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Acute effects of jaw clenching while wearing a customized bite-aligning mouthguard on muscle activity and force production during maximal upper body isometric strength

Adrià Miró, Bernat Buscà*, Jordi Arboix-Alió, Pol Huertas, Joan Aguilera-Castells

Faculty of Psychology, Education Sciences and Sport Blanquerna, Ramon Llull University, 08022, Barcelona, Spain

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ABSTRACT

Background/objectives: The possible mechanisms supporting the relationship between the masticatory and the musculoskeletal systems have been recently investigated. It has been suggested that jaw clenching promotes ergogenic effects on prime movers through the phenomenon of concurrent activation potentiation (CAP). The purpose of this study was to analyse the effects of jaw clenching and jaw clenching while wearing mouthguard (MG) on muscle activity and force output during three upper body isometric strength tests.

Methods: Twelve highly trained rink-hockey athletes were recruited for the study. A randomized, repeated measures within study design was carried out to compare the acute effects of three experimental conditions: jaw clenching while wearing MG (MG), jaw clenching without MG (JAW) and non-jaw clenching (NON-JAW).

Results: Statistical analyses revealed significant higher force output ($p < 0.05$) in all tests for MG conditions with respect to NON-JAW. When comparing JAW and NON-JAW conditions an increased peak force was found in handgrip ($p = 0.045$, $d = 0.26$) and bench press ($p = 0.018$, $d = 0.43$) but not in biceps curl ($p = 0.562$, $d = 0.13$). When comparing MG and JAW conditions, no differences were observed in any force output. In terms of muscle activity, significant differences were found in the agonist muscles of the handgrip test for MG with respect to NON-JAW ($p = 0.031-0.046$, $d = 0.25-1.1$).

Conclusion: This study demonstrated that jaw clenching, with and without MG, may be a good strategy to elicit the CAP phenomenon, which seems to promote ergogenic effects in upper body isometric force production. The non-significant differences observed between JAW and MG suggested that the use of MG doesn't make a difference in enhancing the isometric force production neither the muscle activity in upper body isometric strength.

1. Introduction

The correlation between the stomatognathic system and sports performance has been widely investigated. Most of the studies examined the effect of the oral motor function on certain neuromuscular performance parameters, such as the influence of jaw clenching on strength,[1,2] power,[3–5] muscle activation,[6,7] body posture[8–10] or stability.[5,11] There is evidence that jaw clenching promotes better neuromuscular responses through the mechanism of Concurrent Activation Potentiation (CAP).[12,13] According to Ebben et al., this ergogenic mechanism, elicited by the remote voluntary contraction (RVC) of the mandible muscles, might promote an increased cortical pre-activation, major efficiency in the motor neuron activity and better reflex responses.[13] Thus, when the masticatory muscles are activated because of the jaw clenching, an increased motor cortex activation is observed.[14] This higher activity in the cortical region may induces higher neuromuscular efficiency on the prime mover activation to initiate the targeted actions.[15] Moreover, the excitability of spinal motor neurons might be increased with the contraction of the mandible muscles, thus amplifying the alpha motor neuron activity, gamma loops and

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* Corresponding author.

E-mail addresses: adriama@blanquerna.url.edu (A. Miró), bernatbs@blanquerna.url.edu (B. Buscà), jordiaa1@blanquerna.url.edu (J. Arboix-Alió), polpe@blanquerna.url.edu (P. Huertas), joanac1@blanquerna.url.edu (J. Aguilera-Castells).

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muscle spindles.[16] In addition, it is established that H-reflex, which can be used to analyse the excitability of the spinal alpha motor neurons and the transmission efficiency of afferent synapses, might be facilitated in association with voluntary teeth clenching.[17] This facilitation is evoked by both the supraspinal descending influences from the cerebral cortex and the peripheral afferent impulses from oral-facial region, such as the periodontal mechanoreceptors and muscle spindles.[17,18] The H-reflex begins with the initial activity of the masseter and is linearly increased with the magnitude of the occlusion force.[19] Thus, the magnitude of jaw clenching emerges as a relevant factor to elicit these neuromuscular enhanced effects. In this vein, Arima et al. demonstrated that it is not possible to produce maximal occlusal biting force in maximal intercuspation (centric interposition with the teeth of both dental arches) with uncovered teeth because depressor muscles are active during clenching to protect the teeth.[20] Moreover, when the occlusion is not well equilibrated, biting with uncovered teeth could magnify possible imbalances in the complex of the cranio-cervico-mandibular muscles.[21] For this reason, the use of custom-made, bite-aligning mouthguard (MG) might improve the repositioning of the temporomandibular structure, promoting a higher neuromuscular balance on the masticatory muscles and symmetrizing the masseter and temporalis muscle work. Therefore, wearing a MG may promote a better distribution of the occlusal loads both in the lateral and anterior-posterior direction contributing to a more balanced and powerful occlusion.[5,22]

Although several authors attributed the performance-enhancing effects of CAP to the jaw clenching independently of the use of MG, others suggested that these effects could be magnified wearing a customized bite-aligning MG.[3,12,23–25] It is speculated that, due to MG-induced changes in dental occlusion, central nervous system may receive afferent impulses from the altered jaw position. These alterations of the afferent information in the periodontal ligament, temporomandibular joint or masticatory muscles may cause improvements by efferent adaption or compensation patterns.[7,26] In this vein, Gage et al. demonstrated higher muscle activation on the masticatory muscles when compared the use and non-use of MG in physically active participants.[25] The authors attributed these changes to the repositioning of the temporomandibular joint and an increased vertical dimension of occlusion induced by the use of MG. Additionally, Ebben et al. reported higher muscle activation of masticatory and trunk muscles when using MG.[6] The authors also found an increased prime mover's muscle activation with MG condition during isokinetic and isometric tests. Nonetheless, other investigators showed no positive effects on motor performance nor muscle activity when comparing the use and non-use of customized MG in lower limb power and stability tests.[5]

