at least 1 week was set between each of the training tasks in accordance with the above studies (Svensson et al. 2003, Lu et al. 2013). The training tasks consisted of 41 min of TBT, 41 min of TLT, and 82 min of TBT + TLT. TBT and TLT were based on our previous experimental design (Komoda et al. 2015). 82 min of TBT + TLT consisted of 41 min of TBT and 41 min of TLT. Bite force during the TBT and tongue pressure during the TLT were both measured by a tongue pressure measurement system (JMS Co., Hiroshima, Japan) (Tsuga et al. 2011). Participants held the pressure probe between their anterior teeth or the pressure probe and their left hand during TBT and TLT, respectively.

In training for each task, participants performed 5 s of maximum biting on the anterior teeth three times before and after the TBT, 5 s of maximum tongue lifting three times before and after the TLT, or both tasks before TBT + TLT. Each task training consisted of three series, and one series consisted of one force level (5 kPa or 10 kPa) in accordance with our previous study and to increase the level of complexity of the training task (Komoda et al. 2015). During the first and third series, participants were instructed to perform the different force levels without visual feedback. During the second series, participants were instructed to perform the different force levels with visual feedback of the target force level, calculated from the tongue pressure measurement system on the monitor. In each series, participants alternately performed a 30-s rest block and a 30-s task block during a 360 s period. In the task block, participants alternately performed a 5-s rest block and a 5-s task block with auditory signal (Fig. 1).

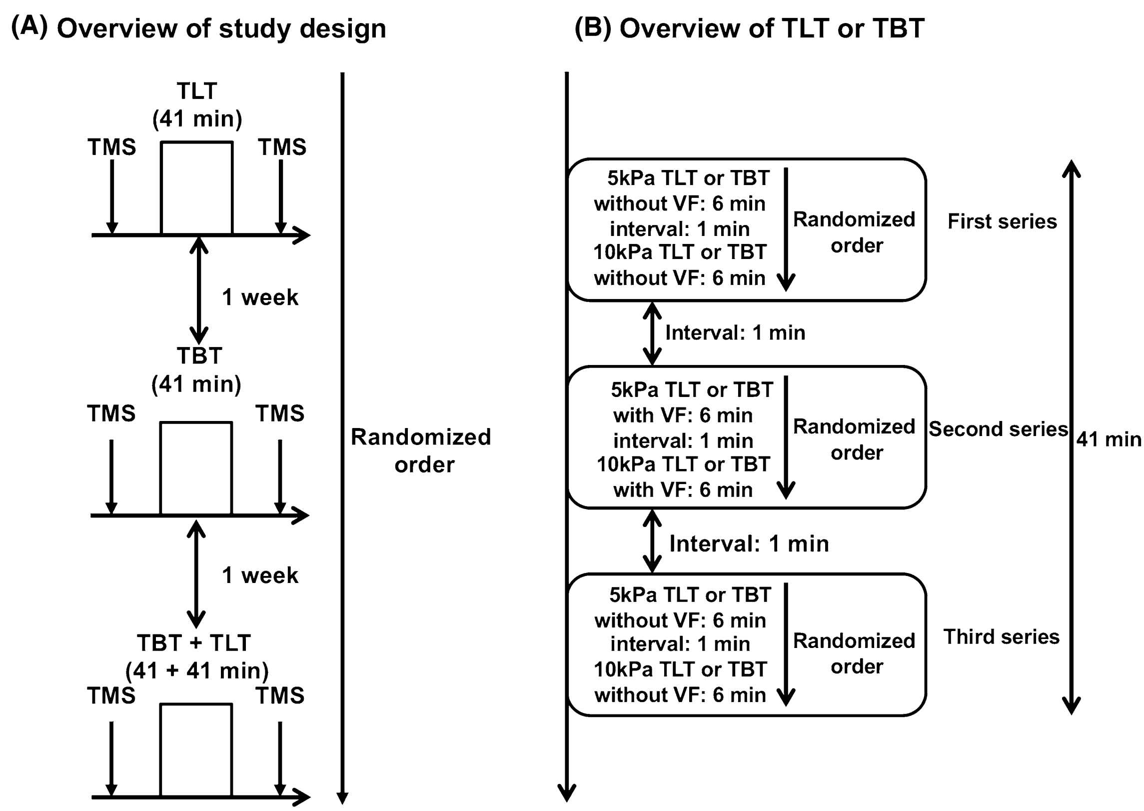


Fig. 1 Overview of study design (**a**) and TBT or TLT (**b**). *TBT* tooth bite task, *TLT* tongue lift task, *VS* visual feedback, *TMS* transcranial magnetic stimulation, *MVC* maximum voluntary contraction

Actual force, electromyographic (EMG) and transcranial magnetic stimulation (TMS) measurements

During training for each task, the EMG activities from the left masseter muscle (LM), the right masseter muscle (RM), the left suprahyoid muscles (LS), and the right suprahyoid muscles (RS) were recorded. The EMG signals were amplified 5000 times (Disa Electronik, Disa 15C01, Skovlunde, Denmark) and filtered in the bandwidth 10 Hz–1 kHz for offline analysis. In all measurements, EMG activity during each task was initially quantified by calculating the root mean square (RMS) EMG amplitude in each 5-s period from each EMG channel. Actual force values of tongue pressure or bite force during each task from the tongue pressure measurement system was also calculated for each 5-s period for all participants in all measurements. The target force level–EMG curve and the target force level–actual force value curves were calculated during all series. To evaluate the accuracy of the performance on each series, the coefficient of determination of the target force level–EMG curve and the target force level–actual force value curve were calculated from all series (Iida et al. 2015).

The measurements of motor-evoked potentials (MEPs) evoked by TMS from each participant were carried out in six sessions: (1) before TBT, (2) 5 min after TBT, (3) before TLT, (4) 5 min after TLT, (5) before TBT + TLT, and (6) 5 min after TBT + TLT (Fig. 1). During the measurements of MEPs evoked by TMS, EMG activities were recorded from the RM, right tongue muscle (RT), and right first dorsal interosseous (FDI: as an internal control). Disposable self-adhesive silver chloride electrodes (Nicolet Disposable Pre-Gelled Surface Electrode, Medtronic, Minneapolis, MN, USA) were placed on the dorsal surface of the tongue with an interelectrode distance of 2 cm (Kothari et al. 2013). Disposable bipolar surface electrodes (Neuroline 720, Ambu, Copenhagen, Denmark) were placed on right FDI and right masseter muscles (Iida et al. 2014, Ikuta et al. 2019). During the masseter MEP measurements, participants kept a special biting device between the anterior teeth (Iida et al. 2014, 2015) to secure constant pre-activation level of the masseter muscles, which is required for TMS to elicit a MEP (Macaluso et al. 1990; Iida et al. 2014; Ortu et al. 2008). During the tongue MEP and FDI MEP measurements, all participants were instructed to keep the tongue and the hand in a natural and relaxed position. The EMG signals were recorded, bandpass-filtered (10 Hz–5 kHz), and stored on a

