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Electromyographic analysis of masticatory and neck muscles in subjects with natural dentition, teeth-supported and implant-supported prostheses

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Abstract

Objectives: To compare the electromyographic (EMG) characteristics of masticatory and neck muscles in patients with natural dentition, teeth-supported prostheses and implant-supported prostheses.

Materials and methods: Twenty-five subjects aged 40–80 years were examined. Five patients had maxillary and mandibular implant-supported fixed prostheses; five patients had mandibular implant-supported fixed prosthesis and maxillary removable complete denture; seven patients had implant-supported fixed prosthesis (one arch) and natural dentition or full-arch tooth-fixed prosthesis (one arch); and eight control subjects had natural dentition or single tooth-fixed prostheses. Surface EMG of masseter, temporal and sternocleidomastoid muscles was performed during maximum teeth clenching and unilateral gum chewing. Interarch dental contacts were assessed with shim stocks.

Results: All groups had similar interarch dental contacts ($P > 0.05$). During clenching, patients with maxillary and mandibular implant-supported fixed prostheses had unbalanced standardized masseter and temporalis anterior activities (74%), with significantly larger values found in the other patients and control subjects (all mean values larger than 86%, $P = 0.017$). All patients chewed with significantly larger muscular potentials than control subjects (on average, 1434–2100 μV s vs. 980 μV s, $P = 0.04$), and had altered muscular patterns (left side, $P = 0.021$). The patients with one arch with natural dentition/tooth fixed prostheses had chewing muscular patterns similar to the control subjects.

Conclusions: Clenching with the analyzed prostheses was performed with a relative increment of temporalis activity. Neuromuscular coordination during chewing was larger in patients who maintained their teeth or dental roots, independently from the number of dental contacts.

Mastication is a complex task that mixes voluntary and automatic motor pathways controlled by central nervous system pattern generators, and is regulated by the feedback from several receptors (extero-, proprio- and viscero-receptors) (Rilo et al. 2007). In humans, the loss of natural dentition can be restored by the use of several kinds of prostheses, which can be supported by the remaining teeth, alveolar mucosa or osteointegrated implants (Jacobs 1998; Ferrario et al. 2004; Al-Omiri et al. 2005; Flanagan 2005; van der Bilt et al. 2006; Feine & Lund 2006; Jacobs & van Steenberghe 2006). Also, both removable and fixed prostheses can be used (Feine et al. 1994; Flanagan 2005). Overall, implant-supported prostheses can restore oral

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function successfully, and both subjective and objective indicators of chewing ability score better compared with conventional complete dentures (Al-Omiri et al. 2005; Flanagan 2005; van der Bilt et al. 2006; Feine & Lund 2006).

Patients' satisfaction, the morphological evaluation of occlusion and the measurement of the actual impact of morphology on stomatognathic function should all be assessed after prosthetic rehabilitations (Al-Omiri et al. 2005; Flanagan 2005; Feine & Lund 2006). Functional evaluations may include the measurement of bite force, the assessment of masticatory movements, as well as surface electromyographic (EMG) recordings of the masticatory muscles (Gartner et al. 2000; van Kampen et al. 2002; Ferrario et al. 2004; van der Bilt et al. 2006; Feine & Lund 2006).

Previous investigations assessed the functional effect of different kinds of prosthetic reconstructions by analyzing several characteristics of muscle contraction during isometric and cyclic activities (van Kampen et al. 2002; Ferrario et al. 2004; van der Bilt et al. 2006). In particular, we previously performed surface EMG analysis of both static (clenching, interarch stability) and dynamic (chewing, neuromuscular coordination) tasks in patients with mandibular fixed implant-supported prosthesis, implant overdentures and natural dentition, finding that both types of prosthetic reconstruction were functionally equivalent, but inferior to natural dentition (Ferrario et al. 2004).