A recent systematic review showed that the use of mouthguards might promote beneficial effects on lower limb muscular power, especially in jump ability and knee extension actions. However, these effects are inconclusive related to agility, sprint, isometric or isokinetic muscular actions.[27] Most of the studies have investigated the neuromuscular performance on several power, strength, or agility tests, but there is a paucity of studies focusing on muscle activity in physically active participants. In addition, most of the reviewed studies analyzing muscle activity in athletes focused on lower body or masticatory muscles. Only one study, led by Limonta et al., focused its investigation on the effects of self-adapted MGs in upper body muscle activity during isometric contractions in physical active participants.[28] The authors concluded that the use of self-adapted MGs promoted a jaw repositioning and thus, producing an ergogenic effect on maximal isometric strength as well as an improvement on the neuromuscular efficiency of the elbow flexors. Nevertheless, the influence of custom-fitted MG on upper body muscle activity while performing isometric strength actions was not found in athletes.

Therefore, the aim of the present study was to investigate the acute effects of jaw clenching and jaw clenching while wearing a customized, bite-aligning MG on masticatory and prime movers muscle activation as well as on force production during maximal upper body isometric tests. It is hypothesized that jaw clenching while wearing a customized, bite-aligning MG promote an increased masseter and agonist muscle activity and isometric force output in handgrip, bench press and biceps curl.

2. Methods

2.1. Study design

A randomized, repeated measures within study design was carried out to analyze the acute effects of jaw clenching while wearing a customized bite-aligning MG on muscle activity and isometric strength output under three experimental conditions: jaw clenching while wearing a customized mouthguard (MG), jaw clenching without wearing mouthguard (JAW) and non-jaw clenching with the mandible muscles in a relaxed position (NON-JAW). Within JAW and MG conditions, participants were instructed to clench their jaws as powerful as possible whereas in NON-JAW condition participants were encouraged to relax their mandible muscles and breathe through the pursed lips.[6,12] Conditions were randomly distributed to avoid the influence of fatigue and the test learning effects. Participants performed three different isometric force tests following the next order: handgrip (HG), bench press (BP) and biceps curl (BC). As dependent variables, force output (in Kg) and surface electromyography (EMG) activity (in μV) of the masseter and prime movers were assessed. For HG test, flexor digitorum (FLEX), extensor digitorum (EXT), biceps brachii (BB), triceps brachii (TB) and anterior deltoid (AD) were recorded. For BP test, biceps brachii (BB), triceps brachii (TB), pectoralis major clavicular (CLAV), pectoralis major sternal (STRN) and anterior deltoid (AD). For the BC test, flexor digitorum (FLEX), extensor digitorum (EXT), biceps brachii (BB) and anterior deltoid (AD). In all tests, masseter activity (MAS) of the dominant side was registered across the three exercises. Dominant side was determined by asking the players their shooting grip preference.

2.2. Participants

Twelve highly trained rink-hockey athletes (age: 24.75 ± 5.75 years; height: 177.04 ± 6.07 cm; weight: 76.22 ± 7.81 Kg; body mass index: 24.3 ± 1.81 kg m^{-2}) competing in the second men's Spanish division (*OkPlata*) participated voluntarily in the present study. All players included in the study were training a minimum of four times per week (approximately 8–12 h/week), 9–10 months per year, and were playing at least one game every weekend throughout the season. A health screening was completed with each subject in accordance with the American College of Sports Medicine exercise testing procedures. Additionally, all participants were also evaluated by an expert dentist before the mouthpiece fitting process to guarantee the adequate dental health. Participants were excluded if they presented any injuries and/or pain related to the temporomandibular structure as well as cardiovascular, musculoskeletal, or neurological disorders. After receiving a clear explanation of the experimental procedures, exercise protocol, benefits, and possible risks associated with their participation, all participants gave their written consent to participate in the study. Six of them declared a regular use of self-adapted MG whereas the other six declared an occasional use or non-use. The study and its protocol were reviewed and approved by the Ramon

Llull University Institutional Review Board (reference number 1920003D) and conducted in accordance with the Declaration of Helsinki (revised in Fortaleza, Brazil, 2013) on Ethical Principles for Research. All participants were asked to refrain from high intensity physical activity for 24 h before the testing session and they consumed no alcohol, coffee or any other type of stimulant that would negatively impact the outcome of the assessments. The participants had the option to withdraw voluntarily from the study at any time.

2.3. Procedure

The study was conducted in 3 sessions. The first session was used to provide all the information about the risks and benefits of the study, to obtain the informed consents, to assess anthropometric measurements and to scan the mouth structure by an expert dentist. In the second session, MG were provided to the athletes and the MG fitting process was conducted. Researchers kept the MG until the testing day to ensure the same conditions of usage. In the third session, after a standardized warm-up consisting on 5 min of jogging, 5 min of callisthenic specific exercises and 5 min of submaximal warm-up test trials, participants performed 2 trials of each test under the 3 experimental conditions. The maximal isometric contraction was maintained for 5 s and a minimum resting time of 3 min between sets and trials was considered. The best peak force (in kg) of the two repetitions and the corresponding EMG activity of the selected muscle groups were considered for the analysis. Finally, a comfort questionnaire was completed by the participants to evaluate their perception toward the oral devices. The questionnaire used Likert item response categories ranging from 1 (“strongly disagree”) to 5 (“strongly agree”). Fig. 1 shows a schematic representation of the study design with the timeline of the different procedures.

