Received: 4 November 2020 | Revised: 7 May 2021 | Accepted: 9 May 2021

DOI: 10.1111/joor.13183

ORIGINAL ARTICLE

JOURNAL OF ORAL REHABILITATION WILEY

Motor learning might contribute to a therapeutic anterior shift of the habitual mandibular position—An exploratory study

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Abstract

Background: Passive mandibular advancement with functional appliances is commonly used to treat juvenile patients with mandibular retrognathism.

Objective: The aim of this study was to investigate whether active repetitive training of the mandible into an anterior position would result in a shift of the habitual mandibular position (HMP).

Methods: Twenty adult healthy subjects were randomly assigned to one of two groups: a training group receiving six supervised functional training sessions of 10 min each and a control group without training. Bonded lateral biteplates disengaged occlusion among both groups throughout the 15-day experiment. Customised registration-training appliances consisted of a maxillary component with an anterior plane and a mandibular component with an attached metal sphere. Training sessions consisted of repeated mouth-opening/closing cycles (frequency: 30/min) to hit an anteriorly positioned hemispherical target notch with this metal sphere. The HMP was registered at defined times during the experiment.

Results: The HMP in the training group showed a statistically significant anterior shift of 1.6 mm (interquartile range [IQR]: 1.2 mm), compared with a significant posterior shift of −0.8 mm (IQR: 2.8 mm) in the control group ($p < .05$). Although the anterior shift among the training group showed a partial relapse 4 days after the first training block, it then advanced slightly in the 4-day interval after the second training block, which might indicate neuroplasticity of the masticatory motor system.

Conclusions: Motor learning by repetitive training of the mandible into an anterior position might help to improve the results of functional appliance therapy among patients with mandibular retrognathism.

KEYWORDS

mandibular advancement, mandibular shift, masticatory system, motor training, mandibular resting position, habitual mandibular position, masticatory muscles, motor skill learning

1 | BACKGROUND

Mandibular retrognathism affects approximately 60% of patients with class II malocclusion.[1] For adolescent patients, orthodontic treatment consists of mandibular advancement using functional appliances. If treatment is maintained over several months, the repeated closing movement of the mandible into this non-natural position can result in a 'new', more anterior, habitual mandibular position (HMP).[2] Animal studies indicate that once this new position is functionally established and stabilised, secondary skeletal changes can occur in the region of both the condyle and fossa temporalis, consolidating the mandibular advancement.[3,4] Studies of rats and mice showed a substantial molecular and cellular remodelling of the condyle in response to different load applications, indicating an up-regulation of different growth factors in the condylar cartilage when it is unloaded from mandibular protrusion.[5-7] The clinical effect of this treatment was confirmed by a systematic review[8] and a meta-analysis of controlled studies,[9] which showed that removable functional appliances have skeletal effects, especially during pubertal growth.

The training effect of current functional appliance therapy can be regarded as untargeted because it is not based on conscious, targeted neuromuscular training of a new motor behaviour. Instead, the mandible is only held in the anterior position because this is the position predetermined by the appliance. Other positions cause local pressure pain and, consequently, are perceived as unpleasant. Hence, the addition of active muscle training could perhaps increase treatment efficacy. Motor learning generally describes changes in muscular interactions such as improvements in the precision of task performance after repetitive motor training with the appropriate muscles.[10] When performing a demanding motor task for the first time, the smallest functional units of the neuromuscular system, that is the motor units, are not usually recruited in the most efficient manner.[11] Motor performance is, however, improved by error feedback obtained over repetitive training cycles.[10,11] Previous studies have focused on how a series of repetitive motor tasks such as hand and leg movements can induce plasticity of corticomotor pathways.[12-14] Moreover, in the rehabilitation sector, task-specific active training is still a state-of-the art auxiliary tool for recovering and improving motor function in the context of musculoskeletal and neurological disorders.[15-19] A neurorehabilitation study of young adults showed that a short period of active motor training was superior to passive training regarding performance improvement.[20] Recent research on oro-facial motor performance also showed improved performance and skill acquisition during oro-facial motor tasks such as tongue protrusion,[21-23] repeated splitting of food morsels,[24-27] repeated clenching[28,29] and repetitive jaw movements.[10] A very recent study provides new evidence that a repeated jaw-protrusion task induces neuroplasticity in the form of increased corticomotor excitability of both the masseter and tongue muscles.[30] The repetition of a demanding motor task is apparently key to learning and acquiring new motor skills.[31,32] It seems that both repetition and periods of adequate sleep (or at least intervals without training) are required to consolidate new behavioural patterns.[33,34] Furthermore, additional visual feedback also seems to improve the motor performance and motor learning of masticatory muscles.[35]

Although active training is regarded in the rehabilitation sector as a gold-standard treatment for improving motor function,[15-17] no studies have yet investigated whether repeated functional training of the masticatory muscles might be applied in order to affect the HMP. The aim of this randomised controlled human study was to test how the HMP would respond to training of the jaw muscles into a protruded mandibular position. During the 15-day training period, biteplates were used to prevent three-dimensional sensory feedback in intercuspation. We hypothesised that the HMP would adjust towards the more anterior target training position. If masticatory muscle training has a positive effect on healthy individuals, this would justify a subsequent clinical study of this approach that also includes growing patients with mandibular retrognathism.

