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Force-controlled biting alters postural control in bipedal and unipedal stance

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SUMMARY Human posture is characterised by inherent body sway which forces the sensory and motor systems to counter the destabilising oscillations. Although the potential of biting to increase postural stability has recently been reported, the mechanisms by which the craniomandibular system (CMS) and the motor systems for human postural control are functionally coupled are not yet fully understood. The purpose of our study was, therefore, to investigate the effect of submaximum biting on postural stability and on the kinematics of the trunk and head. Twelve healthy young adults performed force-controlled biting (FB) and non-biting (NB) during bipedal narrow stance and single-leg stance. Postural stability was quantified on the basis of centre of pressure (COP) displacements, detected by use of a force platform. Trunk and head kinematics were investigated by biomechanical motion analysis, and bite forces were measured using a hydrostatic system. The results revealed that FB significantly improved postural control in terms of reduced COP displacements, providing additional evidence for the functional coupling of the CMS and human posture. Our study also showed, for the first time, that reductions in the sway of the COP were accompanied by reduced trunk and head oscillations, which might be attributable to enhanced trunk stiffness during FB. This physiological response to isometric activation of the masticatory muscles raises questions about the potential of oral motor activity as a strategy to reduce the risk of falls among the elderly or among patients with compromised postural control.

KEYWORDS: biting, postural control, balance, kinematics, stance, jaw motor tasks

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Introduction

Human posture is characterised by inherent instability, known as 'body sway'. Corrective intermuscular and intra-muscular synergy and coordination of the different body regions are needed to counteract the destabilising oscillations arising from internal and external forces (1). This control of the body's position in space for the purposes of stability and orientation is referred to as 'postural control' (2).

Sensory information from the visual, vestibular and somatosensory systems is important input for controlling posture. This information is passed to the different parts of the central nervous system (CNS), where it is integrated and dynamically re-weighted to provide an internal representation of the body and its environment (3). This representation is then used by the higher centres of the CNS to generate and update the motor commands that maintain postural equilibrium. The process of balancing is thus predominantly based on feedback mechanisms involving complex interaction of the sensory and motor systems (4).

Studies on animals have provided information about the neuroanatomical connections of the ner-

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vous trigeminus to vestibular and oculomotor nuclei (5, 6). Projections from trigeminal nuclei to all levels of the spinal cord and to the vestibulocerebellum have also been found (7–10). Taking this neuromuscular integration of the craniomandibular system (CMS) into account, it has been shown that motor activity during jaw clenching contributes to the facilitation of postural reflexes (11–13) in a manner similar to the Jendrassik manoeuvre (14–16). Furthermore, posturographic analysis during quiet stance revealed physiological effects of biting under different occlusal conditions on the stabilisation of human posture (17–20). In contrast to maximum biting, body sway was significantly reduced during submaximum biting, and the centre of pressure (COP) deviated significantly in the anterior direction (21). The authors explained these results on the basis of stiffening of the anterior myofascial chains, which seems to be one component of common motor reactions to new or unfamiliar motor tasks and might, thus, be a strategy for facilitating reflexes and preventing falls (21, 22).

Although posturographic measurement of the COP provides relevant information about the general effects of biting on postural stability, no information is yet available about the coordination of body regions under these conditions. Moreover, to the best of our knowledge, the effect of biting on postural control during more complex balance tasks has not been studied. Such work could provide evidence of the potential of oral motor activity as a strategy for patients with compromised postural control to reduce the risk of falls. The purpose of our study was, therefore, to investigate the effect of submaximum CMS motor activity on postural control in bipedal narrow stance and single-leg stance by means of complex kinematic motion analysis. We hypothesised that force-controlled biting improves postural stability – in terms of reduced COP displacements – and moreover leads to enhanced forward-leaning of the trunk and head.

Material and methods

Subjects

Twelve young adults (age 21·8 ± 1·8 years; 10 male, 2 female) participated in our exploratory study. The subjects' body mass index was 22·9 ± 3·7 kg m^{-2}, and reported weekly physical activity was 2·3 ± 1·2 h. The participants had no known muscular or neurological diseases that could have affected their ability to perform the experiments. Moreover, they all had normal vision and no temporomandibular disorders, as assessed by means of the RDC/TMD criteria (23), and presented with full dentition (except for third molars) in neutral occlusion.

All participants gave their written informed consent to the experiments, which were conducted in accordance with the Declaration of Helsinki. The study was approved by the Ethics Committee of the German Sport University Cologne (no. 38/12).

Apparatuses

Bite force was measured by use of a hydrostatic system consisting of liquid-filled pads fixed to the maxilla by means of an occlusal splint with a planar surface (Fig. 1). A corresponding planar splint stabilised the mandible in an instructed centric relation position (21). Biting on the pads resulted in increased hydrostatic pressure, which was sampled at 1000 Hz and presented to the participants as numerical real-time feedback on a screen positioned at eye level 4·0 m in front of the subjects.