2.4. Performance measures

Handgrip Isometric Strength. In a standing position, the participants hold the dynamometer in the dominant hand, with the arm in the abduction of 45° and the elbow completely extended. After one practice trial of a firm grip, the participants were encouraged to generate their maximal hand force press. Analogical handgrip dynamometer Model T.K.K. 5001 (Takei Scientific Instruments Co. Ltd, Niigat) was used and the handle was adjusted if required.

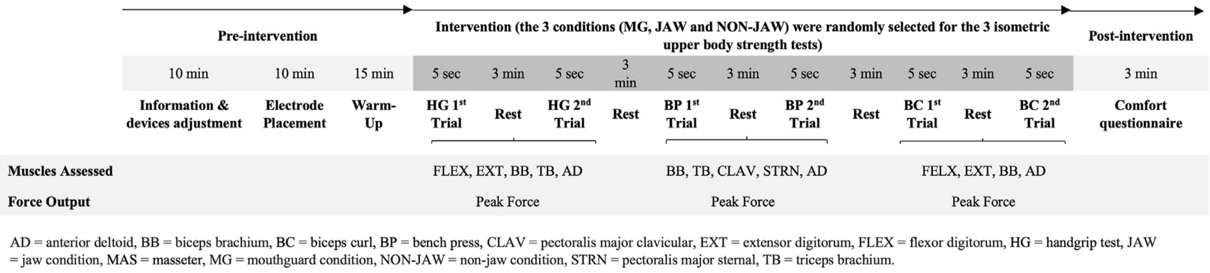
Bench Press Isometric Strength. The test starts with the participants lying in a supine position on the bench, with their feet flat on the floor and shoulders touching the bench. The position of the hands on the barbell was individually selected, but the forefinger had to be inside of the 91 cm mark on the bar.[29] The barbell was fixed at a height allowing an elbow flexion of 90°. During the isometric attempts the maximal force output was measured with a force plate (Kistler 9260AA, Winterthur, Switzerland), placed directly under the bench in line with the barbell (Fig. 2)**.** Peak force reached under isometric BP were recorded by a data acquisition system (Kistler 5695b, Winterthur, Switzerland) at a sampling rate of 1000 Hz and analyzed with the MARS software (Kistler, Winterthur, Switzerland). The force plate was reset when the participant was lying on the bench without applying force to the barbell and with the arms crossed over the chest.

Biceps Curl Isometric Strength. In a standing position, with the dominant arm in a supine position held in a Scott bench and with the elbow fixed at 90°, participants were encouraged to pull as much as possible an ergonomic handle binded to a strain gauge. A S-Type strain gauge (model CZL301C; Phildgets Inc., Alberta, CAN) was connected to Biopac MP150 through a transducer amplifier DA100C (Biopac Systems, Inc., CA, USA) which recorded variations in force during the exercise at a sampling rate of 200 Hz. The participants were allowed to hold the bench structure with the free hand to fix a static position and to guarantee a better stabilization. The software AcqKnowledge 4.2 (Biopac Systems, Inc., CA, USA) plotted and recorded the force.

2.5. Bite-aligning mouthguards

For this study, all participants wore a Class III, customized, bite-aligning RD Mouthguard (RD Mouthguard SL, Terrassa, Spain), designed to stabilize the mandible arch in a long centric position. Maxillary impressions were fabricated by standard trays using an alginate impression material and poured with dental stone to produce the working models. RD Mouthguards were manufactured using an internal layer of 1.4 mm-thick Ethylen-Vinylacetat-

Fig. 2. Execution of the Bench Press Isometric Strength Test.



	Pre-intervention			Intervention (the 3 conditions (MG, JAW and NON-JAW) were randomly selected for the 3 isometric upper body strength tests)											Post-intervention
	10 min	10 min	15 min	5 sec	3 min	5 sec	3 min	5 sec	3 min	5 sec	3 min	5 sec	3 min	5 sec	3 min
	Information & devices adjustment	Electrode Placement	Warm-Up	HG 1st Trial	Rest	HG 2nd Trial	Rest	BP 1st Trial	Rest	BP 2nd Trial	Rest	BC 1st Trial	Rest	BC 2nd Trial	Comfort questionnaire
Muscles Assessed				FLEX, EXT, BB, TB, AD				BB, TB, CLAV, STRN, AD				FELX, EXT, BB, AD			
Force Output				Peak Force				Peak Force				Peak Force			

AD = anterior deltoid, BB = biceps brachium, BC = biceps curl, BP = bench press, CLAV = pectoralis major clavicular, EXT = extensor digitorum, FLEX = flexor digitorum, HG = handgrip test, JAW = jaw condition, MAS = masseter, MG = mouthguard condition, NON-JAW = non-jaw condition, STRN = pectoralis major sternal, TB = triceps brachium.

Fig. 1. Schematic representation of the study design with the timeline of the different procedures
AD = anterior deltoid, BB = biceps brachium, BC = biceps curl, BP = bench press, CLAV = pectoralis major clavicular, EXT = extensor digitorum, FLEX = flexor digitorum, HG = handgrip test, JAW = jaw condition, MAS = masseter, MG = mouthguard condition, NON-JAW = non-jaw condition, STRN = pectoralis major sternal, TB = triceps brachium.

copolymer (EVA). Over this layer, a 4 mm-thick Polyethylene Terephthalate-1 (PETG) with a minimal dentoalveolar discrepancy regarding the morphology of the teeth structure of each participant was applied.