Viking EMG apparatus (Viasys Healthcare, Madison, WI, USA) during the measurements of TMS-evoked MEPs. The TMS was delivered using a Magstim 200 stimulator (Magstim Co., Whitland, Dyfed, UK) with a focal figure-eight coil. To standardize the anatomical locations in accordance with the 10–20 system of electrode placement (Jasper 1958), participants wore a flexible cap on their head where a coordinate system with a 1-cm location was drawn. The coil of the stimulator positioned 45° from the sagittal plane, so that the induced current flowed in a plane perpendicular to the scalp sites (Svensson et al. 2003, 2006; Halkjaer et al. 2006; Baad-Hansen et al. 2009). The scalp sites at which EMG responses were evoked in the tongue, masseter, or FDI muscles were determined according to the lowest stimulus strength. The motor thresholds (MT) of each muscle were measured and defined as the minimum stimulus intensity that produced five out of ten clearly discernible MEPs from the background EMG activity in the muscle (Svensson et al. 2006; Baad-Hansen et al. 2009; Iida et al. 2014). Onset latency was measured from the averaged MEPs from the non-rectified signal (Svensson et al. 2006; Baad-Hansen et al. 2009).

To assess the MEPs, stimulus–response curves and motor cortex mapping were calculated from the MEP signals as previously described (Komoda et al. 2015; Zhang et al. 2016). Stimulus–response curves consisted of 90%, 100%, 120%, and 160% MT. Twelve TMS–MEPs were elicited at each intensity with an inter-stimulus interval of 10–15 s. For motor cortex mapping, eight TMS stimuli at 120% MT at each grid were applied to the sites over the scalp identified on a snugly fitting and flexible cap marked with the 1×1 cm^2 grid in an anterior–posterior and lateral–medial coordinate system (Wilson et al. 1993). The sites over the scalp covered 5 cm from the vertex and 5 cm anterior and posterior to the interaural line (a total of 25 grids). The anterior–posterior grid lines relate to the vertex (Cz) in accordance with 10–20 system of electrode placement. The first grid to be stimulated was always the center of the "hot spot". Then the TMS coil was moved anteriorly and subsequently posteriorly at increasing and decreasing latitudes. The motor cortex areas (cm^2) calculated from MEPs having amplitudes greater than 5 µV (tongue), 10 µV (masseter), and 50 µV (FDI) were determined on the 1×1 cm^2 grid. The center of gravity (COG) was calculated according to Ridding et al. (2000).

Statistical analyses

All data are presented as mean values and standard errors of the mean (SEM). EMG root mean square (RMS) values for each muscle (masseter and suprahyoid muscles) during each motor task were analyzed using two-way repeated measures analysis of variance (ANOVA) with three series (first, second, and third series) and side (left and right) as factors. Actual force values of the two force levels in the three series of TBT and TLT and the coefficient of determination calculated from EMG RMS values and actual force values in the three series during TBT and TLT were analyzed with one-way repeated measures ANOVA. EMG RMS values and actual force values during maximum voluntary contraction (MVC) between before and after training tasks of TBT and TLT were analyzed with a paired *t* test.

The MT of the masseter, tongue, and FDI MEPs and onset latencies of the masseter, tongue, and FDI MEPs at the MT at each session in each training task were analyzed with one-way repeated measures ANOVA. The MEP amplitudes of the masseter, tongue, and FDI MEPs were analyzed using three-way ANOVA with stimulus intensity (90% MT, 100% MT, 120% MT, and 160% MT), training (TBT, TLT, and TBT + TLT) and time (before and after training) as factors. MEP areas of the masseter, tongue, and FDI MEPs were analyzed using two-way ANOVA with training (TBT, TLT, and TBT + TLT) and time (before and after training) as factors. The COG measures and MEP areas were analyzed using one-way ANOVA.

When appropriate, the ANOVAs were followed by post hoc Tukey tests to compensate for multiple comparisons. *P* values less than 0.05 were considered significant. All tests were carried out using STATISTICA (StatSoft Inc., OK, USA). Sample size was calculated using G-Power software analysis assuming an ANOVA and a significant level of 0.05. A sample size of 16 participants achieves 80% power to detect a difference in terms of effect size of 0.17.

Results

Performance of the TBT, TLT, and TBT + TLT

Figure 2a–d shows comparisons of EMG RMS values between each series in each muscle for each training task. EMG RMS values during each motor task were not significantly dependent on series and side (Fig. 2a–d). Figure 2e–g shows comparisons of EMG RMS values and actual forces during maximum voluntary contraction before and after TBT or TLT. There were no significant differences in EMG RMS values and actual forces during MVC between before and after the training for any task (Fig. 2e–h). There were no significant differences in coefficient of determinations of the target force–EMG curves and actual force values on each series in TBT and TLT.

Motor-evoked potential (MEP) recordings

The MTs of the masseter were significantly lower after TBT than before TBT ($P < 0.005$). The MTs of the tongue were significantly lower after TLT than before TLT ($P < 0.05$). In TBT + TLT, the MTs of the masseter and tongue were