To investigate the effect of submaximum biting on postural sway and on coordination of body segments, valid and reliable tools for posturographic and kinematic analysis were used (24, 25).

Postural sway was quantified from COP time series collected by use of a force platform (AMTI, model BP600900*). The force platform was positioned in the floor and sampled at 1000 Hz.

Kinematics were recorded by means of a commercially available opto-electronic system (Vicon Motion Systems†). Opto-electronic motion capture systems as Vicon are considered as the gold standard for 3D motion analysis (24, 26–29). They principally use infrared cameras which track passive reflective markers attached to the subjects' skin. The 3D position of each marker over time is calculated with an accuracy better than 1·0 mm. Based on these data, mathematical human multibody models allow for the calculation of kinematic parameters. In the present study, 3D coordinates of the markers were collected by 13 infra-

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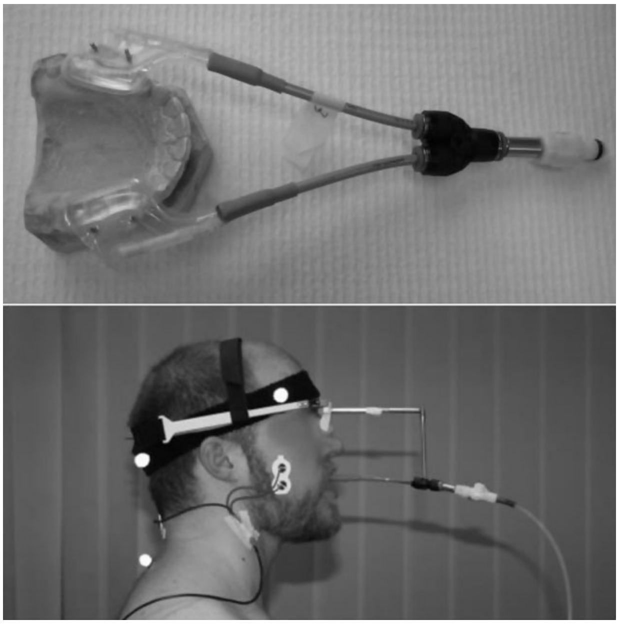

Fig. 1. Hydrostatic bite force measurement system: intra-oral device with liquid-filled pads (above) and its attachment to the head (below).

red cameras (Vicon MX camera system†; resolution: 1280 × 1024 pixels). Thirty-nine reflective markers (diameter 14 mm) were placed on anatomical landmarks of the participants, in accordance with the Vicon Plug-in Gait full-body marker set (30). Detailed information on the marker set can be found in Appendix S1. Kinematics were sampled at 200 Hz, simultaneously with the pressure and posturographic data.

Experimental procedure

All subjects warmed up on a treadmill for 5 min at 1·8 m s^{-1}. Before the experiments, subjects were given standardised verbal instructions about the *oral motor tasks* and the *bipedal and unipedal stances*.

Oral motor tasks. The subjects performed two types of oral motor task–force-controlled biting (FB) and non-biting (NB), which served as the control condition. Force-controlled biting was performed at submaximum bite forces of 150 N, in accordance with previous experiments (21), and corresponded to mean individual maximum voluntary contraction (MVC) of the M. masseter of 15·07% (s.d. 4·47%). Before biting on the pressure pads, the subjects were instructed to position the mandible in centric relation, initially guided by an experienced dentist. This position was stabilised by horizontal force components of the bite force, because the pads were fixed to the maxilla and the plane surfaces of the splints acted as a wedge under the applied bite forces, automatically constraining the mandible posteriorly. In addition to this mechanical consideration, a stable jaw position was confirmed, as in our previous study (21), by use of an ultrasonic 3D jaw motion analysis measurement system that recorded jaw position stability for several subjects during the biting experiments.

The oral device was also worn in NB. The subjects were, however, asked to keep their mandible in a resting position, that is consciously applying no bite force, and monitoring this condition by looking at the feedback screen. This control condition was chosen to avoid divergent cognitive demands between the two oral motor tasks, because it is known that secondary cognitive tasks can affect postural stability differently (31). Thus, if cognitive tasks do affect postural stability, and if oral motor tasks require cognitive attention, their effect in our study should be negligible.

Bipedal and unipedal stances. All participants performed both oral motor tasks during bipedal narrow stance and during unipedal stance on their dominant and non-dominant legs. These support conditions are frequently used as methods to determine postural differences in diverse research investigations (32–36).

In bipedal narrow stance, the subjects stood barefoot, on both feet, on the force platform, with the medial sides of the feet touching each other. In unipedal stance, the subjects were instructed to maintain posture without support from the elevated leg while standing barefoot on the force platform. The leg the subjects used to jump with and land on in single-leg jumps was regarded as dominant.

