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The effect of various jaw motor tasks on body sway

D. HELLMANN*, N. N. GIANNAKOPOULOS*, R. BLASER*, L. EBERHARD* & H. J. SCHINDLER*† *Department of Prosthodontics, Dental School, University of Heidelberg, Heidelberg and †Research Group Biomechanics, Institute for Mechanics, Karlsruhe Institute of Technology (KIT), Karlsruhe, Germany

SUMMARY **Alterations of body sway caused by isometric contractions of the jaw muscles have been reported previously. The objective of this study was to test if motor tasks of the masticatory system with different control demands affect body posture differently during quiet stance. Position and sway displacements of the center of foot pressure (COP) were measured for 20 healthy subjects who either kept the mandible at rest or performed unilateral and bilateral maximum voluntary teeth clenching, feedback-controlled biting tasks at submaximum bite forces, or unilateral chewing. Two weeks later the measurements were repeated. Compared with quiet stance, the COP results revealed significant changes during the feedback-controlled biting tasks. Robust sway reduction and anterior displacement of the COP were observed under these conditions. Body oscillations were not significantly affected by maximum bites or by unilateral chewing. For most of the variables investigated there were no significant differences between unilateral and bilateral biting. Robust sway reduction during feedback-controlled biting tasks in healthy subjects involved a stiffening phenomenon that was attributed to the common physiological repertoire of posture control, and might optimize the stability of posture under these conditions.**

KEYWORDS: **posturography, body sway, centre of foot pressure, jaw motor tasks, jaw clenching**

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Introduction

Bipedal stance is controlled by somatosensory, visual and vestibular systems that are centrally integrated and involve complex interactions among the multiple neural and motor systems (1). In contrast with mechanical static equilibrium, biological static equilibrium is characterized by inherent instability known as body sway. Corrective muscle action must be taken to counter periodic destabilizing oscillations because of gravity. This process of sway regulation, approximately comparable with the balancing of an oscillating inverse pendulum (2), is not fully understood, but it seems that feedback control mechanisms contribute predominantly to the control of body sway (3). It is also known that neck and trunk muscles co-contract with masticatory muscles during clenching (4). This is evidence of the functional integration of the craniocervical region (comparable with the mass of an inverse pendulum) into the neuromuscular system of the body. It also supports the concept that during static and dynamic motor tasks, all subsystems have to be coordinated to enable balanced and stable motor behaviour.

Numerous study results have demonstrated that quiet stance can be perturbed by the stimulation of the various sensory systems (5–7). It has also been reported that, for instance, slight touching of a stable object with a single finger (under force-controlled conditions) had an attenuating effect on body sway (8–10). Previous studies of the effect of isometric masticatory muscle contraction on the balancing behaviour of the body (11, 12) revealed that jaw clenching had a large effect on motor function, i.e. it was contributing to the enhancement of posture stability, perhaps by facilitating reflexes (13–15). A stabilizing effect of occlusal splints has been reported to improve the performance of professional marksmen (11). In this context, it has also been shown that

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clenching of the jaw in different positions reduced body sway differently (16–18). These results are neuroanatomically supported by findings in animal models that confirmed neuronal links of the trigeminal nerve to numerous brainstem nuclei and all levels of the spinal cord (19, 20).

Distinct motor actions of the jaw are indicative of different strategies of central motor control. Maximum voluntary bites, for instance, are characterized by control mechanisms which are probably not essentially affected by variable co-activation strategies, because all the closing muscles involved are activated at their maximum psychophysiological capacity (21). Chewing cycles involve well-trained muscle performance that is, essentially, semiautomatic motor behaviour (22). Unfamiliar tasks, in contrast, provoke the motor control system to establish (from theoretically redundant possibilities) the best fitting co-activation of the involved muscle groups, which have to be adapted sequentially, as is known for novel motor tasks (23).

There are no results from testing of whether oral motor tasks with different control strategies have different effects on the balancing behaviour of the body during quiet stance. The objective of this study was, therefore, to test the hypothesis in healthy subjects (with the aid of quantitative posturography) that maximum voluntary biting, feedback-controlled biting tasks at submaximum forces and unilateral chewing affect body sway in different ways during quiet stance.

Material and methods

Subjects

Twenty healthy subjects, 10 women and 10 men (average age: 24 ± 2 years), were enrolled in the experiments. All subjects had normal weight and a body mass index in the range 18·5–24·9. Exclusion criteria were painful temporomandibular disorders assessed by the RDC/TMD criteria (24) or the need for orthopaedic treatment of painful musculoskeletal disorders in other body regions. The study was approved by the Ethics Committee of the University Medical Center, Heidelberg (no. S-213/2008). All subjects gave their written consent to the experiments, which were conducted in accordance with the Declaration of Helsinki.