2 | METHODS

2.1 | Sample size calculation

A sample size calculation based on a preliminary study estimated a minimum required sample size of six participants per group.[36]

2.2 | Participants

The study took place at Ulm University. Enrolment started in February 2017 and was completed by September 2017. Inclusion criteria were neutral buccal occlusion with a maximum deviation of a quarter cusp mesio- or distocclusion, an overjet ≤ 2 mm and a vertical overbite ≤ 3 mm. Subjects undergoing any orthodontic treatment (including retention) or with any signs or symptoms of a temporomandibular disorder (TMD), as determined by a short pre-study TMD screening according to Ahlers and Jakstat,[37] were excluded. Twenty-one subjects were assessed for eligibility. Only one person was excluded because they did not meet the inclusion criteria. Twenty healthy subjects (10 women and 10 men) with a mean age of 25.3 years (range: 21.3–31.2) were thus enrolled in the study. No subject was lost to follow-up or excluded from analysis.

The study protocol was approved by the Ethics Committee of Ulm University (no. 346/16), and informed written consent was obtained from all participants.

2.3 | Randomisation

Twenty subjects were randomly assigned to a training group ($n = 10$) or a control group ($n = 10$). Because a difference between the sexes regarding a training effect could not be ruled out in general, a randomised block design based on sex was used. To avoid selection bias, allocation concealment was conducted after the 20 subjects had been enrolled in the study. The statistician created a group of 10 opaque concealed envelopes for each sex. In each group, five envelopes contained a piece of paper labelled with the letter 'A', and five envelopes contained the letter 'B'. An independent person drew the envelopes, and subjects were assigned in order of their enrolment. Depending on the letter in the envelope, participants were randomly assigned to a training group (A) or control group (B).

2.4 | Blinding

Because the training had to be supervised, the investigator (M.M.) became aware of the subjects' group allocation after the randomisation process. Participants, conversely, had no prior experience of the experimental task and were unaware of the study's specific purpose. Hence, the patients had no expectations, and a corresponding bias can therefore be ruled out.

2.5 | Chronology of examinations and overview of training protocol

The experiment lasted 15 days in total (Figure 1). The main outcome measure was the HMP. The study protocol for the training group comprised six training sessions subdivided into two training blocks and six examinations of HMP at times T_0–T_5 before and after the training blocks. The same protocol was used for the control group, apart from the training sessions, which were omitted. From T_1 to T_5, occlusion was continuously (24 h/day) disengaged among both the training and control group by use of adhesively fixed biteplates (TempBond™; Kerr).

At the beginning of each session, subjects were asked whether they had experienced any muscular oro-facial pain, muscular tension, bruxism, dental pain, problems with the temporomandibular joint or any other discomfort in the previous period. Moreover, subjects were asked to report any other problem or experience that could have been related to the study. Subjects of the training group additionally had to give feedback after each training session regarding muscular effort and pain during training.

After the biteplates had been removed at T_5, a final questionnaire was completed by both groups regarding their jaw-closing experience after removal of the biteplates.

2.6 | Fabrication of biteplates and registration-training appliances

Dental casts of each subject were mounted in an articulator using an arbitrary face-bow (Artex; Amann Girrbach AG) and a wax bite registration. To eliminate occlusal contact during the experiment, lateral biteplates that completely covered the occlusal surfaces of teeth L5–L7 (Figure 2A) were fabricated bilaterally on the mandibular model. Occlusal surfaces were smoothed to avoid interference contacts in dynamic occlusion. The induced bite-raising of approximately 1 mm on the second molars was determined by the thickness of the biteplates and resulted in a median anterior bite-raising of 3.5 mm (interquartile range [IQR]: 1 mm), measured at teeth 11 and 41.

To monitor and register HMP during training, customised 'registration-training appliances' were fabricated for the maxilla and mandible (Figure 2). To the incisal region of the upper appliance, we attached, by polymerisation, an additional plane with an embedded millimetre grid (Figure 2). The lower appliance covered the anterior teeth (L4–L4). In the midline between the edges of the lower central incisors, we attached a spherical steel indenter 0.7 mm in diameter. The median anterior vertical bite-raising after incorporation of both appliances was 10.8 mm (IQR: 1.1 mm), measured at teeth 11 and 41.