Irrespective of the support condition (bipedal, dominant, non-dominant), the subjects were instructed to maintain an upright position, with their arms hanging at their sides, and to stand as still as possible. They were asked to breathe normally, and to look straight ahead, focusing on the feedback screen. The antero-posterior (AP) position and mediolateral (ML) alignment of the supporting limb(s) were determined by use of marks on the platform. The elevation of the non-supporting leg in unipedal stance was intra-individually standardised by use of a laser pointer.

Experimental design. The order of the support conditions was assigned randomly to the subjects. Counterbalanced, half of the sample started balancing while applying the submaximum bite force, whereas the other group first performed balancing with the mandible at rest. Before changes of the support and biting conditions, the subjects were familiarised with the tasks. All the subjects then completed five valid trials for each of the six test conditions. A trial was considered valid when the intended bite force was maintained within ± 20% throughout the trial. Considering the effort of submaximum biting, recording time was predetermined as 10 s separated by 30-s intervals. Measurements were started when the intended bite force was reached.

Data analysis

For each testing condition all five trials were included in the evaluation. To analyse the effects of biting and support condition, data were processed by use of Vicon Nexus software[†], and different posturographic and kinematic variables were calculated.

Postural stability. The time series of the COP were filtered by use of a fourth-order Butterworth low-pass filter with a cut-off frequency of 10 Hz. The average AP and ML positions of the COP were determined relative to the centre of the base of support (BOS), calculated on the basis of the reflective markers placed on the subjects' feet. Postural stability was quantified on the basis of the COP displacements, as represented by the area of the 95% confidence ellipse (subsequently referred to as the 'sway area') and the COP path length, the latter in the AP and ML directions. The sway area is an indicator of the spatial variability of the COP (37), whereas the path lengths describe the direction and extent of postural sway (38). Use of these variables enables assessment of postural stability during unperturbed stance with high to excellent reliability (39–41).

In this study, intra-session reliability, estimated by use of intra-class correlation coefficients ($ICC_{3,1}$), ranged from 0·607 to 0·961 for the posturographic variables (Table 1), revealing reliability was good to excellent (42). The mean intra-individual variability – measured as the coefficient of variation [CV = (s.d./Mean) × 100] – was 38·50% for sway area, 14·82% for AP path length and 15·83% for ML path length.

Trunk and head kinematics. The three-dimensional coordinates of the reflective markers were processed by use of a generalised spline technique (43). On the basis of these data, kinematics were calculated for the pelvis (PELVIS), torso (TORSO) and head (HEAD) in the transverse plane. To this end, first the centres of PELVIS, TORSO, and HEAD were determined by

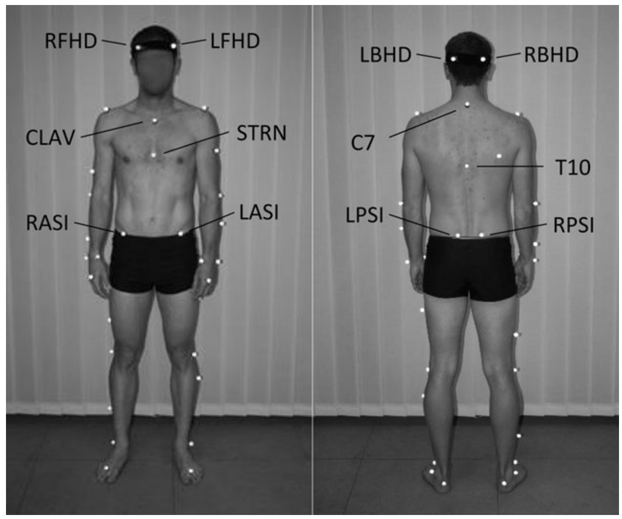

Fig. 2. Positioning of markers on the skin in accordance with the Vicon Plug-in Gait full-body marker set (30). RFHD, right front head; LFHD, left front head; LBHD, left back head; RBHD, right back head; CLAV, clavicle; STRN, sternum; C7, 7th cervical vertebrae; T10, 10th thoracic vertebrae; RASI, right anterior superior iliac spine; LASI, left anterior superior iliac spine; LPSI, left posterior superior iliac spine; RPSI, right posterior superior iliac spine.

Table 1. Intra-session reliability of posturographic and kinematic variables

Variable	COP	PELVIS	TORSO	HEAD
Sway area	0·607–0·945	0·723–0·865	0·747–0·875	0·753–0·876
AP path length	0·905–0·961	0·800–0·936	0·842–0·929	0·890–0·944
ML path length	0·749–0·946	0·880–0·992	0·884–0·988	0·884–0·986

AP, anteroposterior; ML, mediolateral.
Intra-session reliability for the different testing conditions as revealed by intra-class correlation coefficients ($ICC_{3,1}$).
Poor reliability: <0·4; fair reliability: 0·40–0·59; good reliability: 0·60–0·74; excellent reliability: >0·75 (42).

means of the reflective markers placed on the respective body segments – left and right anterior and posterior superior iliac spine (LASI, RASI, LPSI and RPSI) for PELVIS, clavicle (CLAV), sternum (STRN), 7th cervicle vertebrae (C7) and 10th thoracic vetebrae (T10) for TORSO, and left and right front and back head (LFHD, RFHD, LBHD and RBHD) for HEAD (Fig. 2). Finally, the sway area, sway path lengths in AP and ML directions, and the mean positions relative to the BOS were calculated for the above-mentioned body segments.

