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ORIGINAL RESEARCH

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Effects of remote facilitation on ankle joint movement: Focusing on occlusal strength and balance

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Abstract

Background: Remote facilitation refers to teeth occlusion-activated spinal cord activity resulting in increased trunk and limb muscle strength. Facilitation depends on dentition-related pressure during occlusion and masticatory muscle contraction strength.

Aims: This study aimed to clarify the neurophysiological phenomenon and mechanisms by which occlusal strength and balance affect leg muscle activity and smooth joint movement execution.

Materials & Methods: To examine occlusal strength, three conditions were set: no contact between teeth and Moderate- and Maximum-strength occlusion (No-bite, Moderate, and Max conditions, respectively). To assess occlusal balance, we measured occlusal forces and calculated the left-right force ratio. We designated the sides with higher and lower occlusal pressure as hypertonic and hypotonic, respectively. We assessed ankle dorsiflexion movements with joint movement and isometric tasks.

Results: The rate of joint development and peak ankle dorsiflexion torque were significantly higher under occlusion (moderate and max compared to No-bite conditions), and the joint movement performance time was significantly shorter under Moderate compared to No-bite conditions. The joint movement execution time change rate from No-bite to Moderate condition was significantly lower on the Hypertonic side. Joint movement function was most improved under Moderate conditions.

Discussion: While remote facilitation improves with higher occlusal strength, leading to increased muscle strength, there is optimal occlusion intensity in joint movement. Moreover, an occlusal balance-dependent imbalance exists in remote facilitation between the Hyper- and Hypotonic sides.

Conclusion: Thus, low-intensity occlusion is optimal for smooth joint movement, and unbalanced occlusion results in asymmetrical motor function facilitation.

KEYWORDS
ankle joint movement, occlusal balance, occlusal strength, remote facilitation

1 | INTRODUCTION

Teeth occlusion occurs during various types of sports activities,[1–5] exhibiting a significant and immediate impact on motor function.[6–8] This effect is referred to as remote facilitation, which stimulates the activity of the Locus Coeruleus (LC)[9–12] and the spinal cord.[13,14] Remote facilitation is a result of increased trigeminal nerve input that derives from periodontal ligament receptor firing with occlusal pressure and afferent impulses of muscle spindles in the masticatory muscles. Its neurological mechanism on the spinal cord, on which this study also focused, involves trigeminal inputs descending the spinal cord and acting as presynaptic inhibition against Ia fiber endings,[15] enhancing the excitability of the spinal anterior horn cells and leading to activated remote muscles.[6] A recent study reports that the amount of facilitation is determined by the occlusal pressure on periodontal ligament receptors and masticatory muscle contraction strength.[15] Therefore, in recent years, occlusal strength and balance (occlusal pressure left–right ratio) have attracted significant attention.

Concerning occlusal strength, certain studies described that spinal excitability is enhanced with increasing occlusal strength.[16–18] Our research group also investigated teeth occlusion with low-to-high intensity and revealed a correlation between spinal cord excitability and occlusal strength[19] In addition, in line with enhanced spinal cord excitability, muscle strength would be activated immediately.[7,19–22] However, we described in our previous research that spinal reciprocal inhibition (RI), a key function in smooth joint movement, has been completely nonfunctional during high-intensity occlusion (>50% of maximum voluntary contraction [MVC] of the masseter muscle).[19] These studies suggest that low-intensity occlusion (<50% MVC) could be effective in smooth joint movements due to enhanced spinal excitability and sufficient RI while high-intensity occlusion (>50% MVC) might exert effective performance with fixed joints due to enhanced spinal excitability and RI deficit, triggering concurrent activations of both the agonist and antagonist muscles. In fact, previous experiments examining the remote facilitation from maximum effort (high-intensity) occlusion demonstrated effective results in static standing balance stability.[20–24] However, previous studies assessing motor function with teeth occlusion have only examined high-intensity conditions, more detailed studies including low-intensity occlusion would thus be required.

Our research group focuses on occlusal balance and strength. Concerning balance, previous studies described that the more unbalanced the activity of the left and right masseter muscles become, the more asymmetrical the trigeminal input to the LC happens.[25,26] According to a study, which evaluated standing balance with both legs, unbalanced (unilateral) occlusion leads to unbalanced loads on both lower limbs.[27] However, whether unbalanced occlusion asymmetries trigeminal inputs to the spinal cord as well as left–right facilitation to lower limb muscles remains unclear. Another problem is that past studies examined the occlusal balance using the masticatory muscle activity left–right ratio with raw values and did not assess occlusal pressure[26–29] stimulating the receptors in the periodontal ligament. A study investigated occlusion with missing teeth and the left and right trigeminal input, revealing input diminution on the side with missing teeth.[28] Therefore, as the pressure applied to the dentition might be important for the degree the trigeminal input arises, this study aimed to examine the left–right ratio of occlusal pressure.

The present study is significant because it is the first to simultaneously examine factors that affect remote facilitation levels, including occlusal strength and balance. This study aimed to clarify the neurophysiological phenomenon and mechanisms by which occlusal strength and balance affect leg muscle activity and smooth joint movement execution.

This study hypothesized that low-intensity occlusion is effective on smooth joint movement, whereas high-intensity occlusion interferes with it. It was also hypothesized that occlusal balance affects remote facilitation symmetry toward remote muscles, with higher-level facilitation on the occlusion-dominant side.

2 | MATERIALS AND METHODS

2.1 | Experimental approach to the problem

We investigated remote facilitation with motor function assessment, focusing on occlusal strength and balance. Motor function was assessed by dorsiflexion of the ankle joint, a joint movement task of how smooth joint movement would be performed, and an isometric task to assess muscle strength. Three occlusal conditions were set up with different occlusal strengths, and occlusal balance was evaluated based on the left and right occlusal pressures. We designated the sides with higher and lower occlusal pressures as Hypertonic (Hyper) and Hypotonic (Hypo) and examined motor functions for each. We aimed to investigate the relationship between the occlusal balance and the degree of remote facilitation of the left and right sides. We thus calculated the rate of change for each occlusal condition from the No-bite condition based on the parameters obtained from the Hyper and Hypo side motor function evaluations and compared the results.