2.6. Surface electromyography analysis

EMG signal values were recorded using a BIOPAC MP-150 at a sampling rate of 1.0 kHz. Data were bandpass filtered at 10–500 Hz and analysed using the AcqKnowledge 4.2 software (BIOPAC System, INC., Goleta, CA). Root mean square EMG signals were recorded throughout each exercise. Bipolar EMG electrodes (Biopac EL504 disposable Ag–AgCl) with an inter-electrode distance of 2 cm were used. Before performing the experimental test, all participants' skin sites were prepared for electrode application through shaving, exfoliation, and alcohol cleansing to reduce impedance from dead surface tissue and oils. After that, electrodes were placed on the masseter and the prime movers (dominant side) according to the CRAM's recommendations.[30] A common reference electrode will be placed on the cubital styloid apophysis.

2.7. Statistical analysis

Statistical analyses were performed using SPSS software (Version 26.0 for Windows; SPSS Inc, Chicago, IL, USA). The G Power Software (University of Dusseldorf, Dusseldorf, Germany) was used to choose the number of participants (effect size 0.4 SD with an α level of 0.05 and power at 0.95). The normal distribution of the data was confirmed using the Shapiro-Wilk test. All dependent variables were normally distributed except the muscle activity and force output of the Bench Press test. One-way repeated-measures analysis of variance (ANOVA) were carried out to compare the conditions' effects (NON-JAW, JAW, MG) on the muscle activity and force output in Handgrip test (HG_MAS, HG_TB, HG_FLEX, HG_EXT, HG_BB, HG_AD and HG_peakforce) and Biceps Curl test (CB_MAS, CB_FELX, CB_EXT, CB_BB, CB_AD and CB_peakforce). Mauchly's test was used to test the assumption of sphericity and Greenhouse-Greisser correction was applied if it was violated. For pairwise comparisons, post hoc analysis with Bonferroni correction was done in case of significant main effects. For non-parametric variables (BP_MAS, BP_TB, BP_CLAV, BP_STRN, BP_BB, BP_AD, BP_peakforce), Friedman test was used to determine the effect of condition on muscle activity and force production in the bench press. For significant main effect, post hoc Wilcoxon test with Bonferroni correction was done. Moreover, the magnitude of changes between conditions was calculated by Cohen's d effect size and categorized as <0.2, trivial; 0.2 to 0.6, small; 0.6 to 1.2, moderate; 1.2 to 2.0, large; >2.0, very large.[31] All dependent variables were expressed as mean ± standard deviation (mean ± SD) and statistical significance was established at $p < 0.05$.

3. Results

3.1. Handgrip Isometric Strength

A significant main effect was found for conditions in HG_peakforce ($F = 5.916$, $p = 0.009$), HG_MAS ($F = 35.923$, $p = 0.00$), HG_FLEX ($F = 5{,}178$, $p = 0.014$), HG_EXT ($F = 6.742$, $p = 0.005$), HG_BB ($F = 3.579$, $p = 0.043$) and HG_AD ($F = 6.839$, $p = 0.005$). In addition, pairwise comparison revealed a significantly higher HG_peakforce (52.19 ± 9.40 Kg, $p = 0.045$, $d = 0.26$) (Fig. 3), HG_MAS (0.31 ± 0.15 μV, $p = 0.000$, $d = 2.65$) and HG_AD (0.13 ± 0.07 μV, $p = 0.014$, $d = 1.24$) for JAW with respect to HG_peakforce (49.81 ± 9.21 Kg), HG_MAS (0.03 ± 0.02 μV) and HG_AD (0.07 ± 0.03 μV) of NON-JAW. When comparing MG and NON-JAW conditions, pairwise comparison showed a significantly higher HG_peakforce (52.94 ± 9.44 Kg, $p = 0.041$, $d = 0.34$) and an increased neuromuscular activity in all muscle groups ($p = 0.031$–0.046, $d = 0.25$–1.10), except in HG_TB (Table 1). No differences were reported in any variable assessed when comparing JAW and MG conditions.

3.2. Bench Press Isometric Strength

There was a significant main effect on the BP_peakforce ($X^2 = 10.5$, $p = 0.005$), BP_MAS ($X^2 = 7.167$, $p = 0.028$) and BP_CLAV ($X^2 = 6.5$, $p = 0.039$). Pairwise comparison revealed an increased BP_peak force for both JAW (92.04 ± 19.82 Kg, $p = 0.018$, $d = 0.43$) and MG (94.44 ± 18.21 Kg, $p = 0.024$, $d = 0.58$) compared to NON-JAW condition (83.41 ± 19.84 Kg) (Fig. 4). Furthermore, the pairwise comparison revealed a significant increase of the muscle activity in MAS ($p = 0.024$, $d = 0.96$) and CLA ($p = 0.018$, $d = 0.31$) when compared JAW and NON-JAW. However, there were no differences in the EMG activity of any muscle group when comparing MG with NON-JAW and JAW conditions (Table 2).

3.3. Biceps Curl Isometric Strength

There was a significant main effect in CB_peakforce ($F = 3.199$, $p = 0.043$), BC_MAS ($F = 17.609$, $p = 0.001$) and BC_FLEX ($F = 6.728$, $p = 0.005$). Pairwise comparison, showed an increased peak force for MG (24.79 ± 4.07 Kg, $p = 0.022$, $d = 0.24$) but not for JAW (24.31 ± 4.12 Kg, $p = 0.562$, $d = 0.13$) when compared to NON-JAW condition (23.76 ± 4.45 Kg) (Fig. 5). The MAS activity was significantly higher for JAW (0.28 ± 0.13 μV, $p = 0.010$, $d = 1.99$) and MG (0.28 ± 0.16 μV, $p = 0.007$, $d = 1.71$) compared to NON-JAW (0.06 ± 0.07 μV). Additionally, when comparing MG and NON-JAW conditions, an increased FLEX ($p = 0.043$, $d = 0.42$) activity was found. Non-differences were reported in any dependent variable when comparing JAW and MG conditions (Table 3).