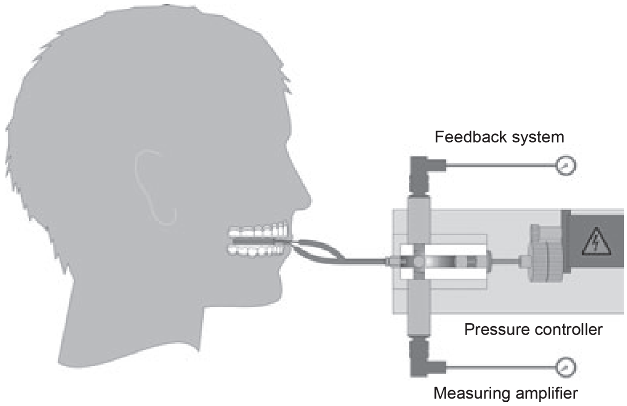

Fig. 1. Schematic representation of the pressure measurement system.

Sway and intra-oral force measurement

Body sway was measured by using a commercially available posturographic platform*, equipped with 2650 pressure sensors to identify the centre of foot pressure (COP). Software provided with the equipment* calculated various results from the raw data delivered by the platform. The data were sampled at 100 Hz.

Force-controlled biting tasks were measured by the use of a recently developed hydrostatic system (Fig. 1) consisting of liquid-filled pads (components of a commercially available intra-oral hydrostatic device†) that were placed unilaterally or bilaterally between the rows of teeth in the premolar to molar regions. Bite forces on the pads result in increased hydrostatic pressure within the liquid. This increase in hydrostatic pressure corresponds directly to the amount of total force exerted on the pads. Because the bilaterally positioned pads were connected, force differences between the left and right sides lead to vertical height differences between the pads. Unilaterally or bilaterally placed pads provoke the neuromuscular system to exert demanding coordination tasks to balance the mandible. Pressure was measured by the use of specific sensors integrated within the hydrostatic system, which also actuated a feedback monitor with a numerical display. The pads of the hydrostatic system were paraocclusally fixed by metal pins to a maxillary plastic splint with a plane occlusal surface. Correspondingly, the mandible was also covered by a planar splint (Fig. 2). Jaw separation

*Zebris FDM-S, Isny, Germany.
†Aqualizer®; Bausch KG, Köln, Germany.

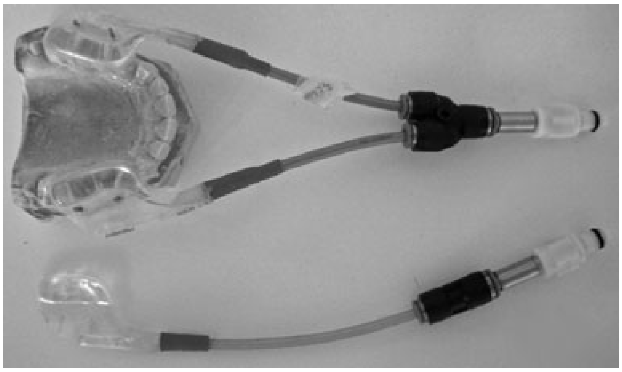

Fig. 2. Intra-oral device used for hydrostatic measurement. Pressure-sensitive pads for unilateral and bilateral biting, with connectors. Bilateral configuration mounted on the plane plastic splint.

ranged from 4 to 6 mm in the molar region. The pressure values were documented at a sampling rate of 1000 Hz, simultaneously with the platform data. Before the experiments, the pressure–force relationship was calibrated.

Experimental procedure

The subjects stood barefoot on the posturographic platform in upright stance. The positions of the feet were determined by the use of paper templates of the individual footprints. The distance between the anterior iliac spines was used as a measure of the separation of the outer edges of the feet.

The subjects were instructed to remain in a habitual quiet stance, with their arms relaxed at their sides, and to gaze straight ahead at the feedback monitor, 100 cm away, at eye level. In this posture, with the mandible at rest, six five-second recordings separated by ten-second intervals were made; these were used to calculate a reference mean for quite stance.