2.2 | Subjects

We recruited 27 healthy participants (13 male and 14 female) with normal occlusion for this study based on occlusal assessments by a dentist. The following items were assessed: angle class, overbite (OVB), overjet (OVJ), midline deviation (MLD), missing teeth (MT), crowding (CRW), and the criteria for normal occlusion were set as Angle Class I.[30] OVB and OVJ less than 5 mm without MLD, MT, and CRW. The subjects displayed no TMJ disorder, neuromuscular disease, history of lower limb surgery, and pain either. The ethics committee of our university provided approval for this study, which was conducted according to the ethical standards of the university and the 1964 Declaration of Helsinki and its later amendments.

2.3 | Limb position for the measurements

The limb position measurement involved 80° hip flexion and 60° knee flexion in a seated position. This right posture was maintained during the experiment by fixing the thigh to the seat and the foot to the footplate (Takei Scientific Instruments).

2.4 | Electromyography (EMG)

Ag/AgCl electrodes (Blue Sensor; METS) were set 20 mm apart for surface EMG. We applied the disposable electrodes to the muscle belly of the tibialis anterior (TA) and the medial head of the soleus (Sol) muscle in the lower limb in accordance with SENIAM.[31] Regarding the masticatory muscles, the electrodes were placed on the masseter muscle and the anterior temporalis muscle. The same electrodes were applied bilaterally to the leg muscles and the masticatory muscles. A ground electrode was positioned on the proximal lower leg. A band-pass filter (10–1000 Hz; amplified ×100) (FA-DL-720-140; 4Assist) was used to filter EMG activity before digital storage (sampling rate of 10 kHz) for offline analyses. Data analyses were performed with PowerLab 8/30 and LabChart 7 (both AD Instruments). Masticatory muscle MVC was measured using cotton rolls placed on the bilateral row of teeth (canines to third molars) to measure a unified left–right occlusal contact area.[32] We also instructed the subjects to avoid changing their facial expressions as much as possible to prevent facial muscle contraction during the measurements. For TA and Sol MVCs, measurements were taken at 0° of plantar dorsiflexion. All MVC measurements were performed for 3 s for each muscle at 80° hip flexion and 60° knee flexion in a seated position, and the stable 1 s value was analyzed.

2.5 | Occlusal balance assessment

To assess individual occlusal balance, we used the Dental Prescale II film (GC) for occlusal force measurement. The subjects were asked to chew a filter containing 150-µm thick color-forming microcapsules for 3 s at maximum effort. The chewed filter displayed a red coloration from the microcapsules that were broken upon the occlusal force exerted by the subjects, which was captured by a scanner for data acquisition. Based on the left and right occlusal forces digitized through the above-described process, we could designate the sides with higher and lower occlusal pressures as Hypertonic (Hyper) and Hypotonic (Hypo), respectively. The lower limbs corresponded to these measurements and designations; if the occlusal force was higher on the right side, the right lower limb was considered the Hyper side.

2.6 | Occlusal conditions

In this study, we set three occlusion conditions: no contact between upper and lower teeth (No-bite condition), moderate-strength occlusion (Moderate condition), and maximum-effort occlusion (Max condition). Subjects felt the most comfortable chewing and performing motor tasks at the strength of the Moderate condition.[19]

2.7 | Motor function assessment

We assessed motor function by the dorsiflexion of the ankle joint and measured two tasks performed by the subject: a joint movement and an isometric task. Measurements were taken on both the Hyper and Hypo sides.

In the joint movement task, the range of movement was 30° of the ankle joint plantar flexion to 0° of the plantar dorsiflexion. The examiner instructed the subject to perform the dorsiflexion as quickly as possible. Each occlusion condition was performed thrice in random order, with a 30-s rest between each trial.

The isometric task was performed at 0° ankle plantar dorsiflexion. The subject was requested to perform the dorsiflexion at maximum effort for 3 s, reaching the peak as soon as possible. Each occlusion condition was performed twice at random, with a 1-min rest between each trial.

Each task movement was cued by presenting two light stimuli in front of the subject. Subjects started the occlusal condition as instructed by the examiner on cue of the first light stimulus, and tried each task movement on cue of the second light stimulus with an interval of 3 s between the two light stimuli. Under the Max condition, the masticatory muscle activity was difficult to maintain beyond 3 s at maximum effort, the subjects thus did not wait for the second light stimulus and performed the dorsiflexion movement at the timing of their convenience.

2.8 | Experimental protocol (Figure 1)

Figure 1 presents the experimental procedure. Initially, masticatory muscle MVC was measured, and occlusal balance was assessed using the Dental Prescale II. Before the motor function task assessment, the MVC of the TA and Sol was measured. The motor function assessment was performed in the order of the joint movement and isometric tasks, and the measurements were started after sufficient practice for each. Task movements were measured bilaterally on the Hyper and Hypo sides, and the measurement order of the sides and conditions was randomized. At the end of the experiment, the masticatory muscle MVC was recorded again and compared with the values before the experiment to confirm the presence of muscle fatigue in the masticatory muscles.

2.9 | Data processing

Based on the left and right occlusal forces, the left and right measuring limbs corresponded to the Hyper and Hypo sides, respectively, and were analyzed.