4. Discussion

The aim of the present study was to investigate the acute effects of jaw clenching and jaw clenching while wearing a customized bite-aligning MG on muscle activity and maximal upper body isometric force. The main finding was that jaw clenching as well as jaw clenching while wearing customized MGs promotes significant ergogenic effects on maximal isometric force production with respect to NON-JAW condition. Participants demonstrated a significant higher peak force in all tests while wearing MG. Likewise, significant higher peak force was also found while jaw clenching without MG, except in BC exercise. This lack of significant differences in BC for JAW with respect to NON-JAW condition may be explained because of the maximal voluntary contraction of the free arm muscles performed by the participants within the three conditions. Indeed, participants were allowed to hold the bank structure with their free hand to promote better stabilization and fix the static position. Thus, the ergogenic effects of CAP might be elicited by the RVC of the free arm muscles in both MG and JAW conditions, but also in NON-JAW condition. As suggested by Ebben et al., different RVC (jaw clenching, Valsalva maneuver, hand gripping, …) may induce the CAP phenomenon and this might be the case of the NON-JAW condition in the BC test of the present investigation.[32] Other studies[23,28,33] also demonstrated ergogenic benefits on maximal upper body isometric strength because of the use of a bite-aligning MG. The authors of these studies attributed the potential neuromuscular improvement of wearing MG to an increased distance between dental arches and a postural repositioning of the temporomandibular structure. This readjustment might promote

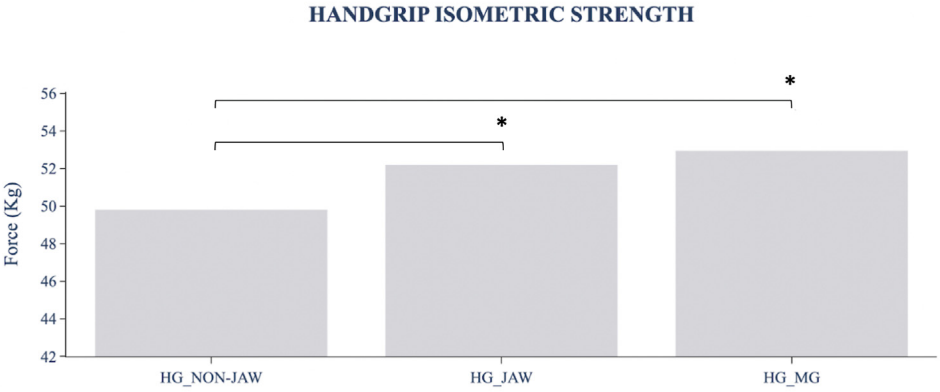


Fig. 3. Comparisons of handgrip isometric strength between the 3 conditions (NON-JAW, JAW and MG). * Significantly higher than NON-JAW condition ($p \leq 0.05$).

Table 1
Mean and SD (in μV) of the muscle activity (EMG) between conditions (NON-JAW, JAW and MG) in handgrip isometric strength test.

	NON-JAW		JAW		ρ	ES	Qualitative outcome	
	Mean	SD	Mean	SD				
HG_MAS	0,03	0,02	0,31	0,15	0,000	**2,65**	***large increase***	[a]
HG_TB	0,48	0,25	0,51	0,31	1000	**0,12**	***trivial***	
HG_FLEX	0,74	0,24	0,79	0,26	0,765	**0,20**	***trivial***	
HG_EXT	0,77	0,41	0,81	0,43	0,470	**0,09**	***trivial***	
HG_BB	0,23	0,15	0,31	0,19	0,513	**0,47**	***small increase***	
HG_AD	0,07	0,03	0,13	0,07	0,014	**1,24**	***large increase***	[a]
	NON-JAW		**MG**		**ρ**	**ES**	**Qualitative outcome**	
	Mean	SD	Mean	SD				
HG_MAS	0,03	0,02	0,32	0,17	0,000	**2,37**	***large increase***	[a]
HG_TB	0,48	0,25	0,56	0,30	0,237	**0,30**	***small increase***	
HG_FLEX	0,74	0,24	0,86	0,30	0,046	**0,44**	***small increase***	[a]
HG_EXT	0,77	0,41	0,88	0,47	0,040	**0,25**	***small increase***	[a]
HG_BB	0,23	0,15	0,39	0,28	0,037	**0,72**	***moderate increase***	[a]
HG_AD	0,07	0,03	0,15	0,10	0,031	**1,10**	***moderate increase***	[a]
	JAW		**MG**		**ρ**	**ES**	**Qualitative outcome**	
	Mean	SD	Mean	SD				
HG_MAS	0,31	0,15	0,32	0,17	1000	**0,04**	***trivial***	
HG_TB	0,51	0,31	0,56	0,30	0,945	**0,16**	***trivial***	
HG_FLEX	0,79	0,26	0,86	0,30	0,085	**0,25**	***small increase***	
HG_EXT	0,81	0,43	0,88	0,47	0,067	**0,16**	***trivial***	
HG_BB	0,31	0,19	0,39	0,28	0,831	**0,34**	***small increase***	
HG_AD	0,13	0,07	0,15	0,10	1000	**0,16**	***trivial***	

AD = anterior deltoid, BB = biceps brachium, ES = effect size, EXT = extensor digitorum, FLEX = flexor digitorum, HG = handgrip test, JAW = jaw condition, MAS = masseter, MG = mouthguard condition, NON-JAW = non-jaw condition, SD = standard deviation, TB = triceps brachium.