Apparently, earlier investigations did not assess patients with mixed situations (implant-supported prostheses together with natural dentition or teeth-supported prostheses), a condition which can be frequently found in the clinical practice.

Additionally, no previous study investigated the effects of prosthetic reconstructions on neck muscles. In humans, functional correlations between trigeminal and cervical neuronal pools, with reciprocal co-activations and inhibitions of masticatory, cervical, shoulder and even upper limb muscles during the performance of selected tasks, have been well demonstrated (So et al. 2004; Ciuffolo et al. 2005; Ferrario et al. 2006). Teeth clenching is normally coupled with a submaximal co-activation of sternocleidomastoid (SCM) muscle (Kibana et al. 2002; Leiva et al. 2003; So et al. 2004; Ciuffolo et al. 2005; Ferrario et al. 2006; Sforza et al. 2006), and experimental modifications of occlusal surfaces and dental contacts can significantly modify SCM muscle contraction patterns (Kibana et al. 2002; Leiva et al. 2003; So et al. 2004; Sforza et al. 2006), but this aspect does not seem to have been assessed after complete prosthetic reconstructions.

In the present study, the EMG characteristics of masticatory and neck muscles of three groups of patients with mandibular and maxillary prostheses have been analyzed during standardized static and dynamic tasks. Data have been compared with those collected in subjects of comparable age, with natural dentition or a single/partial (no more than two teeth) tooth or implant-fixed prosthesis. The null hypothesis was that the subjects in the analyzed groups (natural dentition; complete prostheses with different kinds of support) had no differences in the EMG characteristics of their masticatory muscles during functional tasks.

Materials and methods

Patients

Twenty-five subjects aged 40–80 years were examined. Seventeen were partially or completely edentulous and had been successfully rehabilitated with (A) maxillary and mandibular implant-supported fixed prosthesis (one man, four women, age range 50–71 years), with 12 occluding pairs of teeth; (B) mandibular arch with implant-supported fixed prosthesis and maxillary arch with removable complete dentures (three men, two women, 52–66 years), with 12 occluding pairs of teeth; (C) one arch with implant-supported fixed prosthesis and one arch with natural dentition or full-arch tooth-fixed prosthesis (three men, four women, 54–80 years), with 12–14 occluding pairs of teeth.

All patients with fixed implant-supported prostheses were provided with six osseointegrated implants in their edentulous mandible between the mental foramina and/or in their edentulous maxilla between the sinuses. In patient group A, both arches were provided with implants; in patient group B, only the mandibular arch was provided with implants; and in patient group C, four patients had implants in their maxillary arch and three patients had implants in their mandibular arch. After surgical healing, fixture-supported prostheses were prepared and positioned. All patients had been wearing their prostheses (either implant-supported or teeth-supported) at least for 6 months before EMG examination. All occlusal schemes had a symmetric distribution of the centric contacts in the intercuspal position.

Eight control subjects (five men, three women, age range 40–69 years) were also examined. Four of them had natural dentition, and the other four had one to three single-tooth prostheses on natural teeth. Each subject had 14 occluding pairs of teeth.

For the patients, inclusion criteria were an adequate masticatory efficiency and satisfaction with the prostheses. For both patients and control subjects, exclusion criteria were dental and periodontal problems, muscular pain in the head, neck or shoulders, temporomandibular joint alterations, or neck disturbances. All subjects were informed in full about all experimental procedures and about all possible risks; they signed an informed consent form that was preventively approved by the local ethics committee. All procedures were safe, non-invasive and did not provoke pain or discomfort to the subjects, who were free to stop their examination at any moment. The EMG examination was performed during one of their periodic follow-up visits in a private dental office. The number and distribution of contacts between opposing teeth were also assessed on the same occasion. Surface EMG of the right and left masseter, temporal, and SCM muscles was performed during unilateral gum chewing and during maximum voluntary teeth clenching (MVC).