Subsequently, the subjects performed three types of motor task – maximum biting, force-controlled biting tasks at submaximum bite forces and unilateral chewing – in a predetermined sequence. Maximum voluntary jaw-clenching tasks were executed in intercuspation (IC) and on cotton rolls that were placed bilaterally or unilaterally (UCR; right side) between the posterior teeth. Force-controlled tasks were performed unilaterally (right side) and bilaterally at bite forces of 50, 100, 200 and 300 N (in the following text, these are denoted u50 to u300 for unilateral biting and b50 to b300 for bilateral biting). The subjects were instructed to position the mandible in centric relation before biting on the pressure pads. Because the pads were fixed to the maxilla and because of the plane surfaces of the splints, the position of the mandible was automatically stabilized in the posterior position by horizontal force components of the bite force. Under the applied bite force, the pads behaved like a wedge. Because of the maxillary fixing, the pads could not be displaced anteriorly, as one would expect, but the mandible was moved in the posterior direction. In addition to this mechanical consideration, a stable jaw position (in a range 0·1–0·3 mm) was confirmed by measurements with an ultrasonic 3D jaw-motion-analysis system[‡] that recorded jaw position stability in several subjects during the biting experiments. When the test person reached the intended force, measurements were started. The static experiments took 5 s each. Unilateral chewing (15 chewing cycles) was performed with standardized silicone rubber cubes (25). A single bolus consisted of 17 cubes with 5·6 mm edge length. All motor tasks were repeated three times. The subjects were instructed not to halt respiration during the motor task, but to breathe normally. The experiments were repeated 2 weeks later.

Data analysis

Body oscillations were evaluated from the sway readings of the COP as represented by the radii and area of the 95% confidence ellipse. The average position of the COP was determined within a plane Cartesian coordinate system centred midline between the footprints and the anterior edge of the hind foot (Fig. 3). Accordingly, anteroposterior deviations of the COP are represented on the y-coordinate (negative values imply a posterior position of the COP) and right or left deviations on the x-coordinate (negative values imply a left location of the COP). The variables evaluated were reported as mean values (mean), standard deviations (SDs) and box plots. Intra-individual scatter of bite force and COP variables for the task replicates were clarified by the use of coefficients of variation (CV). Differences between the sway oscillations and COP position at rest and under the various motor tasks were compared by one-way repeated-measures (RM) analysis of variance (ANOVA). Differences between the two experimental

[‡]Zebris WinJaw, Isny, Germany.

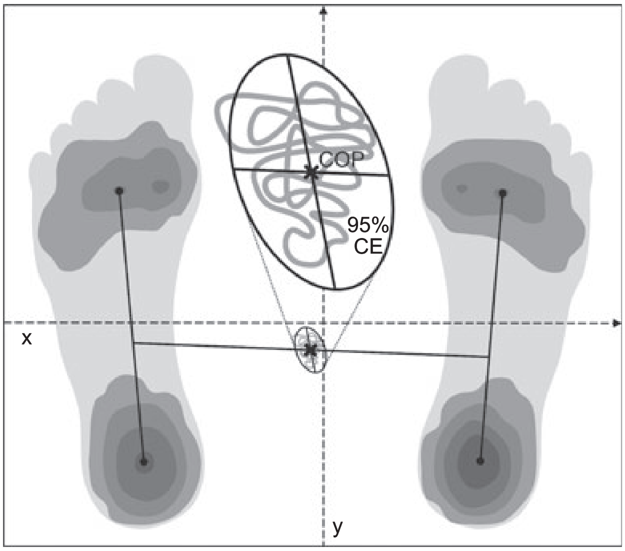

Fig. 3. Illustration of the variables evaluated: COP = centre of foot pressure; x/y = coordinates of the reference system for the COP x- and y-deviations; 95% CE = 95% confidence ellipse (enlarged) with semi-minor and semi-major axes.

sessions, unilateral and bilateral feedback-controlled biting tasks and sex differences were investigated by two-way RM ANOVA. The significance level was set at $P < 0{\cdot}05$ for all analyses. *Post hoc* Tukey tests were used for further analysis of differences.

Results

Table 1 shows the mean and SD of test and retest data for all the variables investigated. There were no significant differences between results from the various maximum bites, from the unilateral biting tasks or from the two experimental sessions. Likewise, no sex differences were observed. Therefore, it seemed justified to pool the data for graphical presentation in five groups, i.e. rest, maximum biting, unilateral submaximum biting, bilateral submaximum biting and chewing.

The mean intra-individual variability (CV) of the three measurement replicates, averaged over all the motor tasks, was 41 ± 15% for the variables of the 95% confidence ellipse, followed by 25 ± 12% for the x–y deviations of the COP. The mean variation of the measured force from the target force was approximately 3·5%. Figures 4 and 5 show box plots of the sway data and the COP deviations during the various motor tasks.

In comparison with quiet stance with the mandible at rest, all the submaximum biting tasks resulted in robust and significant ($P < 0{\cdot}001$) reductions in body sway for all the variables (the semi-axes and area of the 95% confidence ellipse).

The y-position of the COP deviated significantly ($P < 0{\cdot}05$) in the anterior direction for the entire unilateral submaximum biting tasks, in contrast with the x-position of the COP, for which there was no significant deviation from quiet stance.