[a] significantly difference.

higher mandibular stability and an increased biting force, thus magnifying the effects of the concurrent activation potentiation (CAP) elicited by the remote voluntary contraction (RVC) of the masticatory muscles.[32,34] When comparing MG and JAW conditions, no differences were shown in the maximal force production in any test. These findings are in contrast with other studies which reported higher isometric force output in handgrip tests when comparing MG and JAW conditions.[23,33] Nonetheless, other investigators[35] also found no significant differences in the peak force production in a handgrip test. According to Ebben et al., it could be speculated that motor resources may be finite and the overflow-mediated enhancement of the RVC may not be shown in all actions.[32] In fact, a recent systematic review[27] suggested that the use of MG may be especially useful in lower limb muscular power, especially in jump ability and knee extension actions. However, these ergogenic effects are inconclusive on maximal isometric force performance, as well as agility, sprint, or isokinetic actions.

In terms of muscle activity, significant effects were observed in MAS when comparing the two jaw clenching conditions with respect to NON-JAW condition. However, in accordance with Lässing et al., the present study found no significant differences in the activity of the masticatory muscles when comparing MG with respect to JAW condition, even though the cited study reported a more balanced activity of the masticatory muscles.[5] Schulze et al. associated the increased/decreased muscle activity with muscle weakness, possible imbalances or intercuspal disorders in the masticatory structure.[7] According to these authors, participants with higher MAS resting tone or masticatory weakness showed an increased activity of masticatory muscles when using MG. However, participants with a high-normal range of the masticatory activity showed no relevant benefits. In the present study, MAS resting tone or comparisons between both sides of the masticatory muscles were not assessed by EMG analysis. Nonetheless, all participants were previously evaluated by a dentist to guarantee an adequate dental health and were excluded if they presented any injury related to the temporomandibular structure. Thus, in accordance with Schulze et al., the masticatory muscles status and the absence of possible imbalances in the temporomandibular structure could explain the no significant differences observed between MG and JAW conditions in the present investigation.[7] In contrast, other investigators[25] found significant effects in the activity of the masticatory muscles attributed to the use of MG. The authors compared two self-adapted (SA) MG (Power Balance SA-MG: 5.33 mm of interocclusal distance; and Under Armound SA-MG: 3.52 mm of interocclusal distance), with a bite-aligning, customized MG (C-MG: 3.69 mm of interocclusal distance) and no mouthguard (N-MG: 3.54 mm of interocclusal distance). It was shown a higher activation of the masticatory muscles when performing dynamic force tests with Power Balance, SA-MG (5.33 mm of interocclusal distance), supposedly attributed to the increased vertical dimension of occlusion (VDO). Thus, it is hypothesized that the interocclusal distance is a relevant factor to elicit the CAP phenomenon throughout the RVC of the mandible muscles. In this vein, Arima et al. investigated the relationship between the VDO and the masseter activity in healthy participants.[20] They showed that the optimal distance to achieve the maximal occlusal biting force is around 8 mm between the first molars. The MGs used in the present study were fabricated with a thickness of 5.4 mm. Although some investigators[25] found significantly higher muscle activation

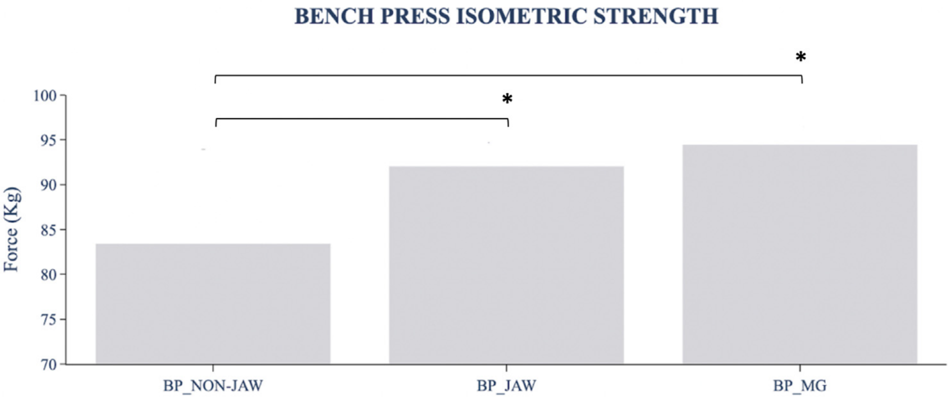


Fig. 4. Comparisons of bench press isometric strength between the 3 conditions (NON-JAW, JAW and MG). *Significantly higher than NON-JAW condition ($p \leq 0.05$).

Table 2
Mean and SD (in μV) of the muscle activity (EMG) between conditions (NON-JAW, JAW and MG) in bench press isometric strength test.