For the analysis of the joint movement task, EMG of TA, and Sol, cocontraction index (CI), joint movement execution time (Time), ankle dorsiflexion peak torque (PT), and rate of joint development (RJD) were calculated. The analysis section of EMG, CI, and Time was divided into

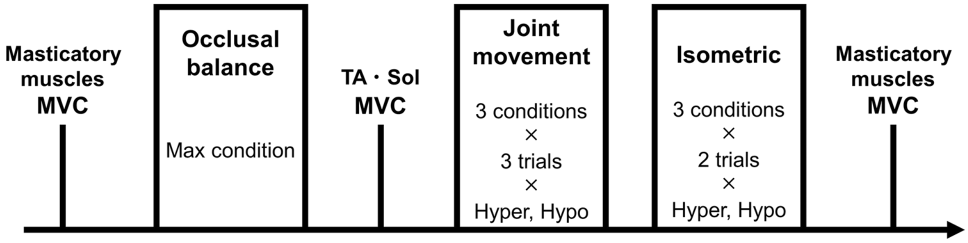

FIGURE 1 Experiment protocol. Before the measurement of the task movements, the occlusal balance was assessed using the Dental Prescale II and the MVC of the TA and Sol was collected. The task movements were performed in the order of the joint movement task and the isometric task. The joint movement task and the isometric task were performed thrice and twice, respectively, under each condition. Occlusal conditions, as well as the Hyper and Hypo sides, were randomly assigned. Rest intervals between each trial were set at 30 s and 1 min for the joint movement task and the isometric task, respectively. The masticatory muscle MVC was measured before and after the experiment. MVC, maximal voluntary contraction; TA, tibialis anterior muscle; Sol, soleus muscle.

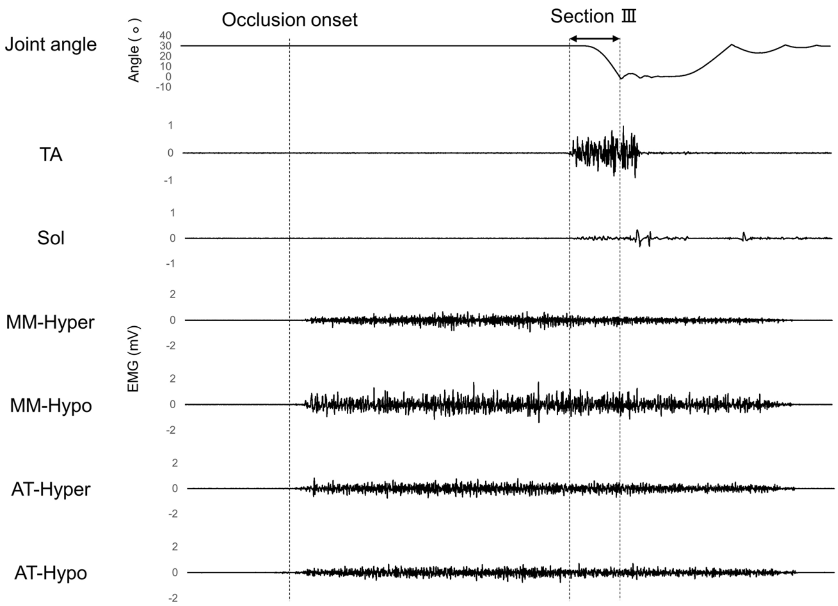

FIGURE 2 Raw data tracing EMG of each muscle. Raw data in the Max condition of the joint movement task from one representative subject. The top graph shows the joint motion from 30° of ankle joint plantar flexion to 0° of plantar dorsiflexion. The graphs below show the EMG of each muscle. AT, anterior temporalis muscle; EMG, electromyography; MM, masseter muscle; Sol, soleus muscle; TA, tibialis anterior muscle.

three sections: (I) TA EMG onset to joint motion onset, (II) TA EMG onset to the end of joint motion, (III) TA EMG onset to the end of joint motion (I + II). The TA EMG onset was defined as the time at which the EMG exceeded the mean EMG ± 3 × standard deviation. All collected EMG data were calculated as the mean EMG of each analysis section and divided by the MVC to form the %MVC. The ankle dorsiflexion PT was defined as the maximum dorsiflexion torque to the end of the joint motion. We calculated RJD as the joint motion range (30°) divided by time (s) and CI as described previously.[33]

We analyzed the isometric task as ankle dorsiflexion PT and used the maximum dorsiflexion torque recorded for 3 s.

2.10 | Statistical analysis

All statistical analyses were conducted using SPSS software (v.24; IBM). The obtained values were calculated as the mean. Repeated-measures one-way analysis of variance (ANOVA) for one factor of the occlusion conditions (No-bite, Moderate, and Max conditions) was used. Multiple comparison tests using the Bonferroni correction were used for comparison between different occlusal conditions as a post hoc analysis. We calculated the change rate from the No-bite to the Moderate and Max conditions, used the corresponding t-test to compare the calculated change rates between Hyper and Hypo, and examined the relationship between occlusal balance and the degree of remote facilitation on the left and right sides. The level of statistical significance was set at $p < 0.05$.

3 | RESULTS

The representative row data in the Max condition of the joint movement task are shown in Figure 2.

3.1 | Joint movement task (Hyper)

3.1.1 | TA EMG (Figure 3)

Repeated-measures one-way ANOVA revealed the main effects of the occlusal conditions in Section I (TA EMG onset to joint motion onset) (F[3, 57] = 4.586 , p = 0.02, η^2 = 0.150). A comparison of TA EMG for each occlusal condition showed that in Section I, TA EMG was significantly higher under the Moderate than under the No-bite condition (p = 0.02).

3.1.2 | Sol EMG (Figure 3)

Repeated-measures one-way ANOVA showed no main effect of the occlusal condition.

3.1.3 | CI (Figure 4)

Repeated-measures one-way ANOVA showed no main effect of the occlusal condition.

3.1.4 | Time (Figure 5)

Repeated-measures one-way ANOVA revealed the main effects of the occlusal conditions in Section I (F[3, 57] = 3.801, p = 0.03, η^2 = 0.128), II (TA EMG onset to the end of joint motion) (F[3, 57] = 4.708, p = 0.01, η^2 = 0.153) and III (I + II) (F[3, 57] = 4.029, p = 0.02, η^2 = 0.134). A comparison of Time for each occlusal condition showed that in Section III, Time was significantly shorter under the Moderate than under the No-bite condition (p = 0.03).

3.1.5 | Ankle dorsiflexion PT (Figure 6)

Repeated-measures one-way ANOVA revealed the main effects of the occlusal conditions (F[3, 57] = 11.157, p < 0.001, η^2 = 0.300). The comparison of ankle dorsiflexion PT for each occlusal condition showed that PT was significantly higher under the Max condition than under the No-bite condition (p < 0.001). In addition, the obtained value was also significantly higher under the Max than under the Moderate condition (p = 0.02).