Intra-session reliability for the kinematic variables was good to excellent (Table 1). The mean intra-individual variability was 49·04 to 49·45%, 3·80 to 4·93%, and 8·32 to 9·11% for sway area, AP and ML path lengths, respectively.

Statistics

All statistical tests were performed by use of IBM SPSS Statistics 20.0‡. First, Kolmogorov–Smirnov, and Mauchly's tests were used to confirm the normality and sphericity, respectively, of the data distribution. Greenhouse–Geisser estimates were used to correct for violations of sphericity.

One-sample *t*-tests were then conducted to analyse discrepancies between requested and generated bite forces. Differences between the submaximum bite forces under the different support conditions were investigated by one-way repeated-measures ANOVA, adjusted by use of the Bonferroni correction for multiple comparisons.

The effects of oral motor tasks (FB, NB) and support conditions (bipedal, dominant, non-dominant) on postural sway and kinematics were analysed by two-way repeated-measures ANOVA. Follow-up Bonferroni corrections were used for multiple comparisons. The effects of support condition on relative ML positions of COP, PELVIS, TORSO and HEAD were only compared between dominant and non-dominant legs, however.

All data are reported as mean values ± 95% confidence intervals. Partial eta-squared (η_p^2) is indicated to give information about effect sizes. For large effects $\eta_p^2 = 0{\cdot}14$, for medium effects $\eta_p^2 = 0{\cdot}06$, and for small effects $\eta_p^2 = 0{\cdot}01$ (44). The level of significance for all statistical tests was *a priori* set to $P = 0{\cdot}05$.

‡International Business Machines Corp., Armonk, NY, USA.

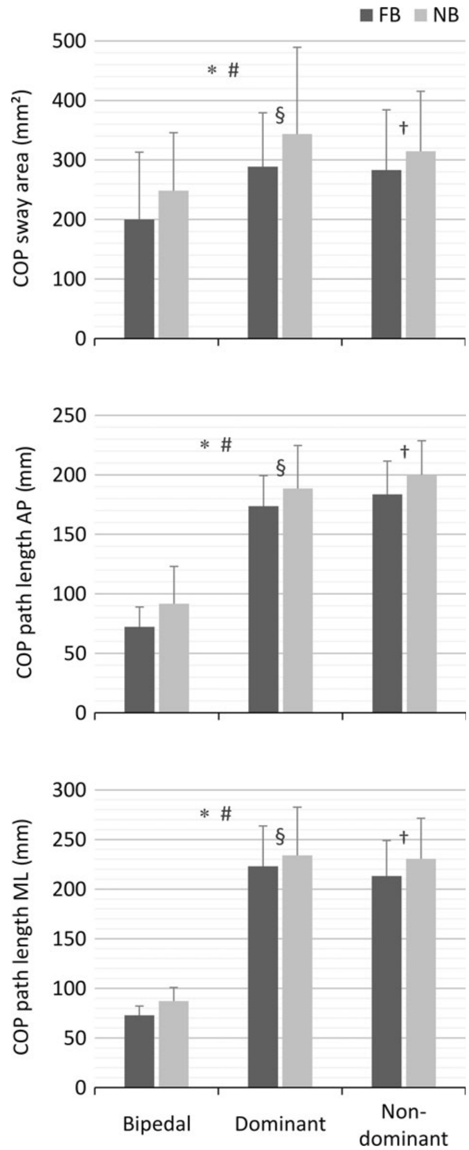

Fig. 3. COP sway area and COP path length in the anteroposterior and mediolateral directions for the different test conditions: force-controlled biting (FB) and non-biting (NB) in bipedal, unipedal dominant and unipedal non-dominant stances. All data are presented as mean values ± 95% confidence intervals. Two-way repeated-measures ANOVA ($P < 0{\cdot}05$): *significant main effect for oral motor task, #significant main effect for support condition, §significant difference between bipedal and unipedal dominant stance and †significant difference between bipedal and unipedal non-dominant stance.