2.7 | Experimental procedure

2.7.1 | Initial session (T_0)

After insertion of the biteplates (without use of adhesive in this session) and registration-training appliances, participants were seated comfortably in an upright position. The metal sphere of the lower appliance was coloured with an indicator spray (Arti-Spray®;

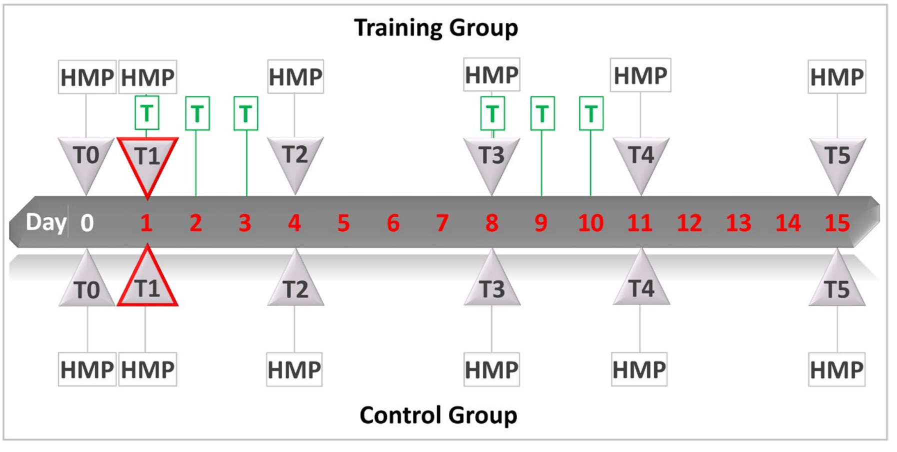

FIGURE 1 Chronological experimental design for both the training and control group. HMP: registration of habitual mandibular position (HMP) in the sagittal dimension; T: training session. T0–T5: times T_0–T_5. Triangles outlined in red indicate adhesive fixation of biteplates. Numbers in red indicate the days when biteplates remained in place

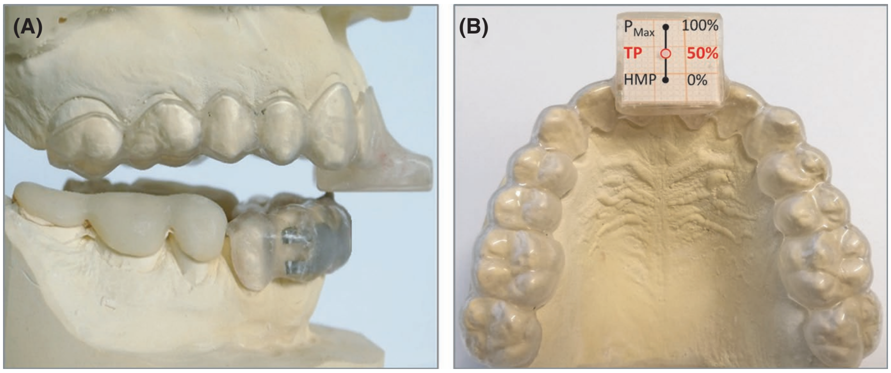

FIGURE 2 (A) Experiment set-up with both the lateral biteplates and registration-training device mounted on the plaster models. The lateral biteplates covering teeth L5–L7 were fabricated using Triad® VLC TranSheet® material (Degu Dent) and extended bucco-lingually just beyond the dental equator to improve retention. The registration-training device consisted of upper and lower appliances, which were thermoformed using 1.0-mm Duran® films (Scheu Dental GmbH). A metal sphere (0.7 mm in diameter) was attached, by polymerisation, to the mandibular thermoplastic appliance to register the HMP. Before registration, this sphere was colour-coated using Arti-Spray® (Bausch). (B) The model of the maxilla shows the anterior plane with embedded millimetre grid (size: 3.5×3.5 cm^2), attached by polymerisation to the maxillary thermoplastic appliance using Orthocryl® (Dentaurum). The half-spherical notch (0.7 mm in diameter) is marked as a red-outlined circle. It was milled in the midline at 50% of the maximum protruded mandibular position and provided sensory feedback during training. HMP, habitual mandibular position; TP, training position; P_{Max}, maximum protrusion

Bausch), and subjects were told to avoid occlusal contacts. Their masticatory muscles were then relaxed using a standardised procedure, during which all occlusal contact had to be further avoided. This procedure consisted of 10 mouth-opening/closing cycles, subsequent biting on dental rolls positioned bilaterally between buccal teeth, and saying 'mama' three times. The HMP was then registered in a standardised way: after the masticatory muscles had been relaxed as described above, subjects were asked to close their jaw and bite on the posterior teeth in their usual way, which meant that they should not consciously close the jaw into a specific position. This closing movement resulted in a mark on the maxillary appliance by the colour-coated metal sphere. The T_0 session also included registration of maximum protrusion, resulting in an additional mark on the maxillary appliance by the colour-coated metal sphere.