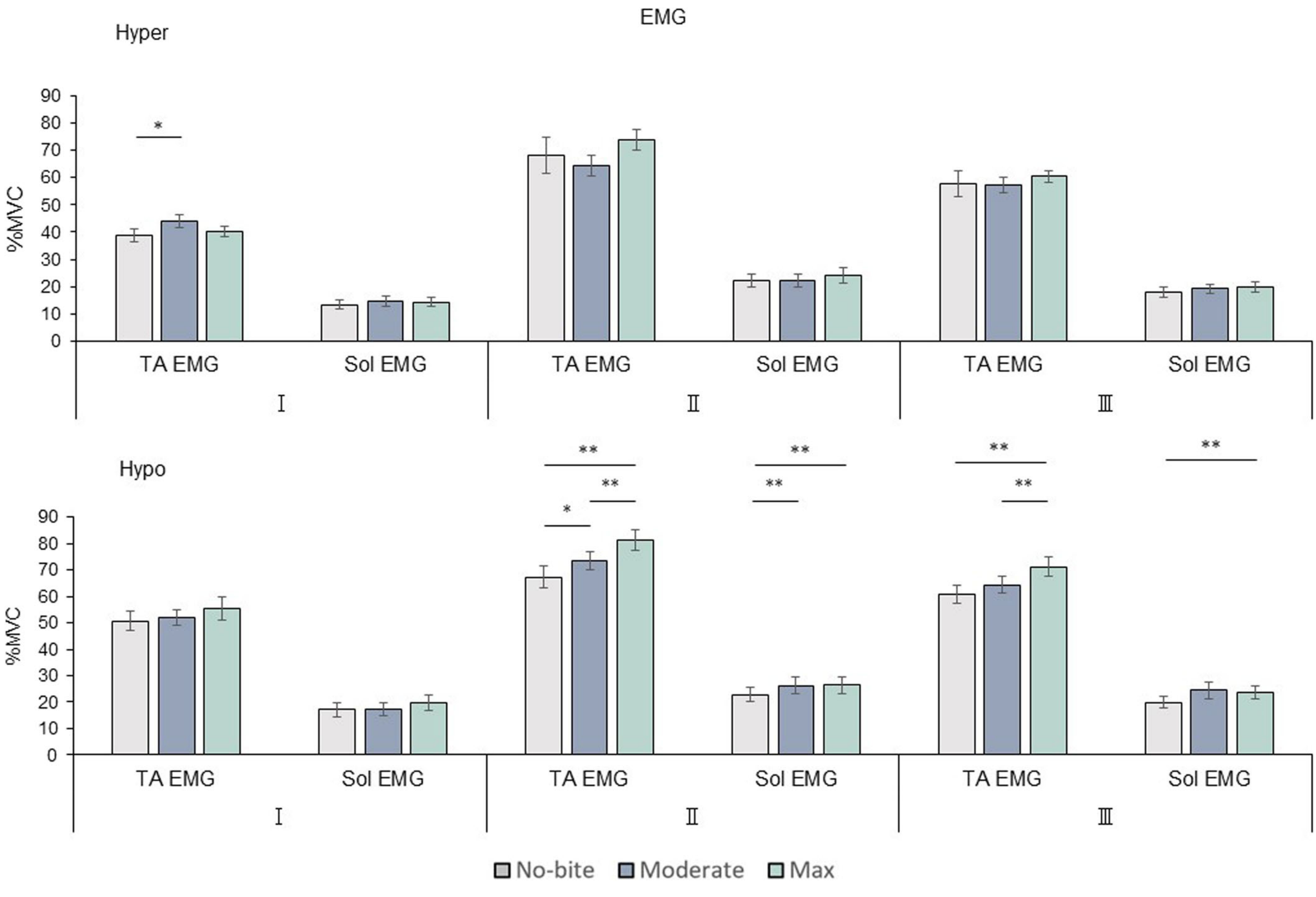

FIGURE 3 TA, Sol EMG. The bar charts represent the mean ± standard error of the TA and Sol EMG in the joint movement task on the Hyper and Hypo sides. The horizontal axis shows occlusal conditions for three sections: I, II, and III. Multiple comparison tests using the Bonferroni correction were performed for comparisons among the conditions. *p < 0.05, **p < 0.01. EMG, electromyography; Sol, soleus muscle; TA, tibialis anterior muscle.