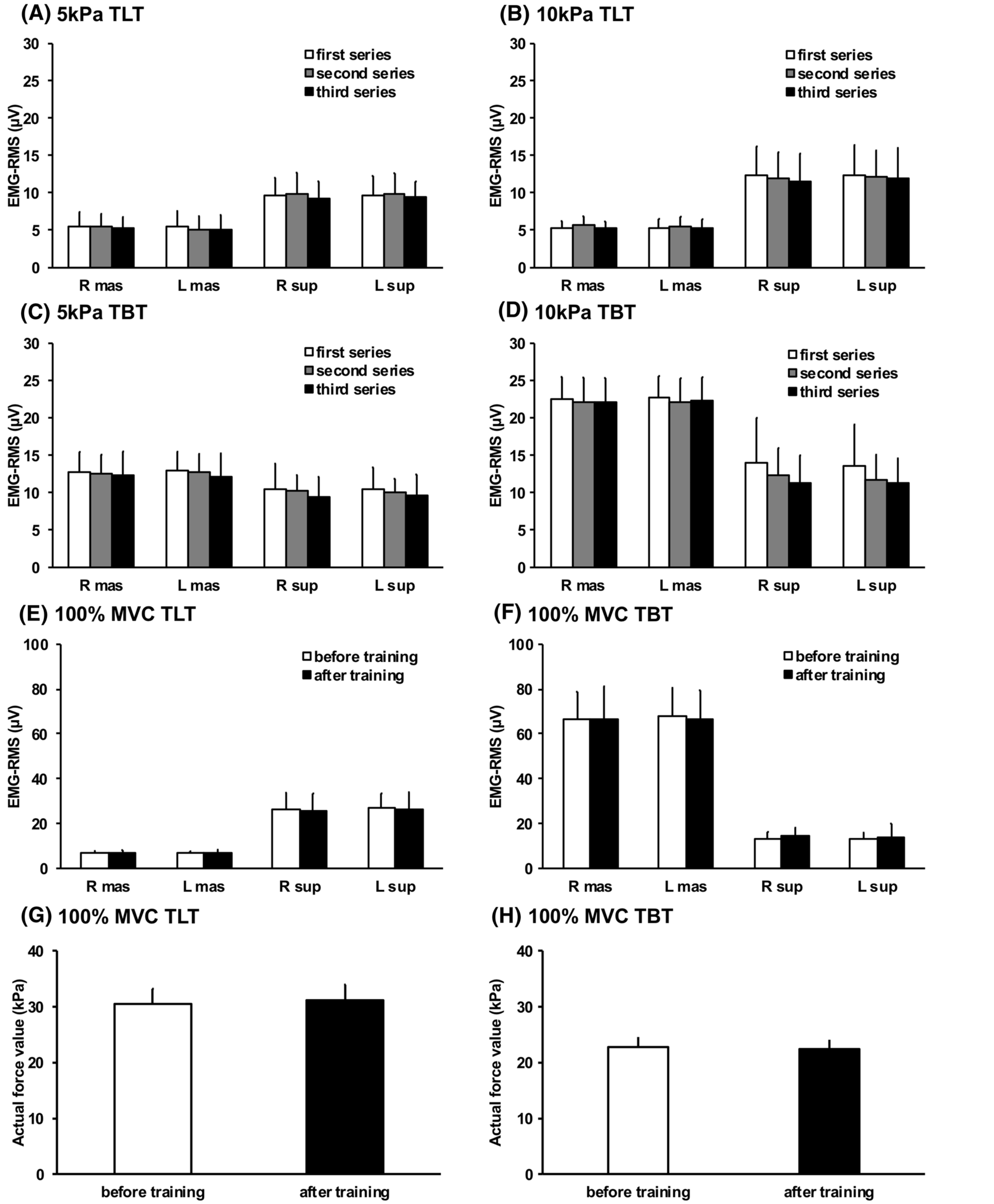


Fig. 2 Comparison of EMG RMS values between each series in each muscle with 5 kPa TLT (**a**), 10 kPa TLT (**b**), 5 kPa TBT (**c**), and 10 kPa TBT (**d**), and EMG RMS values and actual forces during MVC between before and after TLT (**e**, **g**) or TBT (**f**, **h**). *EMG RMS* electromyographic root mean square, *TLT* tongue lift task, *TBT* tooth bite task, *MVC* maximum voluntary contraction, *L* left, *R* right, *mas* masseter muscle, *sup* suprahyoid muscle

significantly lower after TBT + TLT than before TBT + TLT ($P < 0.005$). The MTs of the FDI were not significantly different between before and after training in each task. The onset latencies of the masseter MEPs, tongue MEPs, and the FDI MEPs were not significantly different between before and after training in each training task.

Stimulus–response curves

The tongue MEPs were significantly dependent on stimulus intensity ($F_{3,135} = 2.60$, $P < 0.001$) and on time ($F_{1,45} = 1.38$, $P < 0.001$) but not on training ($F_{2,45} = 29.1$, $P = 0.065$). In TLT, there were significantly higher tongue MEPs after the training task at 160% MT stimulus intensity than before the training task ($P < 0.001$) (Fig. 3a). In TBT + TLT, there were significantly higher tongue MEPs after the training task at 120% MT and 160% MT stimulus intensity than before the training ($P < 0.001$) (Fig. 3c). The masseter MEPs were significantly dependent on stimulus intensity ($F_{3,135} = 3.92$, $P < 0.001$), on training ($F_{1,45} = 48.2$, $P < 0.05$), and on time ($F_{2,45} = 2.35$, $P < 0.001$) (Fig. 4b, c). In TBT, there was significantly higher masseter MEPs after the training at 120% MT and 160% MT stimulus intensity than before the training task ($P < 0.001$) (Fig. 4b). In TBT + TLT, there were significantly higher masseter MEPs after the training task at 120% MT and 160% MT stimulus intensity than before the training task ($P < 0.001$) (Fig. 4c). The FDI MEPs were significantly dependent on stimulus intensity ($F_{3,135} = 3.66$, $P < 0.001$), but they were not significantly dependent on training ($F_{1,45} = 0.01$, $P = 0.990$) and on time ($F_{2,45} = 0.05$, $P = 0.817$) (Fig. 5).

Figure 6 shows comparisons of masseter MEPs, tongue MEPs, and FDI MEPs after the training task among TBT, TLT, and TBT + TLT. The tongue MEPs in TBT + TLT at 120% MT and 160% MT stimulus intensity were significantly higher than in TBT at 120% MT and 160% MT stimulus intensity ($P < 0.001$), and in TLT at 160% MT stimulus intensity ($P < 0.05$) (Fig. 6a). The masseter MEPs were significantly higher in TBT + TLT at 120% MT and 160% MT stimulus intensity than in TLT at 120% MT and 160% MT stimulus intensity ($P < 0.001$) and in TBT at 160% MT stimulus intensity ($P < 0.05$) (Fig. 6b). The FDI MEPs were not significantly dependent on training task ($P = 0.979$) (Fig. 6c).