Results

The submaximum bite force of 150 N, corresponding to 0·3 bar hydrostatic pressure within the pads, was maintained by the subjects throughout measurements

Table 2. *P*-values and effect sizes for posturographic variables

	Variable	Oral motor task		Support condition		Interaction	
		P	η_p^2	P	η_p^2	P	η_p^2
COP	Sway area	0·005*	0·53	0·001*	0·45	0·771	0·02
	AP path length	0·007*	0·50	<0·001*	0·82	0·922	0·01
	ML path length	0·030*	0·36	<0·001*	0·86	0·741	0·03

AP, anteroposterior; ML, mediolateral.
P-values and effect sizes (η_p^2) as revealed by two-way repeated-measures ANOVA ($P < 0{\cdot}05$).
*Statistically significant; small effect: $\eta_p^2 = 0{\cdot}01$; medium effect: $\eta_p^2 = 0{\cdot}06$; large effect: $\eta_p^2 = 0{\cdot}14$ (44).

in bipedal (0·303 ± 0·003 bar), unipedal dominant (0·302 ± 0·006 bar) and unipedal non-dominant (0·302 ± 0·004 bar) stance. Statistical tests revealed no significant differences either of the effectively generated bite forces from the intended bite force or among the applied bite forces under the three support conditions.

Postural stability

Figure 3 shows COP sway area and COP path lengths in AP and ML directions as functions of the variables under investigation. The *P*-values and effect sizes are listed in Table 2.

The statistical analysis revealed main effects of oral motor tasks for both COP sway area and COP path length in the AP and ML directions. Compared with standing with the mandible at rest, submaximum biting significantly reduced COP sway area. For COP path length in the AP and ML directions, ANOVA also revealed significantly greater stability during FB.

Significant main effects of the support conditions were found for COP sway area. Bonferroni adjustments revealed that the differences between bipedal stance and dominant leg ($P = 0{\cdot}017$) and between bipedal stance and non-dominant leg ($P = 0{\cdot}036$) were statistically significant, but those between dominant and non-dominant legs were not. Moreover, there were significant support effects for COP path length in AP and ML directions. In bipedal stance, the subjects swayed significantly less than on the dominant (AP: $P < 0{\cdot}001$; ML: $P < 0{\cdot}001$) and non-dominant (AP: $P < 0{\cdot}001$; ML: $P < 0{\cdot}001$) legs, but there were no significant differences between results for the dominant and non-dominant legs. Furthermore, there were no interactions between oral motor task and support condition for any posturographic variable.

Regarding the relative AP and ML positions, the COP was invariably located anterior and lateral to the centre of the BOS (Table 3). However, the locations were not significantly altered by oral motor tasks or support conditions. There were also no interaction effects.

Trunk and head kinematics

Table 4 shows all *P*-values and effect sizes for the kinematic variables.

Table 3. Relative AP and ML positions of the COP

	Support	AP position		ML position	
		FB	NB	FB	NB
COP	Bipedal	22·97 ± 10·17	21·14 ± 9·76	2·31 ± 3·17	3·53 ± 2·65
	Dominant	34·49 ± 6·80	31·04 ± 6·65	6·17 ± 1·97	6·65 ± 1·35
	Non-dominant	29·36 ± 9·08	30·56 ± 9·82	6·45 ± 3·09	6·20 ± 3·82

AP, anteroposterior; ML, mediolateral; FB, force-controlled biting; NB, non-biting.
Positions of the COP relative to the centre of the base of support. All data are presented as mean values ± 95% confidence intervals. Negative values indicate a posterior and right (bipedal) or medial (unipedal) location, respectively. Units are mm.
Two-way repeated-measures ANOVA ($P < 0{\cdot}05$): All comparisons were not statistically significant.

Table 4. *P*-values and effect sizes for kinematic variables

	Variable	Oral motor task		Support condition		Interaction	
		P	η_p^2	P	η_p^2	P	η_p^2
PELVIS	Sway area	0·210	0·14	0·034*	0·26	0·415	0·08
	AP path length	0·015*	0·43	0·390	0·08	0·173	0·15
	ML path length	0·024*	0·38	0·295	0·10	0·638	0·03
TORSO	Sway area	0·224	0·13	0·031*	0·32	0·371	0·08
	AP path length	0·009*	0·48	0·375	0·09	0·228	0·13
	ML path length	0·020*	0·40	0·257	0·12	0·406	0·07
HEAD	Sway area	0·256	0·12	0·032*	0·32	0·379	0·08
	AP path length	0·005*	0·53	0·634	0·04	0·179	0·15
	ML path length	0·017*	0·42	0·211	0·14	0·317	0·09

AP, anteroposterior; ML, mediolateral.
P-values and effect sizes (η_p^2) as revealed by two-way repeated-measures ANOVA ($P < 0{\cdot}05$).
*Statistically significant; small effect: $\eta_p^2 = 0{\cdot}01$; medium effect: $\eta_p^2 = 0{\cdot}06$; large effect: $\eta_p^2 = 0{\cdot}14$ (44).

For PELVIS (Fig. 4), FB had no statistically significant effect on sway area. In contrast, submaximum biting resulted in significant reductions of sway path length in AP and ML directions. Changing the support condition merely induced significant alteration of the sway area.