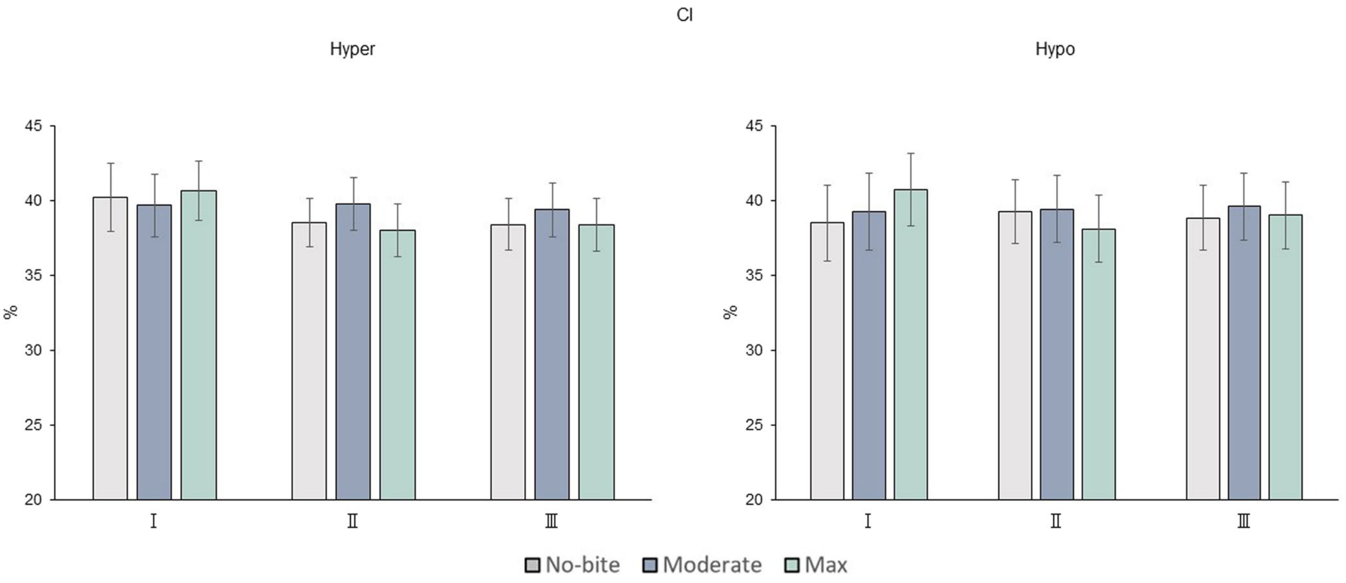

FIGURE 4 Cocontraction index. The bar charts represent the mean ± standard error of the CI (%) in the joint movement task on the Hyper and Hypo sides. The horizontal axis shows occlusal conditions for three sections: I, II, and III. Repeated-measures one-way ANOVA showed no main effect of occlusal condition. ANOVA, analysis of variance; CI, cocontraction index.

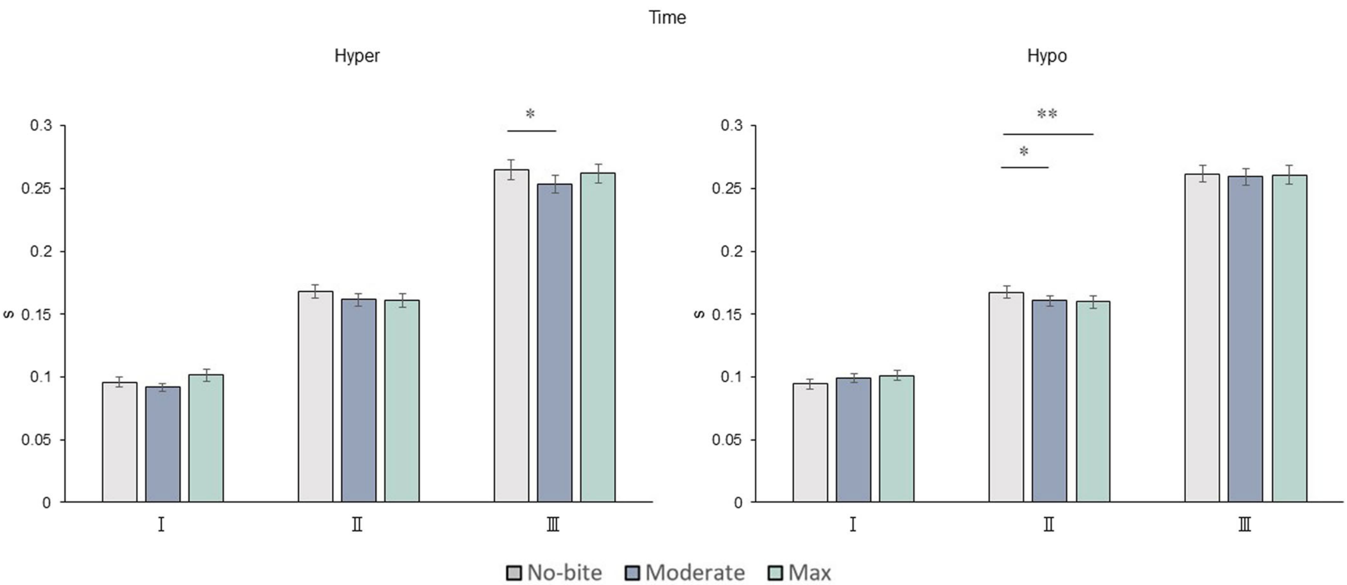

FIGURE 5 Joint movement execution time. The bar charts represent the mean ± standard error of the Time (s) in the joint movement task on the Hyper and Hypo sides. The horizontal axis shows occlusal conditions for three sections. The analysis section of Time was divided into three sections: (I) TA EMG onset to joint motion onset, (II) TA EMG onset to the end of joint motion, (III) TA EMG onset to the end of joint motion (I + II). Multiple comparison tests using the Bonferroni correction were performed for comparisons among the conditions. *$p < 0.05$, **$p < 0.01$. EMG, electromyography; TA, tibialis anterior; Time, joint movement execution time.

3.1.6 | RJD (Figure 7)

Repeated-measures one-way ANOVA revealed the main effects of the occlusal conditions ($F[3, 57] = 6.524$, $p = 0.003$, $\eta^2 = 0.201$). The comparison of RJD for each occlusal condition showed that RJD was significantly higher under the Max than under the No-bite condition ($p = 0.02$).

3.2 | Joint movement task (Hypo)

3.2.1 | TA EMG (Figure 3)

Repeated-measures one-way ANOVA revealed the main effects of the occlusal conditions in Section II ($F[3, 57] = 17.180$, $p < 0.001$, $\eta^2 = 0.398$)

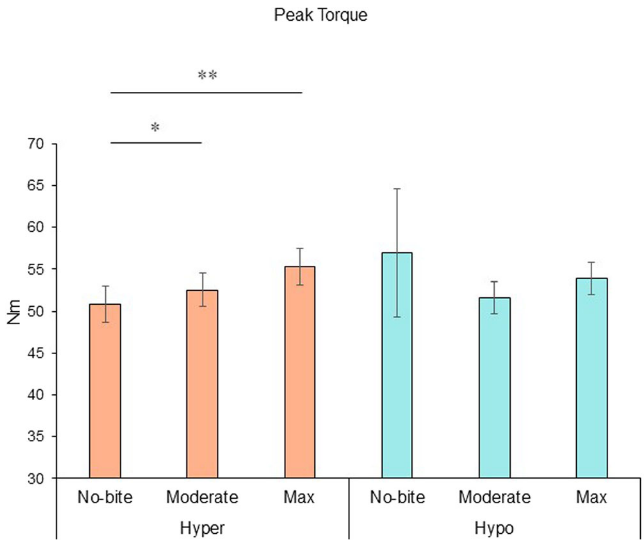

FIGURE 6 Ankle dorsiflexion peak torque (Joint movement). The bar chart represents the mean ± standard error of the ankle dorsiflexion PT (Nm) in the joint movement task. The horizontal axis shows occlusal conditions for the Hyper and Hypo sides. Multiple comparison tests using the Bonferroni correction were performed for comparisons among the conditions. $^*p < 0.05$, $^{**}p < 0.01$. PT, peak torque.