2.7.2 | Preparation steps for subsequent sessions

After the T_0 session, a digital camera (Canon EOS 450d) was used to take a standardised orthoradial image of the maxillary appliance with the coloured marks. To do so, the camera was fixed on a tripod so that the millimetre grids of the training appliances could be photographed in an orthoradial and standardised manner from the same distance at all times. The position of the camera set-up remained unchanged throughout photograph documentation and evaluation. Then, half the distance between the HMP and maximum protrusion was permanently marked on the maxillary appliance by milling a congruent half-spherical notch with the same 0.7 mm diameter as the metal sphere. This 50% position was defined as the target mandibular position for the subsequent training exercises.

2.7.3 | Training sessions

At the beginning of each training session, the registration-training appliances were inserted, and the HMP was registered and documented as described for T_0. To determine the reproducibility of this measurement, this procedure was repeated five times at the beginning of each session (ie T_1–T_5) by five participants in both the training and the control group. The subsequent training procedure consisted of a repetitive jaw motor task supervised by the operator. Each repetition started with the sphere positioned in the notch, followed by maximum mouth opening. Subjects then had to hit the target mandibular position with the metal sphere again by closing their mouth. These opening/closing cycles in an anterior position were performed for 10 min per session at a frequency of 30 cycles/min, prompted by a ticking metronome. If a subject failed to hit the notch, they had to search for it immediately by sliding the mandibular sphere on the upper appliance. In addition to the sensory feedback provided by the sphere and notch, subjects could visually monitor the exercise by using an eye-level mirror. The registration-training appliances were removed at the end of the supervised training session and kept in the clinic to prevent further practice by the subjects.

2.8 | Data analysis and statistics

The images taken of the maxillary appliances with embedded millimetre grids were imported into the software Paint (version 6.3). The coordinates of the pixels in the centre of each HMP were determined with a resolution of 30 μm per pixel.

The software packages MATLAB® (The MathWorks Inc.) and R (version 3.6; R Foundation for Statistical Computing) were used for further data and statistical analyses. To document intersession changes in HMP, the sagittal distances between the first HMP marked at T_0 (=reference point) and the corresponding points marked at T_1–T_5 were determined as metric values. These values were also standardised using the subjects' individual maximum protrusion distances (median: 8.8 mm, IQR: 4.4 mm) as a 100% reference. The two-sided Mann-Whitney *U* test was used to assess differences between the training and control group with regard to age, vertical bite-opening due to biteplates and maximum protrusion, and to compare the age, vertical bite-opening and maximum protrusion of the sexes. A one-sided Mann-Whitney *U* test was used to evaluate how the HMP differed between the baseline and final measurements. This difference was evaluated separately for the training and control group, as well as between groups.

A linear mixed-effects model was used to evaluate differences between the training and control groups regarding HMP. In addition, Brown-Mood's median test was used to compare intra-session reproducibility between the different sessions T_1–T_5.

3 | RESULTS

3.1 | General findings

No participant experienced any muscular pain or temporomandibular joint problems during or immediately after the 15-day experiment (15 days). No permanent occlusal changes were observed after removal of the biteplates.

All 20 participants completed the study and were involved in data analysis. The maximum mandibular protrusion recorded at T_0 did not differ between male and female subjects (Mann-Whitney *U* test, $p > .05$). The data for both genders were therefore pooled. Maximum mandibular protrusion also did not differ significantly (Mann-Whitney *U* test, $p > .05$) between the training group (median: 8.8 mm, IQR: 2.7 mm) and the control group (median: 8.1 mm, IQR: 5.1 mm).

3.2 | Intersession changes in HMP

The main outcome measure was the HMP. Figure 3 shows the absolute and relative changes in HMP from T_0 to T_5 for both groups separately. The boxplots indicate that the 2-week training programme resulted in a significant (one-sided Mann-Whitney *U* test, $p < .005$) anterior shift of the mandible by a median value of 1.6 mm (IQR: 1.2 mm). Without any training, in contrast, the HMP actually shifted posteriorly by −0.8 mm (IQR: 2.8 mm; one-sided Mann-Whitney *U* test, $p < .05$). With regard to individual maximum protrusion, an anterior shift of 17.2% (IQR: 14.9%) was observed for the HMP of the training group, and a posterior shift of 12.5% (IQR: 34.8%), for the control group (Figure 3B). Further analysis using a linear mixed-effects model (Table 1) revealed an estimated difference in anterior shift between the study and control groups of 4.0 mm (CI: 2.49; 5.46, $p = .0001$).