Maximum biting resulted in no significant sway alterations or deviations for either the y-position or the x-position of the COP.

For the unilateral submaximum biting tasks, there were no significant x-deviations of the COP, but the y-position deviated significantly ($P < 0{\cdot}05$) in the anterior direction.

Apart from this significant y-deviation of the COP in the unilateral submaximum tasks, there were no significant differences between the unilateral and bilateral tasks for any of the variables investigated.

Chewing had no significant effect on sway and COP variables.

Discussion

This study showed, for the first time, that oral motor tasks with different control strategies, i.e. maximum biting, submaximum biting and chewing, affect body sway differently. The most interesting result was robust and significant sway reduction during force-controlled biting. In contrast, the maximum biting and chewing experiments caused no significant alteration in body oscillation.

The intra-individual CV and the inter-individual SD, in particular for the COP measurements, were indicative of relatively high variability of the results obtained. In this context, it has been shown that several variables, e.g. body height, age, cognitive indicators and physical health condition, can substantially affect sway behaviour (26–29). On the basis of these findings, it may be inferred that for samples other than that investigated, mean and variance of measurements could change substantially. Therefore, in respect of the above-mentioned variables, the results of this study may not be used as reference values for samples that differ from that investigated (30).

The hydrostatic pressure system was developed as a feasible means of provoking the motor system to balance the mandible at a given bite force in static equilibrium by varying the bilateral forces and

Table 1. Body sway and COP position changes for test and retest as a result of various jaw motor tasks during quiet stance

		Maximum biting				Submaximum biting								
Test		*R*	IC	UCR	BCR	u50	u100	u200	u300	b50	b100	b200	b300	C
	Radius x					•	•	•	•	•	•	•	•	
1	Mean	3·39	2·72	2·60	2·43	1·71	1·86	1·34	1·27	1·60	1·41	1·28	1·28	4·11
	SD	0·97	1·37	1·46	1·22	0·79	0·96	0·60	0·50	0·54	0·61	0·57	0·53	1·44
						•	•	•	•	•	•	•	•	
2	Mean	3·50	2·82	2·25	2·54	1·38	1·44	1·41	1·27	1·59	1·41	1·40	1·22	3·78
	SD	0·87	1·13	1·22	1·34	0·50	0·48	0·52	0·31	0·60	0·56	0·64	0·41	0·96
	Radius y					•	•	•	•	•	•	•	•	
1	Mean	7·24	6·22	6·64	5·29	4·29	4·63	4·13	3·87	3·87	3·57	3·73	3·52	7·87
	SD	2·30	2·66	2·91	2·10	1·08	1·50	1·87	1·04	1·33	0·99	1·27	0·76	2·65
						•	•	•	•	•	•	•	•	
2	Mean	6·95	7·02	6·16	6·50	3·70	3·68	3·79	3·24	3·59	3·50	3·86	3·59	7·88
	SD	1·92	3·02	3·42	3·33	1·61	0·93	1·16	0·93	1·77	1·32	1·87	1·77	2·20
	Area					•	•	•	•	•	•	•	•	
1	Mean	20·70	16·35	15·98	12·52	6·66	7·92	5·28	4·05	5·37	4·42	4·15	3·79	27·82
	SD	8·99	13·76	16·32	11·64	4·71	6·96	4·62	2·00	3·24	2·30	3·09	2·02	17·13
						•	•	•	•	•	•	•	•	
2	Mean	21·43	18·06	13·86	16·01	4·67	4·79	4·68	3·46	5·06	4·56	4·97	3·89	26·23
	SD	10·60	14·82	13·17	16·20	3·73	2·59	2·94	1·70	3·98	3·41	4·63	3·09	12·13
	COP y					•	•	•	•					
1	Mean	8·88	10·86	12·57	12·45	14·88	15·59	16·29	15·88	14·52	11·33	12·48	12·31	6·45
	SD	13·33	13·78	13·10	13·97	15·33	16·96	17·49	18·79	13·76	15·33	16·86	17·08	12·48
						•	•	•	•					
2	Mean	7·24	8·24	9·33	9·13	10·82	12·15	12·80	12·47	8·35	8·94	8·96	9·16	5·45
	SD	11·80	12·67	13·78	13·36	16·09	16·72	17·01	17·51	15·17	15·25	14·77	13·79	11·04
	COP x													
1	Mean	−4·02	−1·97	−2·59	−3·43	−2·84	−3·33	−3·60	−2·93	−0·86	−3·38	−3·24	−3·98	−4·21
	SD	6·99	6·50	6·95	8·07	7·93	7·66	7·49	7·93	11·45	8·37	8·18	8·43	10·12
2	Mean	−3·98	−3·97	−4·01	−4·35	−5·03	−5·35	−5·66	−5·91	−4·78	−4·59	−5·07	−4·84	−7·03
	SD	7·88	8·01	7·34	7·89	8·58	8·71	9·37	9·27	6·14	8·02	6·78	6·22	7·71