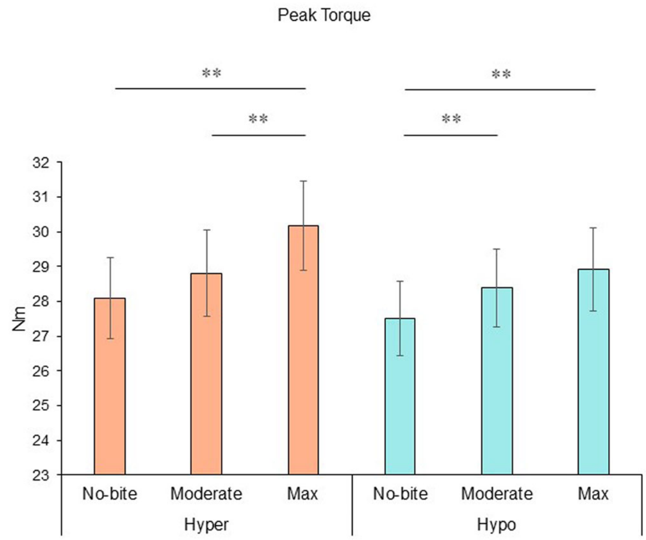

FIGURE 8 Ankle dorsiflexion peak torque (Isometric). The bar chart represents the mean ± standard error of the ankle dorsiflexion PT (Nm) in the isometric task. The horizontal axis shows occlusal conditions for the Hyper and Hypo sides. Multiple comparison tests using the Bonferroni correction were performed for comparisons among the conditions. $^{**}p < 0.01$. PT, peak torque.

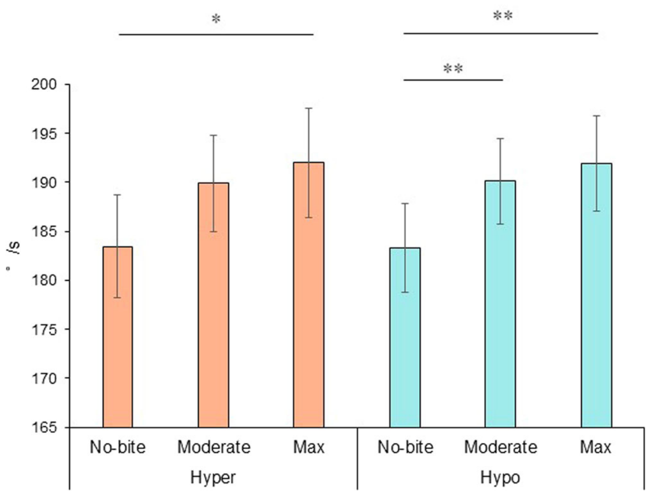

FIGURE 7 Rate of joint development. The bar chart represents the mean ± standard error of the RJD (°/s) in the joint movement task. The horizontal axis shows occlusal conditions for the Hyper and Hypo sides. Multiple comparison tests using the Bonferroni correction were performed for comparisons among the conditions. $^*p < 0.05$, $^{**}p < 0.01$. RJD, rate of joint development.

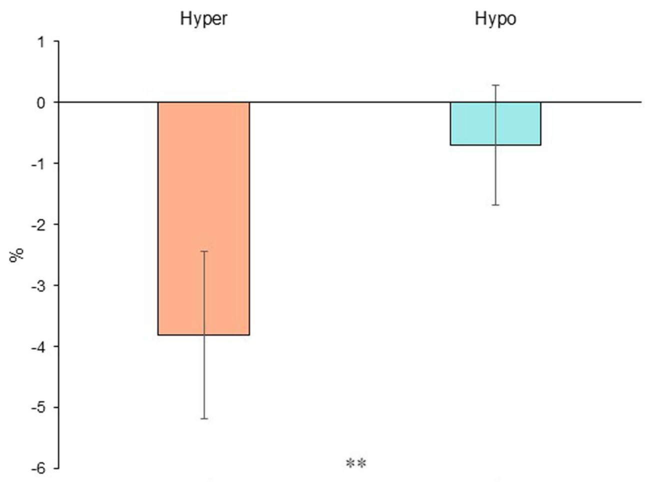

FIGURE 9 The change rate for Time (Section III). The bar chart represents the mean ± standard error of the rate of change for Time of Section III from No-bite to Moderate condition (%) in the joint movement task. The horizontal axis shows the sides of Hyper and Hypo. The corresponding *t*-test was used to compare the value between the Hyper and Hypo sides. $^{**}p < 0.01$.

and III ($F[3, 57] = 15.392$, $p < 0.001$, $\eta^2 = 0.372$). The comparison of TA EMG for each occlusal condition showed that in Section II, the TA EMG was significantly higher under the Max ($p < 0.001$) and Moderate ($p = 0.04$) than under the No-bite condition. Furthermore, the value was significantly higher under the Max than under the Moderate condition ($p = 0.005$) in the same section. When it comes to Section III, the TA EMG was significantly higher under the Max than under the No-bite condition ($p < 0.001$). In addition, the value was significantly higher under the Max than under the Moderate condition ($p = 0.005$).