Figure 4 and Table 2 show the absolute changes in HMP among the six sessions (T_0–T_5) for both the training and control group. The training group (Figure 4A) achieved the largest anterior shift of HMP (median: 1.7 mm) after the first training block (T_2). At T_3, that is after the first subsequent post-training interval, this shift showed a statistically non-significant relapse to a position 0.5 mm anterior to the HMP before training. The second training session again resulted in an anterior shift to 1.2 mm. It should be noted that in the second post-training interval, this shift increased even further to 1.6 mm. Except for the anterior shift from T_0 to T_2 and T_1 to T_2, subsequent intersession changes were not significant (Mann-Whitney *U* test, $p > .05$). In the control group (Figure 4B), a posterior shift of HMP was observed for nearly

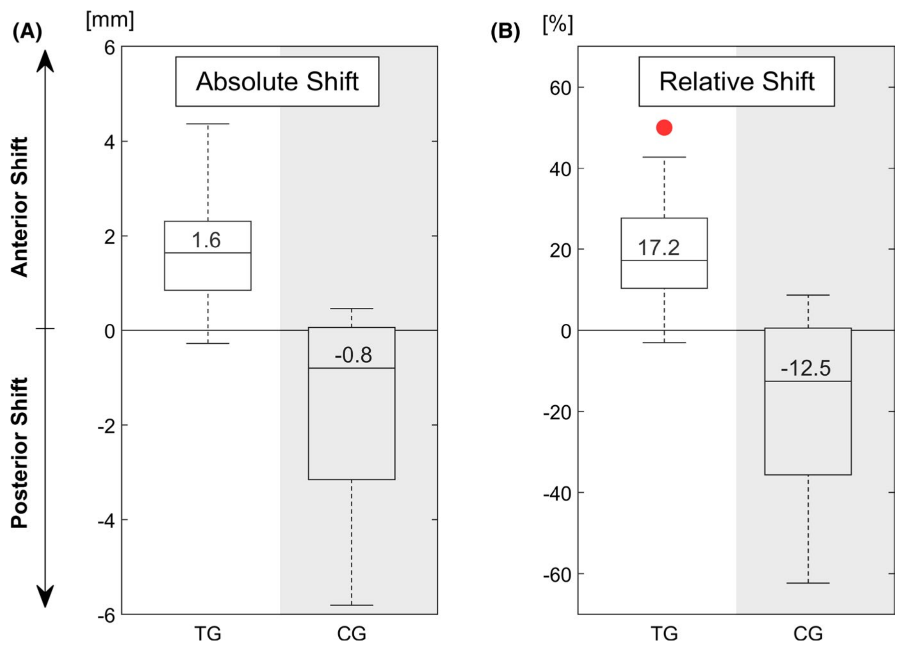

FIGURE 3 (A) Absolute changes in anteroposterior position of the habitual mandibular position (HMP) from T_0 to T_5 for the training group (TG) and the control group (CG). Value 0 on the *y*-axis represents the HMP at T_0 (=reference position). Positive values indicate an anterior displacement, whereas negative values indicate a posterior displacement. (B) Corresponding relative changes as a percentage of the distance between the habitual position and the maximum protruded position of the mandible. The training position is marked as a red dot at 50% of maximum protrusion

TABLE 1 Effect of training on habitual mandibular position, categorised by group

	Training group ($n = 10$)		Control group ($n = 10$)				
	Median	IQR	Median	IQR	*p*-value	Significance	95% CI
T0 vs T1 [mm]	−0.4	1.5	−0.6	1.4	0.194	NS	(−0.31; 1.88)
T0 vs T5 [mm]	+1.6	1.2	−0.8	2.8	0.0001	***	(2.49; 5.46)

Note: *p*-value based on linear mixed-effects models.

Abbreviations: (+), anterior direction; (−), posterior direction; CI, confidence interval; IQR, interquartile range; NS, not significant; T, time.

*$p < .05$; **$p < .01$; *** $p < .001$.