Units for the semi-axes and the centre of foot pressure (COP) positions are mm; for area mm^2 are the units used.
Test 1, test; Test 2, retest; SD, standard deviation; R, jaw at rest position; IC, intercuspation; UCR, unilateral biting on cotton rolls; BCR, bilateral biting on cotton rolls; u50 to u300, unilateral biting with 50 N to 300 N; b50 to b300, bilateral biting with 50 N to 300 N; C, chewing; radii x/y, area/dimensions of the confidence ellipse; COP x/y, deviations in anteroposterior and left/right direction; filled circles indicate significant differences compared with *R*.

interocclusal distances. This balancing behaviour differs from experiments with rigid force transducers, which permit unequal force distribution between the left and right sides of the jaw without bilateral variation of interocclusal height. Taking this into account, the hydrostatic pressure system seems to force the motor system to perfom more demanding muscular coordination than under conditions with rigid intra-oral force transducers. This challenging balancing task might have triggered robust stiffening of the body, possibly caused by the modification of fusimotor drive and corresponding enhanced muscle tone (31). In alert experimental animals, comparable effects can be observed when novel motor tasks are executed (32). The physiological rationale might be a shortening of reflex responses if sudden corrections of the intended motor tasks are needed.

Our results from force-controlled biting tasks are not in agreement with those from a previous uncontrolled study (11) in which significant sway reductions were observed, depending on the position of the mandible modified by occlusal splints. The centric relation position resulted in the largest sway reduction under these experimental conditions. The authors concluded that the centric relation was the jaw position with the most symmetric neuromuscular equilibrium.

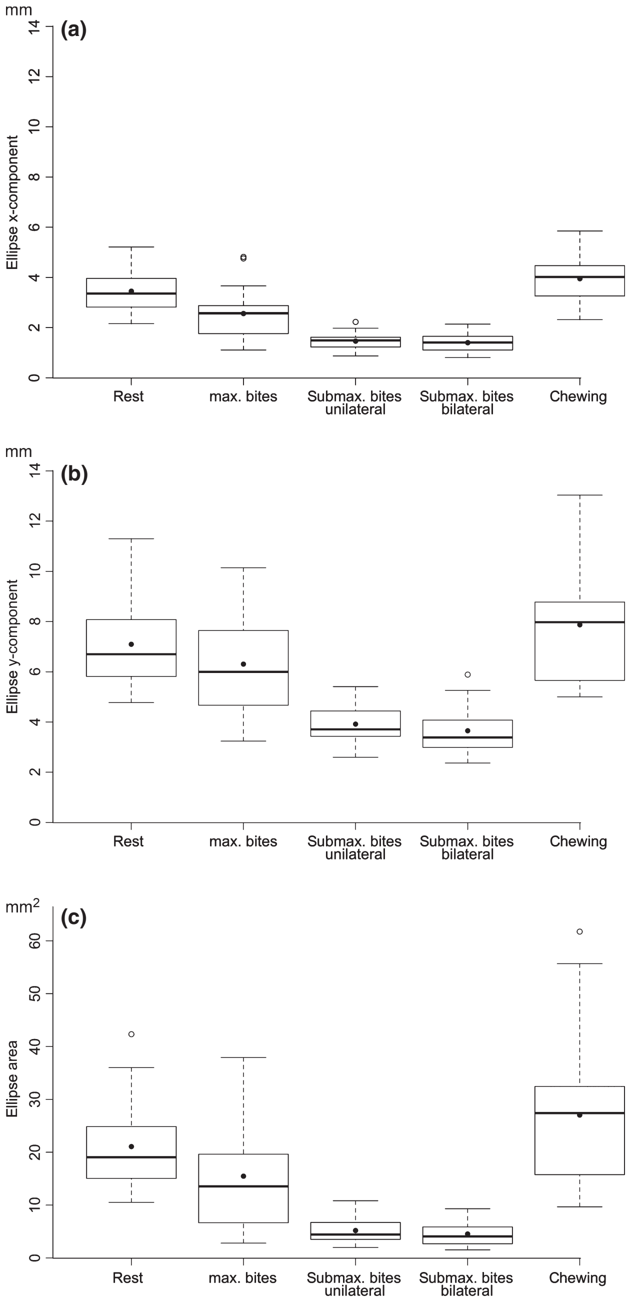

Fig. 4. Box plots of the sway variables for the different motor tasks: (a) x-components, (b) y-components and (c) area of the confidence ellipse; max. bites = pooled data for unilateral and bilateral maximum bites; submax. bites unilateral = pooled data for all unilateral submaximum bites (u50 to u300); submax. bites bilateral = pooled data for submaximum bilateral bites (b50 to b300). Filled circles represent the mean.