	NON-JAW		JAW		ρ	ES	Qualitative outcome
	Mean	SD	Mean	SD			
BP_MAS	0,22	0,17	0,39	0,19	0,024	**0,96**	***moderate increase*** [a]
BP_TB	0,80	0,36	0,84	0,42	1041	**0,09**	***trivial***
BP_CLAV	0,37	0,22	0,46	0,30	0,018	**0,31**	***small increase*** [a]
BP_STRN	0,34	0,16	0,37	0,18	0,717	**0,20**	***small increase***
BP_BB	0,39	0,29	0,50	0,36	0,084	**0,32**	***small increase***
BP_AD	0,79	0,31	0,79	0,28	2811	**−0,02**	***trivial***
	NON-JAW		MG		ρ	ES	Qualitative outcome
	Mean	SD	Mean	SD			
BP_MAS	0,22	0,17	0,38	0,17	0,057	**0,96**	***moderate increase***
BP_TB	0,80	0,36	0,84	0,29	0,408	**0,13**	***trivial***
BP_CLAV	0,37	0,22	0,44	0,23	0,102	**0,30**	***small increase***
BP_STRN	0,34	0,16	0,36	0,16	1440	**0,13**	***trivial***
BP_BB	0,39	0,29	0,54	0,51	0,123	**0,36**	***small increase***
BP_AD	0,79	0,31	0,84	0,28	0,546	**0,16**	***trivial***
	JAW		MG		ρ	ES	Qualitative outcome
	Mean	SD	Mean	SD			
BP_MAS	0,39	0,19	0,38	0,17	1440	**−0,06**	***trivial***
BP_TB	0,84	0,42	0,84	0,29	1440	**0,02**	***trivial***
BP_CLAV	0,46	0,30	0,44	0,23	1440	**−0,06**	***trivial***
BP_STRN	0,37	0,18	0,36	0,16	2262	**−0,08**	***trivial***
BP_BB	0,50	0,36	0,54	0,51	1749	**0,10**	***trivial***
BP_AD	0,79	0,28	0,84	0,28	0,213	**0,19**	***trivial***

AD = anterior deltoid, BB = biceps brachium, BP = bench press test, CLAV = pectoralis major clavicular, ES = effect size, JAW = jaw condition, MAS = masseter, MG = mouthguard condition, NON-JAW = non-jaw condition, SD = standard deviation, STRN = pectoralis major sternal, TB = triceps brachium.

[a] significantly difference.

in the masticatory muscles while wearing MGs with a similar thickness, in the present study, no differences were reported. This data may suggest that VDO is an important factor but not the only influencing the elicitation of the CAP phenomenon. Thus, other factors such as MG material, design or stiffness, as well as the status of the temporomandibular structure, should be considered. In contrast, another study reported lower muscle activity of the MAS and TEMP when professional Karate athletes wore customized MG.[36] The authors revealed that bite-aligning customized MG is designed to protect the teeth, control temporomandibular disorders and reduce orofacial pain by relaxing the masticatory muscles. Thus, reducing the muscle activity of the masticatory muscles and increasing the force output of the prime movers, could suggest an increased neuromuscular efficiency attributed to the MG use.[28] In the present study, the magnitude of the biting force was not directly assessed, however, MAS activity showed no differences when compared JAW and MG conditions. Therefore, we cannot directly associate the magnitude of the occlusal biting force with the prime mover's performance, neither does the use of MG to a greater activation of the MAS.

In the HG test, significant differences were found in the muscular activity of all muscle groups when comparing MG and NON-JAW conditions, except for TB. Other studies also found significant ergogenic effects in handgrip attributed to the use of MG.[23,33] The H-reflex facilitation of the forearm muscles during the voluntary jaw clenching and the CAP phenomenon induced by the RVC of the masticatory muscles seem to be the most appropriate reasons to explain these differences in the neuromuscular performance. However, this increased muscle activation in HG was not observed in BP and BC. A possible explanation for this lack of differences for MG condition in BP may be due to the difficulty to guarantee the relaxed condition of the masticatory muscles. It was observed that during BP test the athletes contracted the neck, core, and mandible muscles even though the command of non-clenching the jaw. In this context, some authors demonstrated that mandible muscle contractions with the jaw opened may also be an effective strategy to elicit the CAP.[37] Thus, the simultaneous contraction of different remote muscle groups and the difficulty to guarantee the relaxed status of mandible muscles under NON-JAW condition could explain this lack of differences when comparing the two jaw clenching conditions with respect to the NON-JAW condition. In the BC, significant differences were found in FLEX activity when comparing MG and NON-JAW conditions. However, no significant differences were found in the other muscle groups. Therefore, the significant differences found in FLEX activity of BC and HG could be explained by a potential interaction between jaw clenching and this forearm muscles. Indeed, Takahashi et al. revealed that the acute effects of voluntary teeth clenching on forearm and hand muscles may be differently modulated depending on the muscle properties, such as cortical origin, excitability or functional demands.[38] This fact could explain the differences found between FLEX and the other muscle groups. Participants of the present study were experienced rink hockey players, widely familiarized with the isometric grip to take the stick. Nonetheless, players are not used to train other muscles under isometric conditions. Thus, the lack specificity in isometric strength with some muscle groups could also explain the absence of significant differences between conditions in BP and BC.

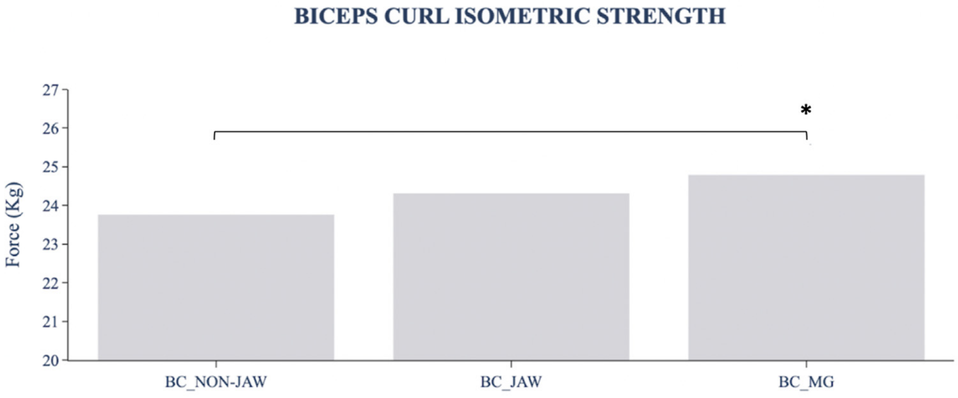


Fig. 5. Comparisons of biceps curl isometric strength between the 3 conditions (NON-JAW, JAW and MG). * Significantly higher than NON-JAW condition ($p \leq 0.05$).