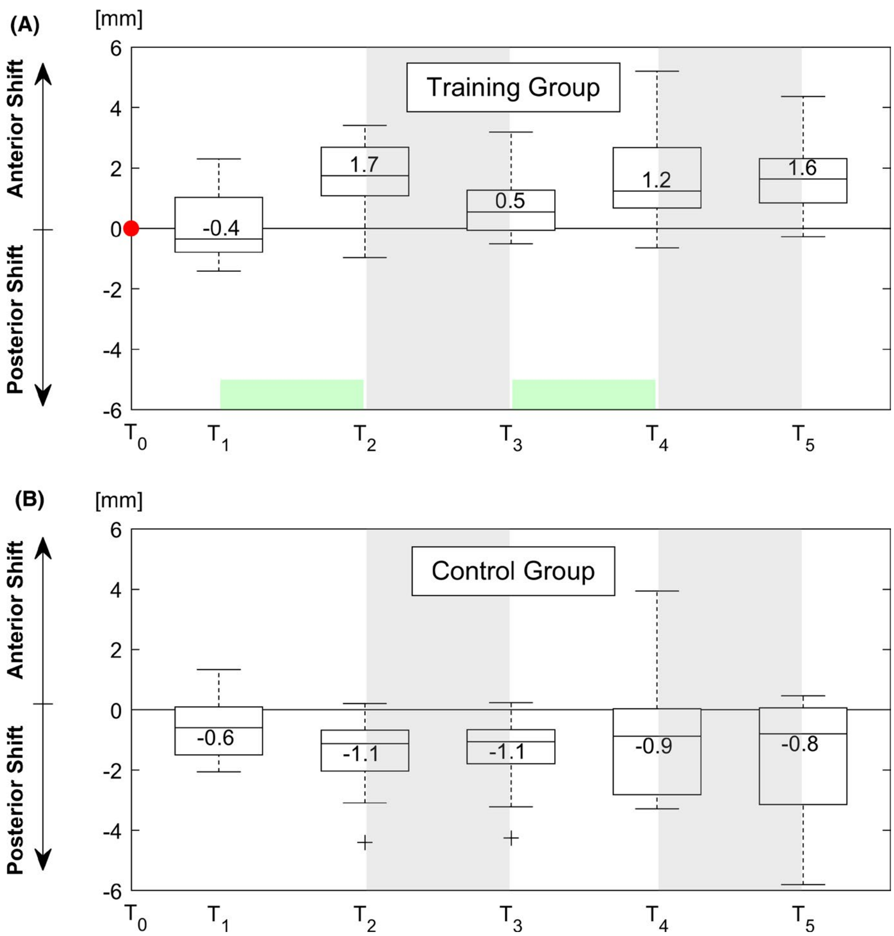

FIGURE 4 (A) Habitual mandibular position (HMP) for the training group at different times during the 15-day interval relative to HMP at T_0 (=reference position, marked as a red dot). The two intervals containing three training sessions each are marked in green. Positive values indicate an anterior displacement, whereas negative values indicate a posterior displacement. (B) Corresponding values for the control group

all subjects during the 2-week study period, indicated by negative median values (range: 0.6–1.1 mm). This posterior shift tended to be most pronounced on day 5 (T_2), although it should be noted that intersession differences were not significant, apart from an initial posterior shift in interval T_0–T_2 (Mann-Whitney *U* test, $p < .05$).

To characterise intra-session reproducibility, we repeated the measurements of HMP five times at the beginning of each session (ie T_1–T_5) for five participants each from the training and control groups. The median sagittal difference in HMP between the five repeated measurements was 1.0 mm. Intra-session reproducibility did not differ significantly between the different measurement sessions T_1–T_5 (Brown-Mood's median test, $p > .05$).

4 | DISCUSSION

This controlled human study examined whether training the mandible into an anterior position located at 50% of subjects' individual maximum protrusion would result in an anterior shift of the HMP. The experiment lasted 2 weeks, each week consisting of three 10-min training sessions on subsequent days and four training-free days afterwards. The study was single-blind, because participants were trained and examined by the same person (M.M.). To enable free positioning of the mandible, which required temporary prevention of the 'reprogramming' of the natural HMP from occlusal guidance, biteplates were adhesively fixed throughout the 2-week study

TABLE 2 Changes in habitual mandibular position (Δ) for the training and control groups at different time intervals

	T0 vs T1			T1 vs T2			T2 vs T3			T3 vs T4			T4 vs T5			T0 vs T5		
	Δ [mm]	*p*-value	Sign.	Δ [mm]	*p*-value	Sign.	Δ [mm]	*p*-value	Sign.	Δ [mm]	*p*-value	Sign.	Δ [mm]	*p*-value	Sign.	Δ [mm]	*p*-value	Sign.
Training group (*n* = 10)	−0.4	.846	NS	+2.1	.029	*	−1.2	.089	NS	+0.7	.165	NS	+0.4	.796	NS	+1.6	.004	**
Control group (*n* = 10)	−0.6	.193	NS	−0.5	.143	NS	+0.1	.684	NS	+0.2	.545	NS	+0.1	.796	NS	−0.8	.037	*

Abbreviations: (+), anterior direction; (−), posterior direction; sign., significance; NS, not significant; T, time.