EMG recordings were performed by a single operator who was blind to the patient's group; all subjects were given a numerical code that was further used for calculations. Occlusal contact detection was performed by a second operator who used the same codes. In all subjects, EMG examination was performed immediately after occlusal analysis.

Occlusal contacts

Occlusal contacts were tested by using 8-mm-wide, 8-μm-thick shim stocks (Hanel, Roeko, D-89122 Langenau, Germany). The same protocol described elsewhere (Anderson et al. 1993; Ferrario et al. 2002a) was used: a single operator positioned the shim stock in correspondence of the occlusal surface of each maxillary teeth and asked the subject to close in intercuspal position with a light to moderate force. The teeth holding the shim stock were recorded as having an occlusal contact with their antagonists. During testing, the subjects were seated on a dental chair with an erected back. The number and location (anterior, contacts measured between incisor and first premolar teeth; posterior, contacts measured between second premolar and molar teeth; both divided into right and left sides) of interarch dental contacts were recorded.

EMG recordings and measurements

Instrumentation

The masseter, anterior temporal and SCM muscles of both sides (left and right) were examined. Disposable, pre-gelled, silver/silver chloride bipolar surface electrodes (diameter 10 mm, interelectrode distance 21 ± 1 mm) (FLAB, Vicchio, Florence, Italy) were positioned on the muscular bellies parallel to muscular fibers (Ferrario et al. 2002b, 2004, 2006). A disposable reference electrode was applied to the forehead. Before electrode placement, the skin was cleaned with ethanol to reduce its impedance.

EMG activity was recorded using a computerized instrument (Freely, De Götzen srl; Legnano, Milano, Italy). The analog EMG signal was amplified (gain 150, peak-to-peak input range from 0 to 2000 μV) using a differential amplifier with a high common mode rejection ratio (CMRR = 105 dB in the range 0–60 Hz, input impedance 10 GΩ), digitized (12 b resolution, 2230 Hz A/D sampling frequency) and digitally filtered (high-pass filter set at 30 Hz, low-pass filter set at 400 Hz, band-stop for common 50–60 Hz noise). Using the EMA software (De Götzen srl), the signals were averaged over 25 ms, with muscle activity assessed as the root mean square (r.m.s.) of the amplitude (V). EMG signals were recorded for further analysis.

Standardization recording

To standardize the EMG potentials of the six analyzed muscles with tooth contact, two 10-mm-thick cotton rolls were positioned on the mandibular first and second molars of each subject, and a 5-s MVC was recorded (Ferrario et al. 2002a, b, 2006). In addition, for standardization of the SCM potentials, a maximal rotation of head and neck without moving shoulders, blocked by one of the experimenters, was performed. The head was moved slowly on each side, and the subject remained in the extreme right and left positions for approximately 5 s. During head–neck rotation, the contralateral SCM muscle is maximally activated (Ferrario et al. 2006; Sforza et al. 2006).

MVC: data collection and analysis

EMG activity was then recorded during an MVC in intercuspal position; the subject was invited to clench as hard as possible and to maintain the same level of contraction for 5 s. The test was repeated three times, and a visual feedback using the amplitudes (r.m.s.) of the EMG signals was provided to all subjects in order to ensure a maximal performance. During these tests, the subjects were verbally encouraged to perform at their best.

For all tests, the subjects sat with their heads unsupported and were asked to maintain a natural erect position. To avoid any fatigue effect, a rest period of at least 3 min was allowed between standardization recording and tests, as well as between each test.

For all tests, the best 3-s period (that with the most constant r.m.s. EMG signal) was automatically selected by the software and used for all subsequent analyses. All calculations were automatically performed by the computer software using the numerical codes, and the group allocation was made only at the end of all calculations.

For each patient, the EMG potentials of the analyzed muscles recorded during the MVC tests were expressed as percent of the mean potential, recorded during the standardization test (MVC on the cotton rolls) (Ferrario et al. 2006), μV/μV × 100. All subsequent calculations were made with the standardized potentials. In addition, a second standardization was made for SCM muscle with the potentials obtained during head–neck rotation, μV/μV × 100. Standardized potentials were used for the calculation of cervical load. The values obtained in the three MVC tests performed by each subject were averaged.