Concerning our results for the controlled bite tasks, however, for which sway reductions in this context were by far the largest, it seems not to be justified to qualify specific jaw relationships on the basis of reduced

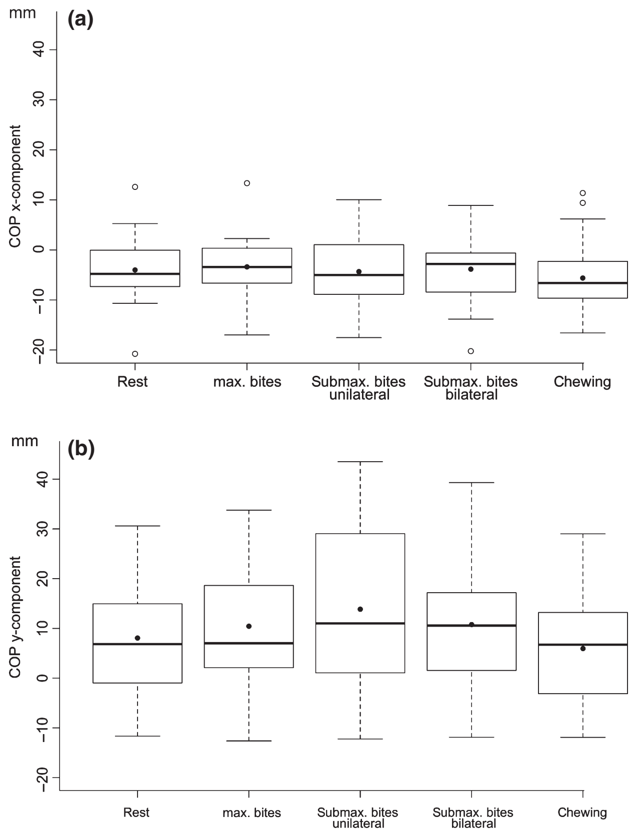

Fig. 5. Box plots of the centre of foot pressure (COP) results for the different motor tasks: (a) COP y-position, (b) COP x-position; max. bites = pooled data for unilateral and bilateral maximum bites; submax. bites unilateral = pooled data for all unilateral submaximum bites (u50 to u300); submax. bites bilateral = pooled data for submaximum bilateral bites (b50 to b300).

body oscillation. The sway reduction is, obviously, a motor reaction that is largely independent of symmetric jaw muscle activation. Also, the finding that the COP of the x-position is not essentially affected by unilateral biting, in contrast with the quiet stance or bilateral tasks, also confirms the assumption that asymmetric loading of the masticatory system does not significantly affect left/right symmetry in upright posture.

The fact that chewing movements under standardized conditions had no essential effect on body sway might be explained by the basically automatic character of this motor action. In contrast with maximum biting and the submaximum tasks, stereotypical neuromuscular activity lacks the psychophysical components that affect motor actions as a result of, for instance, attention, anticipation and/or cognitive stress (33, 34). Furthermore, our findings confirm the above-stated conclusion that posture is not essentially altered under asymmetric loading, because unilateral chewing is a physiologically induced forceful asymmetric motor task. It might be argued that the short time of exposure to the static motor tasks may have masked motor reactions that would have become apparent during longer-lasting motor provocation. This possibility cannot be completely excluded, but in the context of the experimental design, muscle fatigue had to be avoided with the prerequisite of equal exposure times. In the pilot phase of the study, however, experiments with longer-lasting intervals of up to 20 s for quiet stance with the jaw in the resting position or during submaximum biting were performed; results did not deviate essentially from those obtained by use of shorter times.

During the unilateral submaximum biting tasks, the COP y-position deviated significantly in the anterior direction. Previous studies have consistently shown that unilateral chewing and jaw opening induce head extensions (35–37), presumably caused by the sternocleidomastoid and trapezius muscles that co-contract with jaw muscles during biting and chewing (4, 38, 39). The power stroke of a chewing cycle may be roughly compared with the unilateral submaximum biting tasks of this study. Therefore, perturbations as a result of slight head extension could have essentially reduced postural stability in the anteroposterior direction (40). The anterior shift of the COP might, in turn, be a posture-stabilizing response counteracting these perturbations. An appropriate reaction of the motor system to regain stability might be the enhancement of the tone of the anterior muscle chains, which may enforce the safety tolerance against backwards falling, the most crucial direction during a fall caused by external perturbations. This strategy would be in line with the above-mentioned motor reactions on novel motor tasks. It might, furthermore, also explain the left/right COP invariance during all motor tasks, which biomechanically supports the stability of stance under such conditions.