*$p < .05$; **$p < .01$; ***$p < .001$.

period in both the training and the control group. We limited the study to 2 weeks because of the risks of (I) occlusal changes related to the lack of incisal contacts and intrusive effects on buccal segments,[38] and (II) oral-hygiene problems. In addition, we did not wish to disturb the subjects' masticatory function any longer than necessary. In our study, no permanent occlusal changes were observed after the biteplates were removed after the 2 weeks.

Based on previous studies, an observation period of this length is sufficient to discover possible training effects and achieve their consolidation.[26,29,30] The actual sample size of 10 participants per group was larger than the minimum size calculated based on a preliminary study. The study's actual power of 0.83 also confirms that the sample size was sufficient.

Our main finding was that repeated training resulted in a statistically significant anterior shift of HMP of 1.6 mm, whereas bilaterally bonded biteplates alone without any training resulted in a statistically significant posterior shift of 0.8 mm. In view of the quite short study period of 2 weeks, this training effect is quite pronounced. Hence, it seems that the training exercise's duration and nature (ie 50% of maximum protrusion corresponding to a median distance of 4.4 mm) were both sufficient. It is noteworthy in this context that a mandibular advancement of 4 mm also has a quite high clinical effectiveness in functional orthopaedic therapy.[39]

Detailed analysis of the HMP at different times during the 2-week experiment compared with at T_0 revealed that the maximum anterior shift of 20.6% (corresponding to nearly 50% of the target training position) was already achieved after the first training block. This suggests that the effect of motor learning on the masticatory system becomes apparent within a few days. This short-term adaptation capability of the masticatory motor system has already been observed in previous studies examining repeated jaw motor tasks.[29,30] After a significant relapse of the mandible's anterior shift of nearly 1.2 mm during the first training-free interval, the second training session resulted in a further anterior shift. This effect, however, was less pronounced than that of the first training interval, which might indicate that the short-term capacity of adaptation had already been reached within the first days of training. The 4-day, training-free interval after the second training block resulted in a further anterior shift of HMP to 1.6 mm, approximating the maximum anterior position after the first training interval. This perhaps suggests that neuroplasticity had already occurred within the 2-week intervention period. A previous study showed that motor skill learning can rapidly induce such an effect, even after short training sessions.[40] A recent study performed three blocks of jaw-protrusion training tasks on three consecutive days, with each block lasting 13 min, and was able to successfully prove increased neuroplasticity.[30] Another study found a significant increase in grey matter volume in the frontal and parietal brain areas after only two training sessions involving a demanding whole-body balancing task.[41] The continued forward advancement of the mandible after the second training-free interval also supports the conclusion of several studies that an adequate period of rest is important for consolidating novel motor tasks.[34,42,43]

Moreover, it seems that novel motor skills, once learned, persist long after training has finished.[40]

It is generally assumed that motor skill training induces neuroplastic changes more efficiently than strength training.[44] This is especially true if demanding coordination tasks have to be performed.[10] Repetition is also key to learning and acquiring motor skills.[31] The intensity of the training seems important in this context as well; a previous study reported delayed gains in performance only once individual saturation within the initial training sessions had been achieved.[45] It has also been documented that feedback guidance helps to optimise motor performance and motor learning of jaw muscles.[35,46,47] It should be noted here that our study's oral motor task was quite demanding, requiring a high degree of oral sensorimotor control. Furthermore, we provided both sensory feedback by means of the training appliance and visual feedback from a mirror. The pronounced training effect found in our study might have benefited from all these factors.

As shown in Figure 3, fewer outliers were recorded for the training group than for the control group. This might be due to the sensory feedback received by the training group in the new target position. Such feedback might have been essential for the recalibration of neuromuscular control strategies, leading to higher precision during habitual closing movements than among the control subjects, who received no sensory feedback regarding mandibular position. A somewhat surprising finding was that the median HMP of the control group at T_5 corresponded to a retruded position of 9.1% of maximum protrusion. We speculate that this effect might be related to the disturbance of the complex physiological movement pattern of the condyles during jaw opening and closing, consisting of rotational and translational components. More specifically, it seems likely that the biteplates and training device used in our study caused an immediate anterior and caudal positioning of the condyles; this position was registered at T_0 as the reference. During the subsequent adaptation period without sensory feedback on the mandibular position, however, the condyles might have shifted back towards their original position in maximum intercuspation before the intervention. This might be regarded as an attempt by the masticatory motor system to maintain its inherent patterns. The posterior shift in condylar position described here might explain the clinical observation of temporary occlusal changes caused by wearing occlusal splints. In the training group, this phenomenon was impeded by the imposition of a new HMP.