3.2.2 | Sol EMG (Figure 3)

Repeated-measures one-way ANOVA revealed the main effects of the occlusal conditions in Section II ($F[3, 57] = 12.707$, $p < 0.001$,

$\eta^2 = 0.328$) and III ($F[3,\ 57] = 3.763$, $p < 0.001$, $\eta^2 = 0.126$). A comparison of Sol EMG for each occlusal condition showed that in Section II, Sol EMG was significantly higher under the Max ($p = 0.001$) and Moderate ($p = 0.003$) than under the No-bite condition. Moreover, in Section III, the value was significantly higher under the Max than under the No-bite condition ($p < 0.001$).

3.2.3 | CI (Figure 4)

Repeated-measures one-way ANOVA revealed the main effects of the occlusal conditions in Section I ($F[3,\ 57] = 4.586$, $p = 0.04$, $\eta^2 = 0.150$). However, we observed no significant difference among the occlusal conditions based on the post hoc analysis.

3.2.4 | Time (Figure 5)

Repeated-measures one-way ANOVA revealed the main effects of the occlusal conditions in Section II ($F[3,\ 57] = 10.363$, $p < 0.001$, $\eta^2 = 0.285$). The comparison of Time for each occlusal condition showed that in Section II, Time was significantly shorter under the Max ($p = 0.001$) and Moderate ($p = 0.01$) than under the No-bite condition.

3.2.5 | Ankle dorsiflexion PT (Figure 6)

Repeated-measures one-way ANOVA showed no main effect of the occlusal conditions.

3.2.6 | RJD (Figure 7)

Repeated-measures one-way ANOVA revealed the main effects of the occlusal conditions ($F[3, 57] = 15.059$, $p < 0.001$, $\eta^2 = 0.367$). The comparison of RJD for each occlusal condition showed that RJD was significantly higher under the Max ($p < 0.001$) and Moderate ($p = 0.002$) than under the No-bite condition.

3.3 | Isometric task (Hyper)

3.3.1 | Ankle dorsiflexion PT (Figure 8)

Repeated-measures one-way ANOVA revealed the main effects of the occlusal conditions ($F[3, 57] = 19.036$, $p < 0.001$, $\eta^2 = 0.423$). The comparison of ankle dorsiflexion PT for each occlusal condition showed that PT was significantly higher under the Max than under the No-bite condition ($p < 0.001$). In addition, the value was also significantly higher under the Max than under the Moderate condition ($p < 0.001$).

3.4 | Isometric task (Hypo)

3.4.1 | Ankle dorsiflexion PT (Figure 8)

Repeated-measures one-way ANOVA revealed the main effects of the occlusal conditions ($F[3,\ 57] = 13.221$, $p < 0.001$, $\eta^2 = 0.337$). A comparison of ankle dorsiflexion PT for each occlusal condition showed that PT was significantly higher under the Moderate than under the No-bite condition ($p < 0.001$). In addition, the value was also significantly higher under the Max than under the No-bite condition ($p = 0.001$).

3.5 | The change rate (Hyper, Hypo) (Figure 9)

The change rate from the No-bite to Moderate condition of Time in Section III in the joint movement task was compared between Hyper and Hypo, indicating a lower rate of change on the Hyper side ($p = 0.005$). We observed no significant differences in the change rates in other parameters between Hyper and Hypo.

4 | DISCUSSION

To the best of our knowledge, this is the first study that focused on occlusal strength and balance, and that investigated the effect of remote facilitation using motor function assessment. Our main findings showed that, with regard to occlusal strength, joint movement function and muscle strength improved with occlusion conditions (Moderate and Max conditions) and that the Moderate condition was the most effective for the smooth execution of joint movements. Related to occlusal balance, we observed a significant shortening of the change rate from No-bite to Moderate condition in the Hyper side compared with that in the Hypo side based on the results of the Time in Section III (TA EMG onset to the end of joint motion), indicating that an unbalanced occlusion results in an unbalanced effect of remote facilitation on the motor function with the lower limbs.

Concerning occlusal strength, RJD in the joint movement task and ankle dorsiflexion PT in the isometric task were significantly higher under the occlusion (Moderate and Max) conditions compared to the No-bite condition. Therefore, teeth occlusion was proven effective in improving smooth joint movement and muscle strength. The results of the present study are suggested to be due to the activation of the TA, the main active muscle of the ankle dorsiflexion movement, via the remote facilitation effect from teeth occlusion. In a previous study, the results of a significantly higher H-reflex (spinal excitability) recorded by the test stimulation of the common peroneal nerve during occlusion with a masseter muscle contraction strength of 25% MVC or higher were recognized.[18] Therefore, it is feasible that spinal excitability was enhanced by the remote facilitation effect during the task movement with occlusion conditions in the present study, resulting in the recruitment of larger motor units of the TA, potentially improving smooth joint movement execution and muscle strength.

Concerning the RJD improvement under Max conditions, the results contradict the hypothesis of this study that high-intensity occlusion interferes with joint movement. RI reportedly ceased to function with a masseter muscle contraction strength of 50% MVC or more,[19] and it was expected that the Max conditions of the present study would promote the excessive activity of antagonist muscles. However, the EMG analysis results showed no significant difference in CI (ratio of the antagonist muscle activity to the agonist muscle) under the Max condition compared to those under the No-bite condition, suggesting that the excessive activity of the antagonist muscle could not be observed and it did not interfere with joint movement under the Max condition.