The submaximum biting task also resulted in significant sway alterations for TORSO (Fig. 4). Compared with NB, the AP and ML path lengths were significantly shortened during FB. However, FB did not influence the sway area. Apart from that, sway area was significantly affected by the support conditions.

For HEAD (Fig. 5), the AP and ML path lengths, again, were both indicative of improved stability during FB. With regard to the three support conditions, ANOVA only revealed statistically significant differences for sway area.

For all body segments and variables under investigation, no interaction effects were apparent.

The relative positions of PELVIS, TORSO and HEAD are shown in Table 5. Neither the AP nor ML positions of any of the body segments deviated significantly between oral motor tasks and support conditions. Apart from this, no significant interactions were observed for any body segment and kinematic variable.

Discussion

The purpose of our study was to investigate whether FB affects postural stability and the kinematics of the trunk and head during bipedal narrow stance and single-leg stance.

This study showed that biting at a submaximum force significantly altered postural stability in terms of reduced COP displacements. Both COP sway area and COP path length in AP and directions were significantly smaller than for NB. These sway reductions were independent of support condition, which was confirmed by the absence of any interaction effect. Force-controlled biting, moreover, significantly reduced trunk and head oscillations, as was apparent from reduced AP and ML path lengths of PELVIS, TORSO and HEAD. For both posturographic ($\eta_p^2 = 0{\cdot}36$–$0{\cdot}53$) and kinematic ($\eta_p^2 = 0{\cdot}12$–$0{\cdot}53$) data, biting predominantly had large effects, approximately as large as support effects. Hence, the effect of FB can be interpreted as substantial.

The observed significant sway reductions are in agreement with the findings of previous studies (20, 21, 45). The results, therefore, reveal that force-controlled oral motor activity not only alters postural stability during normal stance but also during more demanding tasks, for example single-leg stance. However, the effect of FB was not as high as in the study of Hellmann *et al.* (21). This could indicate that the effect of oral motor activity on postural stability is less pronounced during more demanding balancing tasks.

The relative positions of the COP, and of PELVIS, TORSO and HEAD, were not statistically different among the experimental conditions for either the AP or ML positions. Thus, we could not confirm the anterior shift of the COP found in a previous study (21).