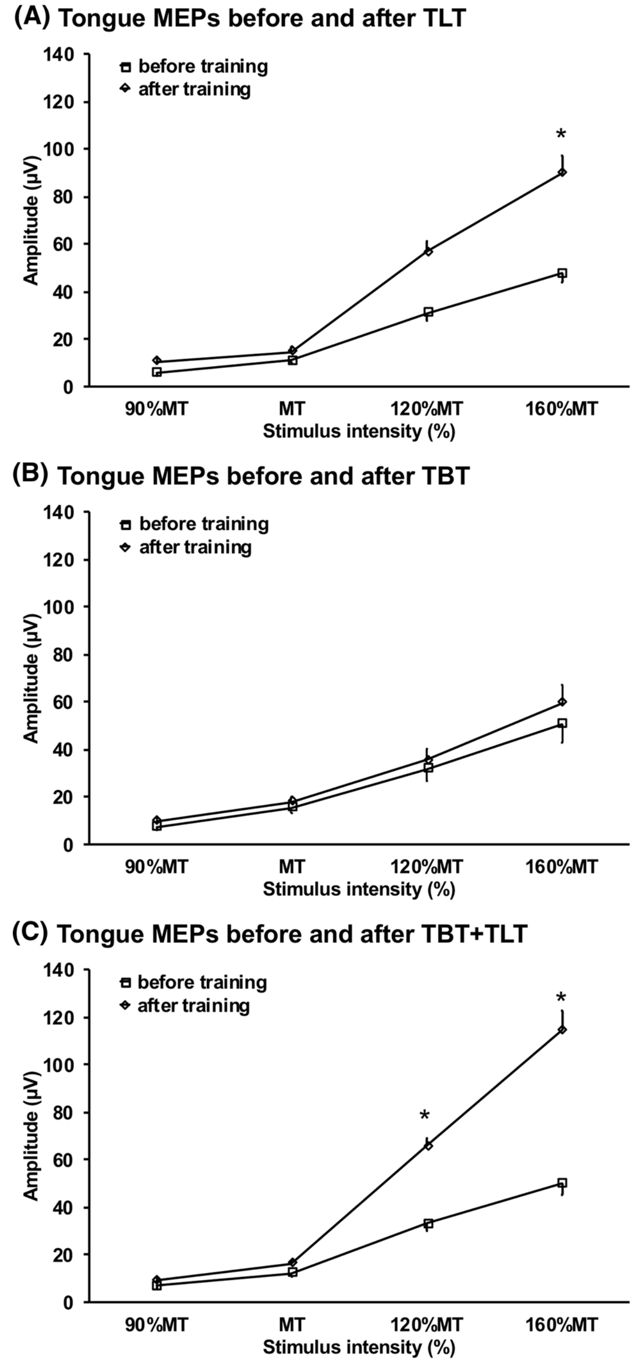


Fig. 3 Stimulus–response curves obtained by TMS of the tongue area of the motor cortex in TLT (**a**), TBT (**b**), and TBT + TLT (**c**). *Significantly higher after task than before task ($P < 0.001$). *TMS* transcranial magnetic stimulation, *MEP* motor-evoked potential, *TLT* tongue lift task, *TBT* tooth bite task, *MT* motor threshold

Motor cortex areas

Tongue MEP areas were significantly dependent on training ($F_{2,90} = 3.80$, $P < 0.05$) and on time ($F_{1,90} = 46.7$, $P < 0.001$). In TLT and TBT + TLT, there were significantly larger motor cortex areas from which TMS evoked tongue MEPs by 120% MT after the training task (21.8 ± 3.7 mm^2 and 23.8 ± 2.0 mm^2, respectively) than before the training task (16.7 ± 3.9 mm^2 and 17.6 ± 2.6 mm^2, respectively) ($P < 0.001$). These tongue MEP areas were significantly higher after TBT + TLT (23.8 ± 2.0 mm^2) than after TLT (21.8 ± 3.7 mm^2) ($P < 0.05$) and after TBT (19.9 ± 3.4 mm^2) ($P < 0.001$) (Fig. 7). Masseter MEP areas were significantly

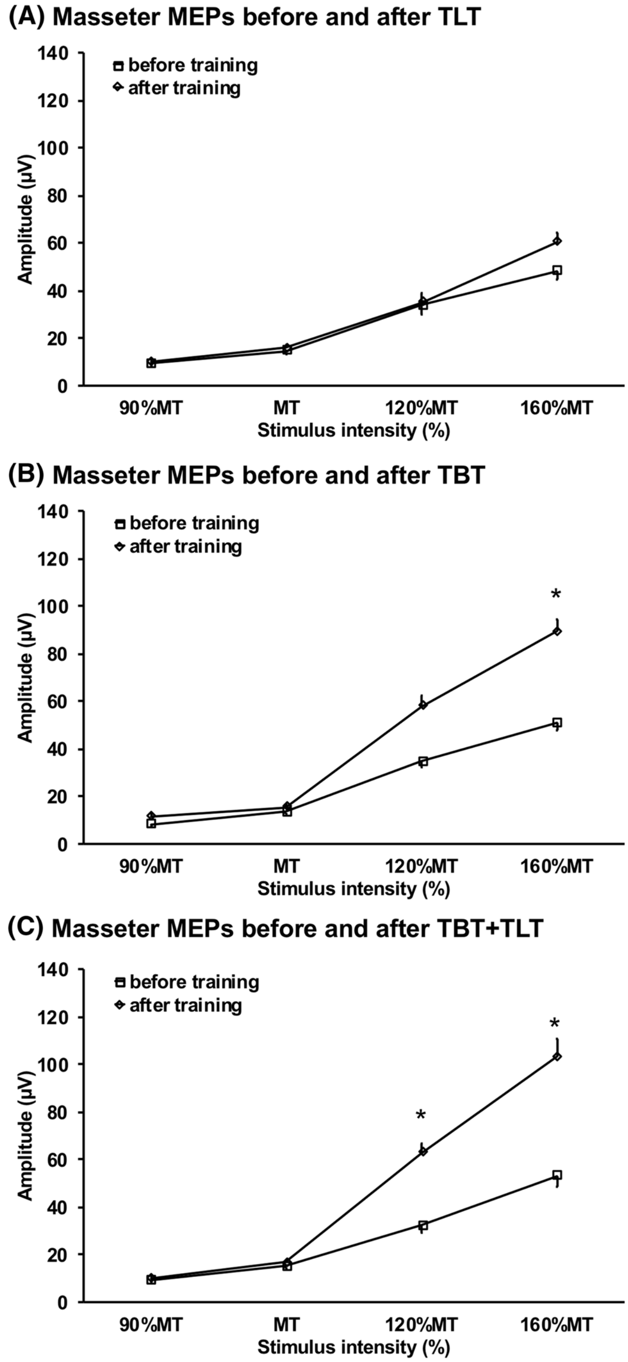


Fig. 4 Stimulus–response curves obtained by TMS of the masseter area of the motor cortex in TLT (**a**), TBT (**b**), and TBT + TLT (**c**). *Significantly higher after task than before task ($P<0.001$). *TMS* transcranial magnetic stimulation, *MEP* motor-evoked potential, *TLT* tongue lift task, *TBT* tooth bite task, *MT* motor threshold