In the joint movement task, the Time of Section III (TA EMG onset to the end of joint motion) on the Hyper side was significantly shorter under the Moderate condition than under the No-bite condition. Based on the results of Time, including Section I (TA EMG onset to joint motion onset), low occlusal strength was observed to be optimal for smooth joint motion, which supports the hypothesis. This result was likely to be affected by the significant increase of TA EMG in Section I under the Moderate condition. A previous report demonstrated that time extension of the electro-dynamic delay (EMD) impairs the subsequent rate of force exertion (RFD) on the hamstring, meaning that the EMD duration affects the following movement.[30] Although there was no significant shortening of Time in Section I under the Moderate condition in this present study, the remote facilitation of occlusion contributed to an increased TA EMG in EMD, leading to a significant shortening of Time in Section III. Furthermore, we observed no significant increase for the Sol EMG compared to the No-bite conditions. Therefore, the Moderate condition in this study was established to provide the optimum strength for joint movement since it activated the main action muscle, TA, as well as maintained RI toward the antagonist muscle, Sol. This consequence is supported by a previous study we conducted, which clarified that RI remained and worked sufficiently at occlusal strengths of less than 50% MVC.[19]

In terms of occlusal balance, the change rate from No-bite to Moderate condition was significantly shorter on the Hyper than on the Hypo side at Time of Interval III, revealing that the degree of remote facilitation differs between the two sides. In other words, the results suggest that an unbalanced occlusion results in a similarly unbalanced motor function. According to the EMG results, on the Hyper side, TA EMG increased significantly in section I, while on the Hypo side, a significant increase in TA EMG was observed after the onset of joint movement (Sections II and III), indicating an occlusal balance-dependent unbalanced remote facilitation effect. Unilateral occlusion reportedly shifts the amount of load on both lower limbs during static standing to the side opposite the occluded side.[27] Considering the results of the present study, it is possible that only unilateral trigeminal input resulted in a unilateral dominance of the remote facilitation. As functional unbalances in the lower limb reportedly represent a risk factor for injury development,[34] this supports the possibility that the asymmetrical remote facilitation of an unbalanced occlusion might be a risk factor for injury occurrence.

4.1 | Limitation

A limitation of this study is that the assessment of occlusal balance using the Dental Prescale II could not be carried out under Moderate conditions. The measurement band of this instrument measures maximum occlusal forces in the range of 10–120 MPa, and values below 10 MPa are excluded from the analysis due to noise correction. Therefore, the occlusal forces obtained under the Moderate condition, which is a low-intensity occlusal condition, were below 10 Mpa in most subjects and did not reflect the occlusal forces in all dentitions. However, based on the EMG analysis of the masticatory muscles (Tables 1a and 1b), the %MVC of the masseter muscle and temporalis muscle was higher on the Hyper side under the Moderate condition. Therefore, the Moderate condition in the present study was expected to show a similar occlusal balance to that under the Max condition.

5 | PERSPECTIVE

The effects of tooth occlusion and occlusal splints (OSs) have been investigated in various sports in terms of exerting an immediate impact on motor function.[35–38] The present study investigated the

TABLE 1a Masticatory muscles background EMG (Moderate condition).

	MM-Hyper	MM-Hypo	AT-Hyper	AT-Hypo
Joint Movement				
Hyper	24.94 ± 19.39	23.14 ± 16.09	36.99 ± 19.75	37.65 ± 20.89
Hypo	22.31 ± 17.53	20.31 ± 14.89	34.45 ± 18.21	35.72 ± 19.29
Isometric				
Hyper	34.97 ± 18.57	30.79 ± 18.68	49.34 ± 17.43	47.41 ± 18.74
Hypo	33.11 ± 17.99	29.86 ± 16.71	47.81 ± 18.41	45.86 ± 21.22

Note: The data are represented as the mean ± standard error. MM and AT muscles background EMG (%MVC).

Abbreviations: AT, anterior temporalis muscle; EMG, electromyography; MM, masseter muscle.

TABLE 1b Masticatory muscles background EMG (Max condition).

	MM-Hyper	MM-Hypo	AT-Hyper	AT-Hypo
Joint Movement				
Hyper	75.97 ± 19.67	73.74 ± 19.56	89.58 ± 16.02	91.16 ± 14.47
Hypo	75.72 ± 18.17	73.02 ± 20.77	91.14 ± 22.04	89.17 ± 14.36
Isometric				
Hyper	72.86 ± 20.28	69.70 ± 18.66	86.34 ± 16.36	86.39 ± 15.55
Hypo	72.34 ± 16.86	68.69 ± 17.35	86.03 ± 23.62	82.76 ± 15.19

Note: The data are represented as the mean ± standard error. MM and AT muscles background EMG (%MVC).

Abbreviations: AT, anterior temporalis muscle; EMG, electromyography; MM, masseter muscle.

effects of occlusal strength and balance on remote facilitation using motor function assessment. With an increase in occlusal strength, remote facilitation and muscle strength increased, but an optimal strength for the smooth joint movement was identified, i.e., low-intensity occlusion (Moderate condition). Our study revealed that an unbalanced occlusion leads to asymmetrical facilitation of motor function, and our results highlight the possible benefits of correcting occlusal balance to prevent injury occurrence and improve performance. Based on a previous study that revealed that balanced occlusion can be achieved with OSs according to differences in pupil diameters between the left and right measured with and without the OS,[26] athletes with unbalanced occlusion would benefit from wearing an OS while engaging in athletic activity. Future studies should include further examination of movements that are more similar to competitive movements and a detailed study of the relationship between occlusal balance, movement symmetry, and injury occurrence.

AUTHOR CONTRIBUTIONS

Yuki Yamada: conceptualization; data curation; formal analysis; investigation; methodology; project administration; validation; visualization; writing – original draft; writing – review and editing. **Ryo Hirabayashi**: conceptualization; data curation; formal analysis; funding acquisition; investigation; methodology; project administration; resources; software; supervision; validation; visualization; writing – original draft; writing – review and editing. **Yoshiyuki Okada**: formal analysis; investigation; methodology; project administration; writing – review and editing. **Hirotake Yokota**: conceptualization; methodology; writing – review and editing. **Chie Sekine**: conceptualization; methodology; writing – review and editing. **Mutsuaki Edama**: conceptualization; investigation; methodology; project administration; supervision; validation; writing – review and editing.

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CONFLICT OF INTEREST STATEMENT

The authors declare no conflict of interest.

DATA AVAILABILITY STATEMENT

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

TRANSPARENCY STATEMENT

The lead author Yuki Yamada affirms that this manuscript is an honest, accurate, and transparent account of the study being reported; that no important aspects of the study have been omitted; and that any discrepancies from the study as planned (and, if relevant, registered) have been explained.

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