Table 3
Mean and SD (in μV) of the muscle activity (EMG) between conditions (NON-JAW, JAW and MG) in biceps curl isometric strength test.

	NON-JAW		JAW		ρ	ES	Qualitative outcome
	Mean	SD	Mean	SD			
BC_MAS	0,06	0,07	0,28	0,13	0,010	**1,99**	***large increase*** [a]
BC_FLEX	0,96	0,39	1,04	0,40	0,191	**0,23**	***small increase***
BC_EXT	0,48	0,26	0,51	0,25	1000	**0,11**	***trivial***
BC_BB	1,49	0,62	1,57	0,61	1000	**0,14**	***trivial***
BC_AD	0,51	0,54	0,52	0,52	1000	**0,02**	***trivial***
	NON-JAW		MG		ρ	ES	Qualitative outcome
	Mean	SD	Mean	SD			
BC_MAS	0,06	0,07	0,28	0,16	0,007	**1,71**	***large increase*** [a]
BC_FLEX	0,96	0,39	1,13	0,43	0,043	**0,42**	***small increase*** [a]
BC_EXT	0,48	0,26	0,54	0,28	0,161	**0,22**	***small increase***
BC_BB	1,49	0,62	1,59	0,57	1000	**0,16**	***trivial***
BC_AD	0,51	0,54	0,65	0,58	0,270	**0,25**	***small increase***
	JAW		MG		ρ	ES	Qualitative outcome
	Mean	SD	Mean	SD			
BC_MAS	0,28	0,13	0,28	0,16	1000	**−0,01**	***trivial***
BC_FLEX	1,04	0,40	1,13	0,43	0,112	**0,20**	***small increase***
BC_EXT	0,51	0,25	0,54	0,28	1000	**0,12**	***trivial***
BC_BB	1,57	0,61	1,59	0,57	1000	**0,02**	***trivial***
BC_AD	0,52	0,52	0,65	0,58	0,266	**0,24**	***small increase***

AD = anterior deltoid, BB = biceps brachium, BC = biceps curl test, ES = effect size, EXT = extensor digitorum, FLEX = flexor digitorum, JAW = jaw condition, MAS = masseter, MG = mouthguard condition, NON-JAW = non-jaw condition, SD = standard deviation.

[a] significantly difference.

There are several limitations in the current study that should be considered. Firstly, the substantial number of maximal isometric contractions performed by the participants during the study may lead to a decrease of the neuromuscular performance. However, the reason of designing a one-day testing protocol was to ensure the same placement of the EMG electrodes among the tests and conditions. Secondly, in the BC, the participants contracted the free arm musculature to hold the bench and guarantee a better static position. This RVC could affect the prime mover performance through the CAP phenomenon. Thirdly, postural adjustments in the temporomandibular structure that require a long-term adaptation cannot be determined in the present study since MG was delivered the same testing day to ensure the same usage conditions among the athletes. Although all of them reported comfortability and no difficulties in breathing, the lack of familiarization with the oral device may influenced the maximum biting force under MG condition. Fourthly, it is interesting to note that beyond the isometric handgrip strength used to take the stick, the participants of the present study had no experience in isometric workout. This lack of training experience under isometric conditions could also influence the maximal force production and muscle activity for the mentioned actions. Finally, since the participants of the preset study used customized MG, which are designed to align the jaw structure and elicit a more balance occlusion, a fourth experimental condition (clenching a placebo or standard MG) should have been included in the present study.

5. Conclusion

The findings of the present study suggested that jaw clenching, with and without MG, is a good strategy to increase the upper body isometric strength compared to NON-JAW condition. An increased isometric force output was found in all tests for MG respect to NON-JAW conditions, whereas this increase was only observed in two of the three tests when comparing JAW and NON-JAW conditions. However, the non-significant differences found in force production neither in muscle activity between MG and JAW conditions, suggested that the ergogenic effects observed in the present investigation could be attributed to the jaw clenching, even though the use or non-use of MG.

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Authorship

All persons who meet authorship criteria are listed as authors, and all authors certify that they have participated sufficiently in the work to take public responsibility for the content, including participation in the concept, design, analysis, writing, or revision of the manuscript. Furthermore, each author certifies that this material or similar material has not been and will not be submitted to or published in any other publication.

Indicate the specific contributions made by each author (list the authors' initials followed by their surnames, e.g., C.Y. Cheung). The name of each author must appear at least once in each of the three categories below.

Conception and design of study: Adrià Miró, Bernat Buscà, Joan

Aguilera-Castells; acquisition of data: Adrià Miró, Bernat Buscà, Joan Aguilera-Castells, Jordi Arboix-Alió, Pol Huertas; analysis and/or interpretation of data: Adrià Miró, Bernat Buscà, Joan Aguilera-Castells, Jordi Arboix-Alió., Drafting the manuscript: Adrià Miró, Bernat Buscà; revising the manuscript critically for important intellectual content: Adrià Miró, Bernat Buscà, Joan Aguilera-Castells and Jordi Arboix-Alió. Approval of the version of the manuscript to be published (the names of all authors must be listed): Adrià Miró, Bernat Buscà, Joan Aguilera-Castells, Jordi Arboix-Alió, Pol Huertas.

Declaration of competing interest

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