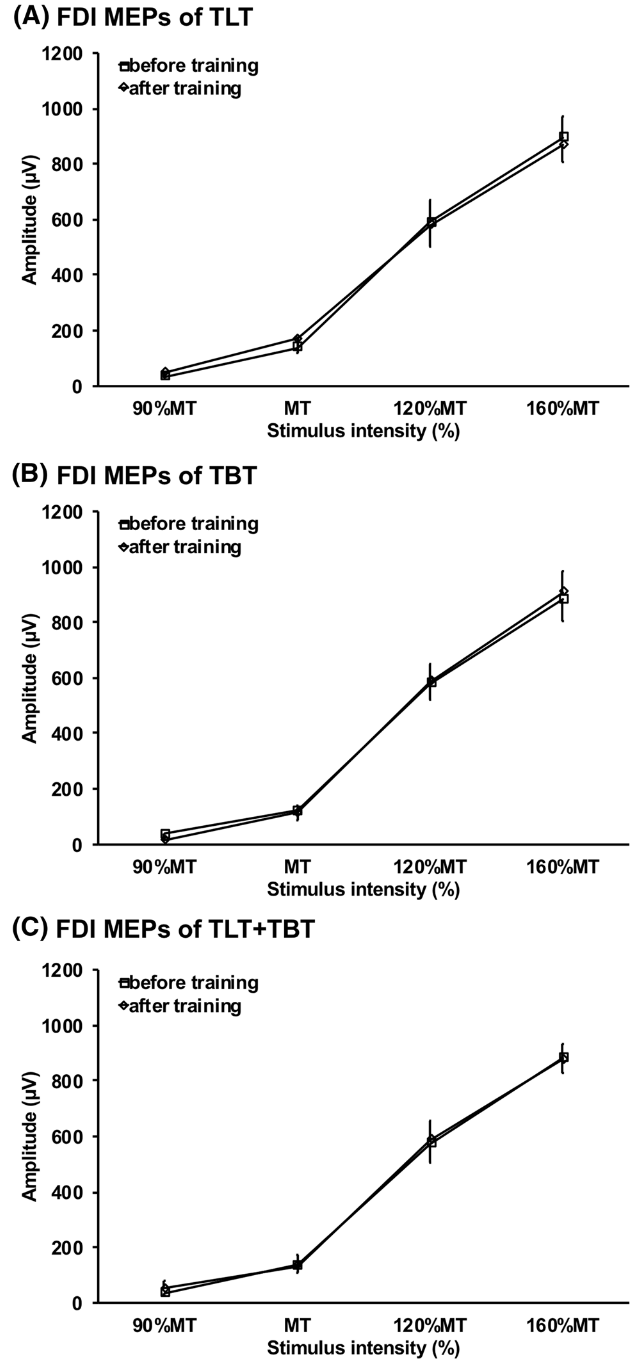


Fig. 5 Stimulus–response curves obtained by TMS of the FDI area of the motor cortex in TLT (**a**), TBT (**b**), and TBT + TLT (**c**). *TMS* transcranial magnetic stimulation, *MEP* motor-evoked potential, *FDI* first dorsal interosseous, *TLT* tongue lift task, *TBT* tooth bite task, *MT* motor threshold

dependent on training ($F_{2,90}=3.03$, $P<0.05$), and on time ($F_{1,90}=50.7$, $P<0.001$). In TBT and TBT + TLT, there were significantly larger motor cortex areas from which TMS evoked masseter MEPs by 120% MT after the training task (21.8 ± 2.9 mm^2 and 23.9 ± 1.6 mm^2, respectively) than before the training task (16.6 ± 3.1 mm^2 and 16.4 ± 4.0 mm^2, respectively) ($P<0.001$). The masseter MEP motor cortex maps were significantly higher after TBT + TLT (23.9 ± 1.6 mm^2) than after TBT (19.8 ± 4.8 mm^2) ($P<0.05$) and after TLT (19.9 ± 3.4 mm^2) ($P<0.001$) (Fig. 8). FDI

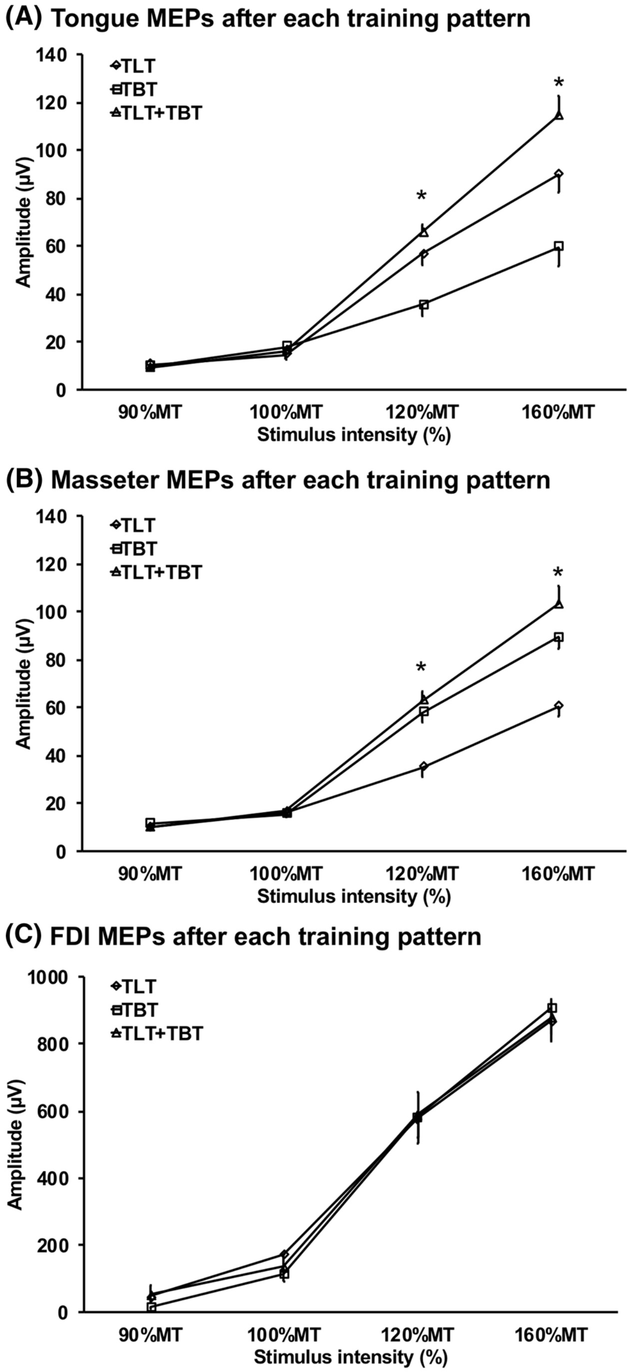


Fig. 6 Comparisons of masseter MEPs, tongue MEPs, and FDI MEPs after the tasks among TBT, TLT, and TBT + TLT. *Significantly higher tongue MEPs with TLT + TBT with 120% MT and 160% MT stimulus intensity than with TBT ($P<0.001$), and with 160% MT stimulus intensity than with TLT ($P<0.05$) (**a**). *Significantly higher masseter MEPs at TLT + TBT with 120% MT and 160% MT stimulus than with TLT ($P<0.001$), and with 160% MT stimulus intensity than with TBT ($P<0.05$) (**b**). *TMS* transcranial magnetic stimulation, *MEP* motor-evoked potential, *FDI* first dorsal interosseous, *TLT* tongue lift task, *TBT* tooth bite task, *MT* motor threshold

MEP areas were not significantly dependent on training ($F_{2,90}=0.31$, $P=0.732$) and on time ($F_{1,90}=0.01$, $P=0.981$) (Fig. 9). There were no significant changes among sessions for any of the COG outcomes (Table 1).

Discussion

Overall, the present study demonstrated the striking plasticity in corticomotor control of both tongue and jaw muscles and the effect of a combined training task on these different muscle groups. In the jaw sensorimotor task, the performance of a repetitive 1 h tooth clenching/biting tasks on 5 continuous days can trigger neuroplastic changes in the corticomotor control of the jaw musculature (Iida et al. 2014). Zhang et al. (2016) investigated the effect of short-term (1 h) sensorimotor training of the jaw muscles on corticomotor pathways, and their findings suggested that the short-term training task induced signs of neuroplastic changes in the corticomotor pathways related to the masseter muscle. The present study applied a similar experimental design (e.g., short-term TBT) and demonstrated that the MT of the masseter MEP after the training task were significantly lower than before the training task ($P<0.005$), whereas the MT of the tongue and FDI MEPs did not change after the training task in TBT. In stimulus–response curves following the TBT, there was significantly higher masseter MEPs after the training at 120% MT and 160% MT stimulus intensity than before the training task ($P<0.001$). Moreover, in TBT, there was a significantly larger motor cortex area from which TMS could evoke masseter MEPs after the training task compared to before the task ($P<0.001$), whereas the tongue motor cortex area and FDI motor cortex area were not significantly different after the TBT. In addition, the present study demonstrated that there were no significant changes between before and 5 min after training for any of the COG outcomes of masseter MEPs. The present results convincingly suggest that a short-term TBT can indeed trigger neuroplastic changes in excitability of the corticomotor control of the masseter muscle. On the other hand, our previous study investigating the effect of TLT over 5 consecutive days on the excitability of the corticomotor representation of the human tongue and jaw musculature suggested that 5-day repeated TLT can trigger neuroplasticity reflected in sustained increased excitability of the corticomotor representation of not only the tongue muscles, but also the masseter muscles (Komoda et al. 2015). However, the present results show that the MT of tongue MEPs and the tongue motor area were not significantly different between before the TBT and after the TBT; this finding suggests that a short-term jaw sensorimotor task in contrast to a 5-day repetitive jaw sensorimotor task cannot trigger neuroplastic changes of the tongue motor representations in the human