One limitation of the study that must be considered is that all the experiments performed involved short-term exposure of the motor system, which cannot simulate long-lasting effects of permanent functional changes in the masticatory system. It can, however, elucidate the potential of the oral motor system to affect motor control of the body during stance. It might be of future interest to investigate the effects of feedback-controlled oral balancing tasks in patients with increased body sway under static and dynamic experimental conditions.

Nevertheless, the robust sway reduction during balancing tasks in healthy subjects suggests that this stiffening phenomenon is part of the common physiological repertoire of posture control. It might be a strategy to shorten reflex responses to optimize the stability of posture under these conditions.

As one clinical implication of our findings, it may be concluded that with regard to jaw relationships or pathophysiological states of the masticatory system, the use of static posturography as a valuable tool to support diagnostic or therapeutic decisions is not supported by our results. In contrast, the results imply that novel or unfamiliar motor tasks, and possibly any changes in jaw position, might have the capacity to affect body sway in healthy subjects if the jaw motor system is isometrically activated under such conditions. Further studies must be conducted to elucidate whether these responses differ between healthy subjects and, for instance, patients with craniomandibular disorder. Currently, it seems premature to apply posturography in clinical dentistry.

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References

1. Horak PB, MacPherson JM. Postural orientation and equilibrium. In: Shepard J, Rowell L, eds. Handbook of physiolgy, section 12, exercise: regulation and integration of multiple systems. New York: Oxford University Press, 1996:255–292.
2. Loram ID, Lakie M. Human balancing of an inverted pendulum: position control by small, ballistic-like, throw and catch movements. J Physiol. 2002;540:1111–1124.
3. Peterka RJ, Loughlin PJ. Dynamic regulation of sensorimotor integration in human postural control. J Neurophysiol. 2004;91:410–423.
4. Ehrlich R, Garlick D, Ninio M. The effect of jaw clenching on the electromyographic activities of 2 neck and 2 trunk muscles. J Orofac Pain. 1999;13:115–120.
5. Day BL, Severac Cauquil A, Bartolomei L, Pastor MA, Lyon IN. Human body-segment tilts induced by galvanic stimulation: a vestibularly driven balance protection mechanism. J Physiol. 1997;500(Pt 3):661–672.
6. Johansson R, Magnusson M. Human postural dynamics. Crit Rev Biomed Eng. 1991;18:413–437.
7. Kavounoudias A, Gilhodes JC, Roll R, Roll JP. From balance regulation to body orientation: two goals for muscle proprioceptive information processing? Exp Brain Res. 1999;124: 80–88.