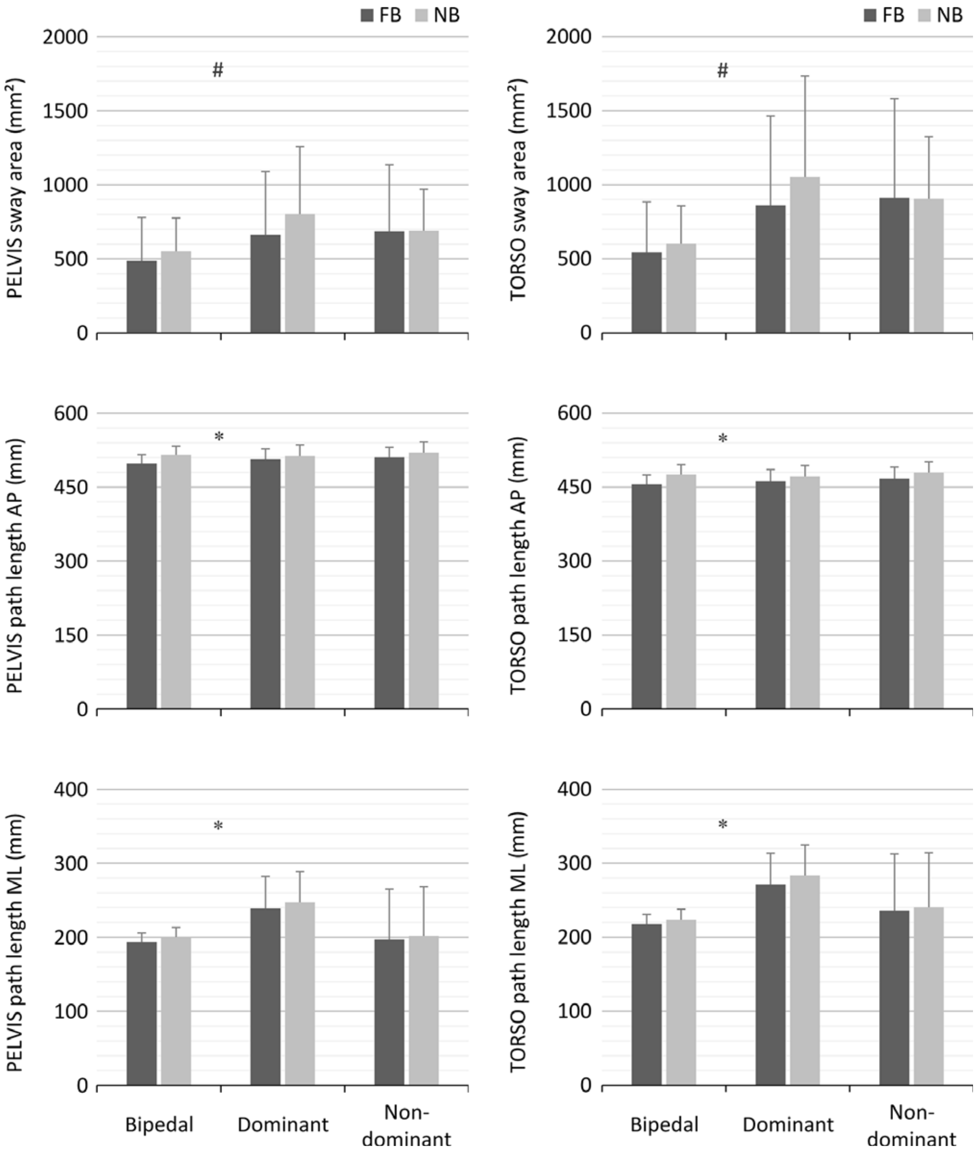

Fig. 4. Sway area and sway path lengths in the anteroposterior and mediolateral directions for PELVIS (left) and TORSO (right) as a function of the testing conditions: force-controlled biting (FB) and non-biting (NB) in bipedal, unipedal dominant and unipedal non-dominant stances. All data are presented as mean values ± 95% confidence intervals. Two-way repeated-measures ANOVA ($P < 0{\cdot}05$): *significant main effect for oral motor task, #significant main effect for support condition, §significant difference between bipedal and unipedal dominant stance and †significant difference between bipedal and unipedal non-dominant stance.

The hypothesised stiffening effects caused by changes of single myofascial chains under the effect of cranio-mandibular muscle activity (21, 22) do not, therefore, seem entirely convincing. Instead, the reduced COP displacements could be attributed to the facilitating effects of submaximum biting (11–13, 46), suggesting a neural coupling of the CMS to the postural control system.

Force-controlled biting also resulted in reduced path lengths of the body segments under investigation. Because of the systematic alterations of all the segments' path lengths, it could be concluded that increased postural stability during isometric masticatory activity might be caused by an improved 'ankle strategy', in which sway regulation closely resembles balancing a single-segment inverted-pendulum pivot-

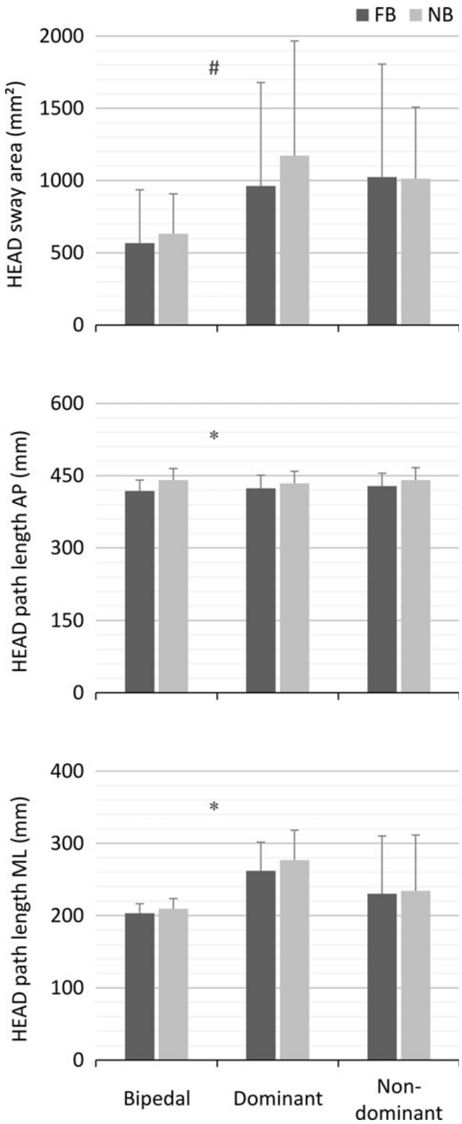

Fig. 5. Sway area and sway path lengths in the anteroposterior and mediolateral directions for HEAD as a function of the testing conditions: force-controlled biting (FB) and non-biting (NB) in bipedal, unipedal dominant and unipedal non-dominant stances. All data are presented as mean values ± 95% confidence intervals. Two-way repeated-measures ANOVA ($P < 0{\cdot}05$): *significant main effect for oral motor task, #significant main effect for support condition, §significant difference between bipedal and unipedal dominant stance and †significant difference between bipedal and unipedal non-dominant stance.

ing about the subtalar joint (46). Alternatively, the decrease in trunk and head oscillations could be attributed to generally increased muscle tone of the trunk, for example as a result of general changes of intermuscular coordination.