Mandibular advancement with functional appliances has proved effective in the treatment of adolescent patients with mandibular retrognathism,[9,48,49] and active training is the gold-standard treatment for improving motor function in the rehabilitation sector.[15-19] Moreover, recent research on oro-facial motor training has proved that repeated oro-facial motor tasks can also improve motor performance and skills[10,23,27] and that an active and repeated jaw-protrusion task leads to neuroplasticity.[30] The implementation of motor learning in dentofacial orthopaedics in addition to established treatment with functional appliances could be very simple and would be non-invasive. These factors inspired us to investigate and develop the functional training approach as an additional tool for use in dentofacial orthopaedics. To the best of our knowledge, our experimental study of healthy young adults is the first to have evaluated how motor learning affects the establishment of a more anteriorly located HMP. One limitation of our study, however, is that the results for younger adults are not directly transferable to adolescents. Our main reason for investigating functional training of masticatory muscles among young adults instead of the target patient group (ie class II patients with mandibular retrognathism prior to their pubertal growth peak) relates to strict ethical standards regarding the inclusion of underage individuals in experimental or clinical research. Hence, this study aimed to investigate the adaptability of the HMP in more general terms, to possibly provide a solid basis for the justification of subsequent clinical studies that include growing patients with mandibular retrognathism. Because children and adolescents can be considered even better at learning motor skills than adults,[50] the effect observed for adults is hopefully a promising indication that similar adaptations would be observed among younger individuals. A further limitation of our study is that it does not include follow-up measurements to investigate the long-term effects of the intervention. The experiment was terminated after 2 weeks because it was anticipated that leaving the biteplates *in situ* for a longer period would have negative side effects. We assumed that the results of follow-up measurements after a period without biteplates would be of no great value, due to the sensory feedback provided by intercuspation without bite plates.

Hence, based on the results of this study, we believe repeated training of the masticatory motor system is a promising approach for supporting mandibular advancement among adolescent class II patients. Further controlled clinical studies involving growing class II patients are required before clinical application of our novel approach, to examine the benefits of active training for supporting the 'unconscious' adaptation of mandibular position during functional appliance therapy. Moreover, training stimuli with different training durations and target training positions might also be investigated.

5 | CONCLUSIONS

The following conclusions can be drawn from the results of this study:

1. Repetitive training of the mandible into an anterior position, combined with lateral biteplates for the elimination of occlusal contacts, results in an anterior shift of HMP.
2. The insertion of lateral biteplates without any training results in a posterior shift of HMP, although interindividual variability was quite high for this result.
3. The effect of motor learning on the masticatory system is already clearly apparent after 3 days of training.
4. The more pronounced anterior position of the mandible after the second non-training interval might indicate the occurrence of neuroplastic effects.

5. Motor learning in the form of repetitive training of the mandible into an anterior position might be a promising supplemental tool for increasing the effectiveness of functional appliances among growing class II patients; however, further clinical studies are required to prove this assumption.

ACKNOWLEDGEMENTS

All authors gave their final approval and agreed to be accountable for all aspects of the work.

CONFLICT OF INTEREST

The authors declare that they do not have any conflict of interest.

AUTHOR CONTRIBUTIONS

Glöggler Julia C. contributed to conception, design, data acquisition, analysis and interpretation, and drafted and critically revised the manuscript. Hellmann Daniel contributed to conception, design, data analysis and interpretation and critically revised the manuscript. Von Manstein Maja contributed to conception, design and data acquisition and critically revised the manuscript. Jäger Rudolph contributed to performance of all statistical analyses and interpretation of data and critically revised the manuscript. Repky Stefan contributed to performance of all statistical analyses and interpretation of data and critically revised the manuscript. Beyersmann Jan contributed to performance of all statistical analyses and interpretation and critically revised the manuscript. Lapatki Bernd G. contributed to conception, design, analysis and interpretation of data and critically revised the manuscript.

ETHICAL APPROVAL

All procedures performed in studies involving human participants were in accordance with the ethical standards of the institutional and/or national research committee and with the 1964 Declaration of Helsinki and its later amendments or comparable ethical standards. This article does not contain any studies with animals performed by any of the authors.

DATA AVAILABILITY STATEMENT

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

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How to cite this article: Glöggler JC, Hellmann D, Von Manstein M, et al. Motor learning might contribute to a therapeutic anterior shift of the habitual mandibular position—An exploratory study. *J Oral Rehabil*. 2021;48:891-900. https://doi.org/10.1111/joor.13183