8. Holden M, Ventura J, Lackner JR. Stabilization of posture by precision contact of the index finger. J Vestib Res. 1994;4:285–301.
9. Clapp S, Wing AM. Light touch contribution to balance in normal bipedal stance. Exp Brain Res. 1999;125:521–524.
10. Riley M, Stoffregen TA, Grocki MJ, Turvey MT. Postural stabilization for the control of touching. Hum Mov Sci. 1999;18:795–817.
11. Gangloff P, Louis JP, Perrin PP. Dental occlusion modifies gaze and posture stabilization in human subjects. Neurosci Lett. 2000;293:203–206.
12. Sforza C, Tartaglia GM, Solimene U, Morgun V, Kaspranskiy RR, Ferrario VF. Occlusion, sternocleidomastoid muscle activity, and body sway: a pilot study in male astronauts. Cranio. 2006;24:43–49.
13. Miyahara T. Modulation of soleus H-reflex by teeth clenching. Kokubyo Gakkai Zasshi. 1991;58:670–686.
14. Miyahara T, Hagiya N, Ohyama T, Nakamura Y. Modulation of human soleus H reflex in association with voluntary clenching of the teeth. J Neurophysiol. 1996;76:2033–2041.
15. Takada Y, Miyahara T, Tanaka T, Ohyama T, Nakamura Y. Modulation of H reflex of pretibial muscles and reciprocal Ia inhibition of soleus muscle during voluntary teeth clenching in humans. J Neurophysiol. 2000;83:2063–2070.
16. Bracco P, Deregibus A, Piscetta R. Effects of different jaw relations on postural stability in human subjects. Neurosci Lett. 2004;356:228–230.
17. Sakaguchi K, Mehta NR, Abdallah EF, Forgione AG, Hirayama H, Kawasaki T *et al.* Examination of the relationship between mandibular position and body posture. Cranio. 2007;25:237–249.
18. Bracco P, Deregibus A, Piscetta R, Ferrario G. Observations on the correlation between posture and jaw position: a pilot study. Cranio. 1998;16:252–258.
19. Ruggiero DA, Ross CA, Reis DJ. Projections from the spinal trigeminal nucleus to the entire length of the spinal cord in the rat. Brain Res. 1981;225:225–233.
20. Devoize L, Domejean S, Melin C, Raboisson P, Artola A, Dallel R. Organization of projections from the spinal trigeminal subnucleus oralis to the spinal cord in the rat: a neuroanatomical substrate for reciprocal orofacial-cervical interactions. Brain Res. 2010;1343:75–82.
21. Kroemer KH, Marras WS. Towards an objective assessment of the ''maximal voluntary contraction'' component in routine muscle strength measurements. Eur J Appl Physiol Occup Physiol. 1980;45:1–9.
22. Lund JP. Mastication and its control by the brain stem. Crit Rev Oral Biol Med. 1991;2:33–64.
23. Carson RG, Riek S. Changes in muscle recruitment patterns during skill acquisition. Exp Brain Res. 2001;138:71–87.
24. Dworkin SF, LeResche L. Research diagnostic criteria for temporomandibular disorders: review, criteria, examinations and specifications, critique. J Craniomandib Disord. 1992;6:301–355.
25. Slagter AP, Bosman F, Van der Bilt A. Comminution of two artificial test foods by dentate and edentulous subjects. J Oral Rehabil. 1993;20:159–176.
26. Fujita T, Nakamura S, Ohue M, Fujii Y, Miyauchi A, Takagi Y *et al.* Effect of age on body sway assessed by computerized posturography. J Bone Miner Metab. 2005;23:152–156.
27. Andersson G, Hagman J, Talianzadeh R, Svedberg A, Larsen HC. Effect of cognitive load on postural control. Brain Res Bull. 2002;58:135–139.
28. Dault MC, Geurts AC, Mulder TW, Duysens J. Postural control and cognitive task performance in healthy participants while balancing on different support-surface configurations. Gait Posture. 2001;14:248–255.
29. Mientjes MI, Frank JS. Balance in chronic low back pain patients compared to healthy people under various conditions in upright standing. Clin Biomech (Bristol, Avon). 1999;14:710–716.
30. Bauer C. Reliability of static posturography – a Review. Physioscience. 2008;4:65–70.
31. Aniss AM, Diener HC, Hore J, Gandevia SC, Burke D. Behavior of human muscle receptors when reliant on proprioceptive feedback during standing. J Neurophysiol. 1990;64:661–670.
32. Prochazka A. Sensorimotor gain control: a basic strategy of motor systems? Prog Neurobiol. 1989;33:281–307.
33. Van Boxtel A, Jessurun M. Amplitude and bilateral coherency of facial and jaw-elevator EMG activity as an index of effort during a two-choice serial reaction task. Psychophysiology. 1993;30:589–604.
34. Lundberg U, Kadefors R, Melin B, Palmerud G, Hassmen P, Engstrom M *et al.* Psychophysiological stress and EMG activity of the trapezius muscle. Int J Behav Med. 1994;1:354–370.
35. Eriksson PO, Haggman-Henrikson B, Nordh E, Zafar H. Co-ordinated mandibular and head-neck movements during rhythmic jaw activities in man. J Dent Res. 2000;79:1378–1384.
36. Yamabe Y, Yamashita R, Fujii H. Head, neck and trunk movements accompanying jaw tapping. J Oral Rehabil. 1999;26:900–905.
37. Haggman-Henrikson B, Eriksson PO. Head movements during chewing: relation to size and texture of bolus. J Dent Res. 2004;83:864–868.
38. Ries LG, Alves MC, Berzin F. Asymmetric activation of temporalis, masseter, and sternocleidomastoid muscles in temporomandibular disorder patients. Cranio. 2008;26:59–64.
39. Shimazaki K, Matsubara N, Hisano M, Soma K. Functional relationships between the masseter and sternocleidomastoid muscle activities during gum chewing. Angle Orthod. 2006;76:452–458.
40. Kogler A, Lindfors J, Odkvist LM, Ledin T. Postural stability using different neck positions in normal subjects and patients with neck trauma. Acta Otolaryngol. 2000;120:151–155.

Correspondence: Daniel Hellmann, Department of Prosthodontics, Dental School, University of Heidelberg, Im Neuenheimer Feld 400, 69120 Heidelberg, Germany.
E-mail: daniel.hellmann@med.uni-heidelberg.de