In addition to the effects of biting, significant differences between the support conditions were observed. As might be expected, COP displacements in unipedal stance were significantly larger than for standing on both legs. The increased COP sway area and COP path length in the ML direction are obviously attributable to the smaller BOS, especially because, during single-leg support, ML fluctuations cannot be controlled by load–unload mechanisms. Instead, two inverted-pendulum systems are present in the frontal plane when the body is in single-leg support (47). First, the total body pivots about the supporting subtalar joint; second, the upper body pivots about the hip joint (46). Although the larger COP sway area and ML path length seem consistent, narrowing of the BOS in the frontal plane also increased the COP path length in the sagittal plane. With regard to the findings of Gribble and Hertel (35, 48) and Miller and Bird (49), one explanation could be that in bipedal stance, the more subtle plantar flexors and dorsiflexors of the ankle control posture, whereas in single-leg stance, AP neuromuscular control is primarily based on gross movement of the hip. Apart from that, none of the variables was significantly different for the dominant and non-dominant legs, which is in accordance with latest reports (50).

One limitation of our study that should be considered is the short-term exposure of 10 s, which can neither simulate long-lasting effects of biting nor fulfil recommendations for posturographic assessments (≥25 s) (51). The duration of measurement was restricted by the effort of the isometric masticatory contractions, however. Notwithstanding this, Parreira *et al.* (51) recently pointed out that durations ≥ 10 s are sufficient to enable differences between postural control to be distinguished. Another limitation might be the lack of active controls, such as those used by Miyahara *et al.* (11). These authors showed that both voluntary clenching of the teeth and contraction of upper limb muscles increased the amplitude of the soleus H reflex, with increases during teeth clenching being greater than those induced by contraction of upper limb muscles (11). We suggest, therefore, that similar or smaller effects would have been observed among active controls. Further studies in which the stabilising effects of FB are compared with submaximum clenching of the fists should, nevertheless, be conducted.

As the main result of our study, it may be emphasised that FB significantly reduced postural sway in unipedal and bipedal narrow stance. This not only dis-

Table 5. Relative AP and ML positions of PELVIS, TORSO and HEAD

		AP position		ML position	
	Support	FB	NB	FB	NB
PELVIS	Bipedal	−53·87 ± 15·36	−58·17 ± 14·04	11·72 ± 8·27	11·12 ± 7·64
	Dominant	−41·71 ± 15·71	−46·18 ± 14·33	49·25 ± 23·39	50·02 ± 24·74
	Non-dominant	−46·35 ± 20·57	−45·30 ± 21·05	55·35 ± 25·09	56·62 ± 25·05
TORSO	Bipedal	−6·98 ± 17·08	−12·38 ± 15·56	−10·75 ± 8·59	−10·35 ± 7·17
	Dominant	9·91 ± 17·33	4·37 ± 14·72	56·34 ± 27·73	57·25 ± 28·27
	Non-dominant	3·25 ± 21·67	3·62 ± 21·91	48·31 ± 23·66	50·43 ± 24·84
HEAD	Bipedal	22·71 ± 35·52	25·80 ± 17·84	5·03 ± 8·76	5·63 ± 7·37
	Dominant	52·73 ± 20·10	46·62 ± 16·72	48·42 ± 25·36	49·34 ± 26·47
	Non-dominant	46·36 ± 23·71	46·59 ± 23·99	52·95 ± 23·26	55·43 ± 23·63

AP, anteroposterior; ML, mediolateral; FB, force-controlled biting; NB, non-biting.
Positions of PELVIS, TORSO and HEAD relative to the centre of the base of support. All data are presented as mean values ± 95% confidence intervals. Negative values indicate a posterior and right (bipedal) or medial (unipedal) location, respectively. Units are mm. Two-way repeated-measures ANOVA ($P < 0{\cdot}05$): All comparisons were not statistically significant.

plays the stabilising effect of oral motor tasks under more complex conditions but also provides additional evidence of the functional coupling of the CMS and human posture. The question of whether the coupling is mechanical or neural remains unanswered, however (52). The present study also showed, for the first time, that the sway reductions of the COP during FB were accompanied by reduced trunk and head oscillations, which might be attributable to enhanced trunk stiffness. The results imply that FB induced coactivation of the trunk muscles. This, in turn, might have contributed to improved postural stability.

Finally, it should be mentioned that all these effects were measured in healthy subjects, so even if there is evidence of comorbidity of masticatory, neck and lower-back-muscle pain (53–56), no conclusions about pathophysiological interactions can be drawn on the basis of these findings (21, 52). These physiological responses to isometric activation of the masticatory muscles suggest, nevertheless, that oral motor activity could be a strategy for the elderly or for patients with compromised postural control, for example to reduce the risk of falls.

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Conflicts of interest

We confirm that the authors of this article have no conflicts of interest.

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Supporting Information

Additional Supporting Information may be found in the online version of this article:

Appendix S1. The table lists the thirty-nine markers, which were placed on the skin to the participants in accordance with the Vicon Plug-in Gait full body marker set (30).