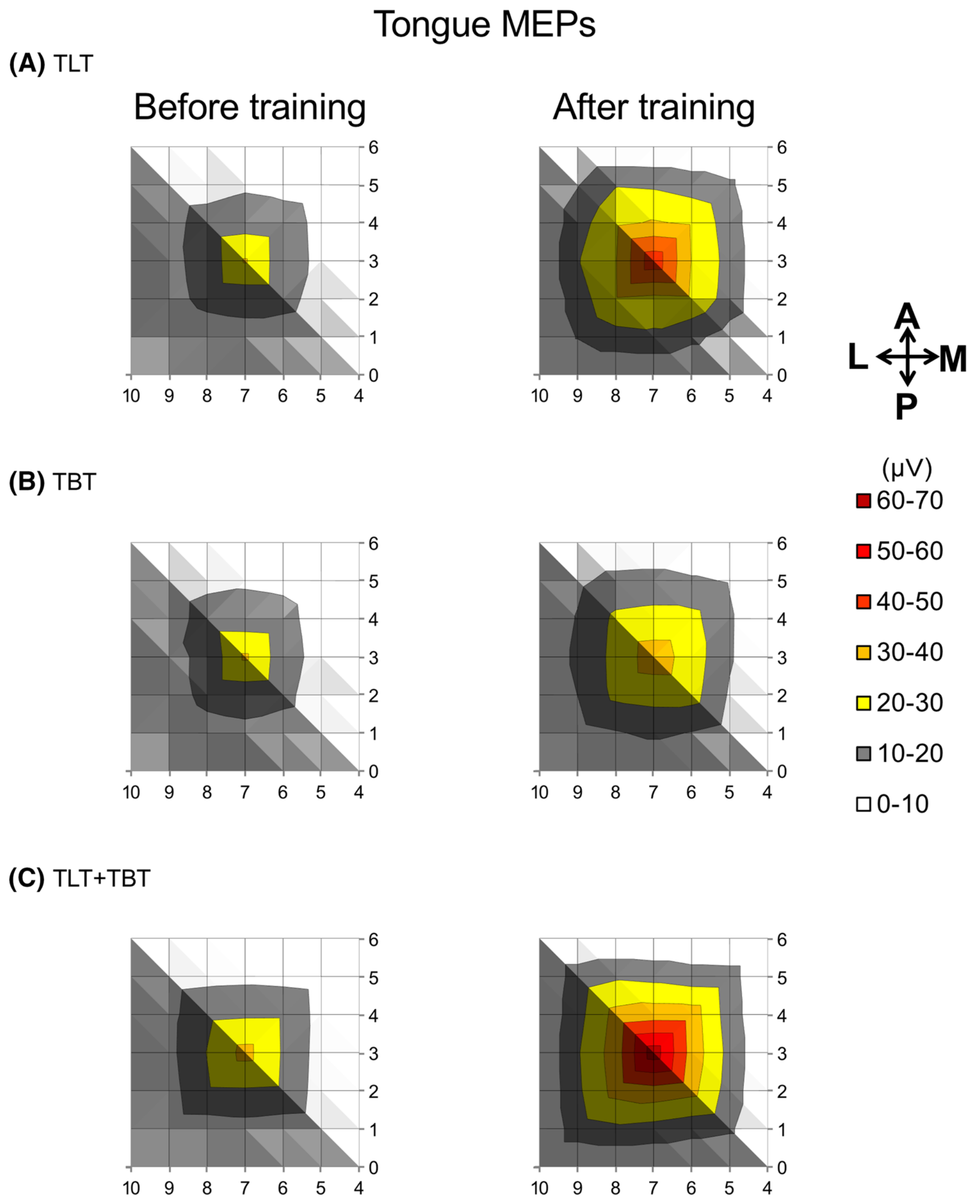


Fig. 7 Motor cortex maps of the tongue area in TLT (**a**), TBT (**b**), and TBT + TLT (**c**) generated in 16 participants (mean amplitudes) by TMS of multiple scalp sites arranged in a 1 × 1-cm^2 grid. Arrows indicate directions (*A* anterior, *L* lateral, *M* medial, *P* posterior). The value zero on the *y*-axis corresponds to the Cz line (interaural line). *FDI* first dorsal interosseous, *TLT* tongue lift task, *TMS* transcranial magnetic stimulation, *Cz* vertex, *MEP* motor-evoked potential, *TMS* transcranial magnetic stimulation, *TLT* tongue lift task, *TBT* tooth bite task, *Cz* vertex

motor cortex. Additional studies are needed to investigate further the effects of a short-term jaw sensorimotor task on the excitability of the corticomotor control of both the jaw and tongue musculature.

Previous TMS studies have demonstrated that neuroplastic changes in the corticomotor excitability specifically related to tongue motor control can be induced when human participants learn to perform tongue protrusion tasks (Svensson et al. 2006; Boudreau et al. 2007; Baad-Hansen et al. 2009), complex tongue tasks (Kothari et al. 2013), and TLT (Komoda et al. 2015). The present findings are consistent with the specificity suggested by these previous studies since we found that short-term TLT also can trigger neuroplastic changes reflected in increased excitability of the corticomotor control of tongue musculature but not of jaw musculature. Furthermore, in investigating the effect of a combined training task involving both jaw and tongue movements on the excitability of the corticomotor control of the tongue and jaw musculature, the present study showed that the tongue MEPs at 120% MT and 160% MT stimulus intensity were significantly higher in TBT + TLT than in TBT ($P < 0.001$). In addition, the masseter MEPs at 120% MT and 160% MT stimulus intensity were significantly higher in TBT + TLT than in TLT, and in TBT at 160% MT stimulus intensity ($P < 0.001$), and the tongue areas in the motor cortex after TBT + TLT were significantly higher than after TLT and after TBT ($P < 0.001$). These novel findings suggest that a combined sensorimotor task involving both jaw and tongue muscles may be associated with a larger degree of neuroplasticity in the corticomotor control of these muscles than