To assess muscle symmetry, within each subject the EMG waves of paired muscles were compared by computing a percentage overlapping coefficient (POC, %) (Ferrario et al. 2002b). POC is an index of the symmetric distribution of muscular activity as determined by occlusion. The index ranges between 0% and 100%: when two paired muscles contract with perfect symmetry, a POC of 100% is obtained. Masseter, temporalis and SCM POCs were obtained for each subject.

Because an unbalanced contractile activity of contralateral masseter and temporalis muscles, for instance right temporalis and left masseter, might give rise to a potential lateral displacing component, the torque coefficient (TC, %) was assessed. TC ranges between 0% (complete presence of lateral displacing force) and 100% (no lateral displacing force) (Ferrario et al. 2006).

To compare the standardized muscular activities of masseter and temporalis muscles, an antero-posterior coefficient (APC, %) was computed, as the ratio between the non-overlapped and the overlapped masseter and temporalis muscle areas of both sides (Ferrario et al. 2006). The index ranges between 0% (unbalanced standardized masseter and temporalis potentials) and 100% (well comparable standardized masseter and temporalis potentials). When standardized muscular potentials are not balanced between the two analyzed masticatory muscles, the occlusal center of gravity (MVC on the occlusal surfaces as compared with MVC on the cotton rolls) might be displaced onwards (temporalis prevalent) or backwards (masseter prevalent). To individuate the most prevalent pair of masticatory muscles, the activity index (Ac, %) was also computed as the percentage ratio of the difference between the mean masseter and temporalis standardized potentials, and the sum of the same standardized potentials (Naeije et al. 1989; Ferrario et al. 2002b). This index is positive (up to 100%) when the masseter muscle standardized potentials are larger than the temporalis muscles ones, negative (up to − 100%) when the temporalis muscles potentials are larger, and null when they are equal.

The mean (masseter and temporalis) total standardized muscle activities (μV/μVs %) were computed as the integrated areas of the EMG potentials over time (Ferrario et al. 2004).

In addition, an SCM 'cervical load' (%) was assessed as the percentage ratio between the SCM muscle potentials recorded during MVC (this should be a submaximal contraction for SCM muscle) and the muscle potentials obtained during the maximum contraction standardization task (e.g. contralateral neck rotation against resistance). This index indicates the percentage of SCM co-contraction during teeth clenching: a cervical load of 0% denotes no concomitant activity, while a cervical load of 100% implies a maximal contraction of SCM muscles during MVC (Ferrario et al. 2006; Sforza et al. 2006).

Gum chewing: data collection and analysis

Masseter and temporalis muscles' electrical activity was recorded during unilateral (left and right) chewing of sugarless gum (1.5 g; Mentadent Integral, Unilever Italia, Milano, Italy) (Ferrario et al. 2004). For each patient, the EMG potentials produced in the first 15 s of each unilateral chewing were recorded and standardized as detailed before (μV/μV × 100). From the EMG potentials recorded from the four tested muscles during each chewing test, a masticatory frequency was obtained. A bivariate analysis was performed on the simultaneous differential left–right masseter and temporal activity (Lissajous plot) (Ferrario et al. 2004).

A Lissajous plot (Cartesian axis representation) is made with the differential left–right masseter activity serving as the *x*-coordinate, and the differential temporal activity as the *y*-coordinate (Fig. 1). Within each subject and chewing test, differential data were normally distributed; from the pairs of coordinates, Hotelling's 95% confidence ellipse and the 90% standard ellipse were calculated ($\mu V^2/\mu V^2 \times 100^2$). The confidence ellipse is a region that covers the population center with a given probability (inferential statistic), while the standard ellipse contains a given part of the sample data (descriptive statistic) (Ferrario et al. 2004). The confidence ellipse can be used to assess the repeatability of the pattern of contraction of a group of muscles during the execution of a standardized movement (e.g. right and left masseter and temporalis unilateral gum chewing): small ellipses will correspond to highly repeatable muscular patterns, while large ellipses will indicate a larger variability for the same task. Only data about the confidence ellipse were further reported in the current report.