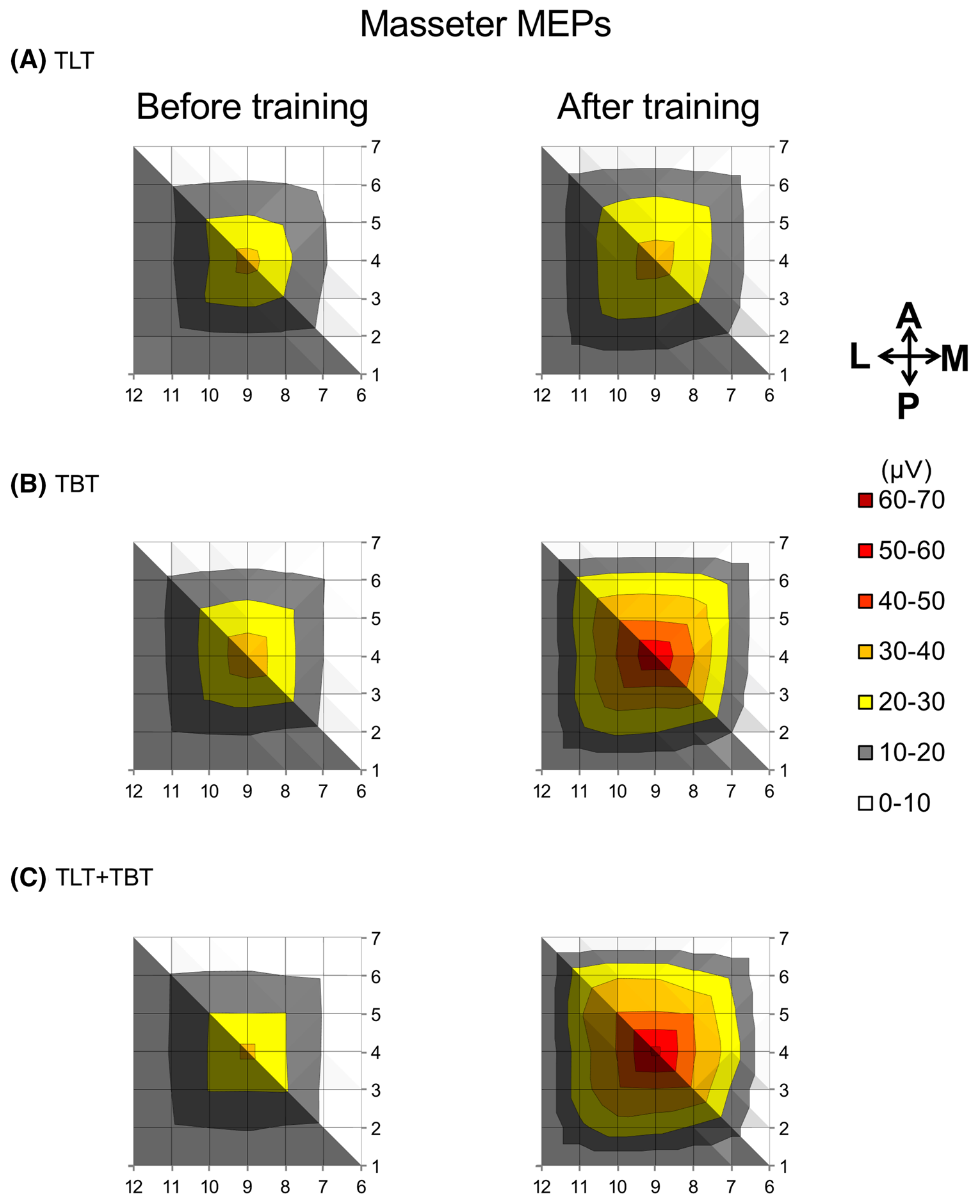
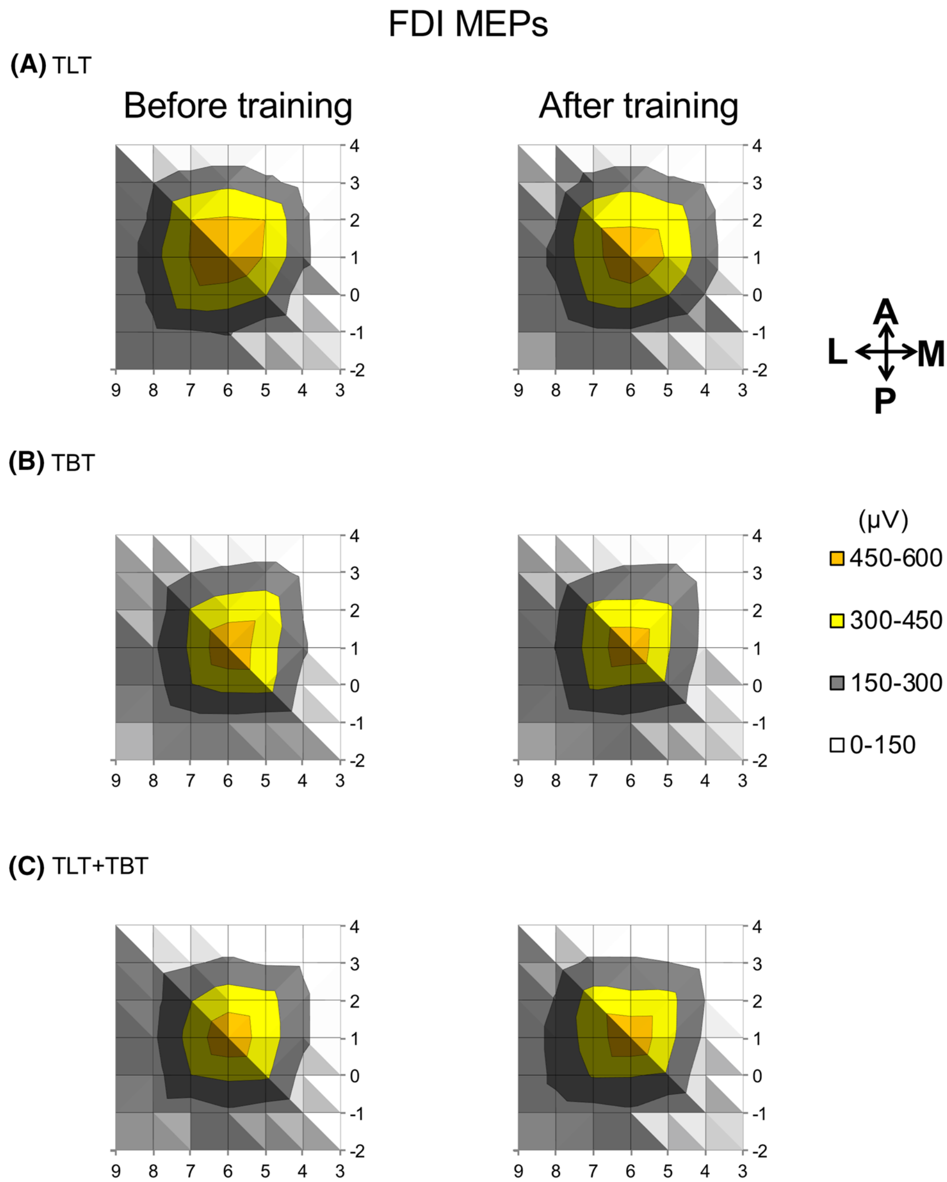


Fig. 8 Motor cortex map of the masseter area in TLT (**a**), TBT (**b**), and TBT + TLT (**c**) generated in 16 participants (mean amplitudes) by TMS of multiple scalp sites arranged in a 1 × 1-cm² grid. Arrows indicate directions (*A* anterior, *L* lateral, *M* medial, *P* posterior). *MEP* motor-evoked potential, *TMS* transcranial magnetic stimulation, *TLT* tongue lift task, *TBT* tooth bite task, *Cz* vertex

either task alone. The combined task also may have clinical utility in patients who are suffering from impairment of sensorimotor functions involving the jaw and tongue muscles, such as chewing or swallowing impairment. In swallowing, for example a combination of sensory stimuli (pharyngeal electrical stimulation and cold oral stimulation) combined with swallowing has recently been shown to enhance motor cortex excitability and suggested to be of potential clinical usefulness in dysphagic patients (Magara et al. 2016, 2018). These types of studies seem to suggest that combination of training and/or stimulation paradigms may cause greater changes in corticomotor excitability and, therefore, could offer patients a more effective treatment outcome.

In addition, relevant to our findings is a study by Svensson et al. showing that the tongue protrusion task is associated with neuroplasticity of corticomotor excitability related to the tongue musculature after 1 h of tongue training (Svensson et al. 2006; Baad-Hansen et al. 2009). Boudreau et al. (2010) demonstrated that bi-directional tongue training and multi-directional tongue training differentially altered the excitability of the tongue motor cortex. Furthermore, Lu et al. (2013) have demonstrated that a single bout of low-level tooth clenching activity (10 N) for 1 h following the same protocol used for the tongue task training studies failed to evoke any signs of neuroplasticity related to the control of the masseter muscle. These studies suggest that neuroplasticity in the motor cortex may depend on the duration, direction, and force level of the specific sensorimotor task. On the other hand, our present study showed that although a learning effect of each motor task was not apparent in the

Fig. 9 FDI motor cortex maps in TLT (**a**), TBT (**b**), and TBT + TLT (**c**) generated in 16 participants (mean amplitudes) by TMS of multiple scalp sites arranged in a 1 × 1-cm² grid. Arrows indicate directions (*A* anterior, *L* lateral, *M* medial, *P* posterior). *FDI* first dorsal interosseous, *MEP* motor-evoked potential, *TMS* transcranial magnetic stimulation, *TLT* tongue lift task, *TBT* tooth bite task, *Cz* vertex



behavioral data, a short-term TBT or TLT could nevertheless trigger neuroplastic changes in excitability of the corticomotor control of the masseter muscle or tongue musculature, respectively. Perhaps the applied outcome measures for the behavioral data were too insensitive to detect an improvement or manifest behavioral changes take longer time to develop in response to a novel training task than changes in the associated corticomotor pathways. Further, it may be useful to investigate the minimum level of jaw and tongue motor tasks training parameters (duration, time, repetition, etc.) that may lead to longer lasting neuroplasticity of corticomotor excitability related to the jaw and tongue musculature and learning effect in the jaw and tongue motor performance.

A methodological limitation of our study was that the enhanced neuroplastic effects of the combined task involving both jaw and tongue movements (TLT + TBT), compared to the TLT or TBT alone, could be, at least in part, due to the longer duration of the TLT + TBT training. An additional group of either a 41-min TLT + TBT or a 82-min TBT and TBT would have been optimal, and could be incorporated into future studies to address further the effects on corticomotor pathways of combined tongue and jaw tasks. It should also be noted that although some studies have tested for neuroplasticity after the training has ceased (Svensson et al. 2006; Baad-Hansen et al. 2009; Magara et al. 2018), the present study did not perform follow-up TMS measurements. Thus, to clarify further the neuroplastic effects of a combined task involving both jaw and tongue movements, further investigations are warranted to define the effects as well as possible carry-over neuroplastic effects of a long-term task combining both jaw and tongue movements. Such

Table 1 Center of gravity measures from the cortical motor maps of the tongue, masseter and first dorsal interosseous (FDI) muscles

Measurement point	COG measure (cm)	
	Ant–Post	Lat–Med
TLT		
Tongue		
Before task	3.1 ± 0.1	8.0 ± 0.1
After task	3.1 ± 0.1	8.0 ± 0.1
Masseter		
Before task	4.1 ± 0.1	9.0 ± 0.1
After task	4.0 ± 0.1	9.0 ± 0.1
FDI		
Before task	1.3 ± 0.3	6.1 ± 0.2
After task	1.3 ± 0.2	6.0 ± 0.2
TBT		
Tongue		
Before task	3.1 ± 0.2	8.0 ± 0.1
After task	3.1 ± 0.1	8.1 ± 0.3
Masseter		
Before task	4.0 ± 0.2	9.1 ± 0.1
After task	4.1 ± 0.2	9.1 ± 0.1
FDI		
Before task	1.3 ± 0.3	6.0 ± 0.2
After task	1.3 ± 0.3	6.0 ± 0.2
TLT + TBT		
Tongue		
Before task	3.1 ± 0.1	8.0 ± 0.2
After task	3.0 ± 0.1	8.1 ± 0.3
Masseter		
Before task	4.0 ± 0.1	9.0 ± 0.1
After task	4.1 ± 0.2	9.1 ± 0.1
FDI		
Before task	1.3 ± 0.3	5.9 ± 0.3
After task	1.3 ± 0.3	6.1 ± 0.2

Ant–Post anterior–posterior, *Lat–Med* lateral–medial, *TLT* tongue lift task, *TBT* teeth bite task, *FDI* first dorsal interosseous

information might also be useful clinically to improve oral rehabilitation paradigms for patients with dysphasia or dysmasesis.

In conclusion, the present results suggest that a short-term jaw or tongue sensorimotor task can trigger neuroplastic changes in excitability of the corticomotor control of the masseter muscle or tongue muscle, respectively, and a combined task involving both jaw and tongue movements is associated with a larger degree of neuroplasticity in the corticomotor control of these muscles than either task alone. These findings may have implications for functional rehabilitation of complex sensorimotor oral functions involving the jaw and tongue musculature in patients suffering from orofacial sensorimotor dysfunctions.

Author contributions TI, MK, OK, BS, and PS wrote the main manuscript text, and YK and SS prepared table and figures, and polished up reference lists.

Compliance with ethical standards

Conflict of interest This study was funded by the Section of Clinical Oral Physiology, Department of Dentistry, Aarhus University and the Danish Dental Association, Denmark. In addition, this study was supported by Technology of Japan, and a Grant-in-aid for scientific research (17K11786) from the Japanese Society for the Promotion of Science. The participation of BJS was also supported by Grants from the Canadian Institutes for Health Research, the Canadian Foundation for Innovation, and the Canada Research Chair programme.

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