In subjects with a normal neuromuscular coordination, the centers of the ellipses describing unilateral chewing plotted as a Lissajous figure should be located in the first (right side) and third (left side) quadrants of a Cartesian coordinate system (Ferrario et al. 2004), with about the same amplitude (distance of the center of the ellipse from the origin of axes), and a 180° difference between the phases (angle between the *x*-axis and the center of the ellipse). To assess if the left- and right-side chewing tests were performed with symmetrical muscular patterns, from the centers of the two confidence ellipses (left- and right-side chewing) calculated in each patient, the symmetrical mastication index (SMI, %) was computed (Ferrario et al. 2004). SMI ranges between 0% (asymmetrical muscular pattern) and 100% (symmetrical muscular pattern).

The mean (masseter and temporalis) total muscle activities during chewing were computed as the integrated areas of the EMG potentials over time (Ferrario et al. 2004). For each patient, both the absolute activity (μVs), directly calculated from the r.m.s. amplitude EMG potentials recording during chewing, and the 'standardized' activity, from the standardized EMG potentials (μV/μVs %), were calculated.

Measurement variability

EMG measurement variability in normal subjects was assessed in our laboratory by repeated analyses of seven subjects chosen at random (Ferrario et al. 2006). For all EMG variables, the intraclass correlation coefficients were larger than 0.62, showing a good accuracy of the measurements, without random errors (paired Student's *t*-test, $P > 0.05$).

Statistical comparisons among the study groups

Descriptive statistics (mean, standard deviation) were computed for all variables within a patient group. Considering the small number of patients in each group, non-parametric tests were used for the comparisons among the study groups. Categorical data (interarch contacts) were compared by a χ^2-test. Age and EMG variables were compared by a Kruskal–Wallis test (the non-parametric analog of the analysis of variance). The level of significance was set at 5% for all statistical analyses.

Results

The mean ages and the number and location of interarch dental contacts did not differ among the four analyzed groups (Table 1, age: Kruskal–Wallis test; contacts: χ^2-test; for both, $P > 0.05$).

During the MVC test, no significant differences among groups were found for EMG symmetry (POC index of masseter, temporalis and SCM muscles), torque, activity index, co-contraction of SCM muscle during teeth clenching, and overall muscular activity (Table 2, Kruskal–Wallis test, all *P* values larger than 0.05).

Significant differences among patient groups were found only for the APC index. Overall, the control group and patient groups B (mandibular implants and maxillary complete dentures) and C (implants in one arch, natural dentition in the other one) had similar APC indices (mean values larger than 86%, showing balanced standardized masseter and temporalis anterior activities), while patient group A (both arches with implants) had a reduced value. Additionally, a trend in different activity

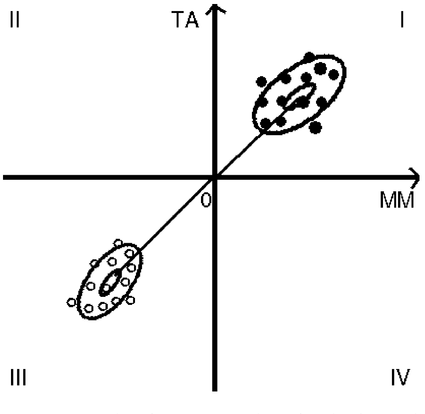

Fig. 1. Example of Lissajous plot of right (I quadrant)- and left (III quadrant)-side chewings. Thirteen chewing movements were recorded during unilateral right (filled dots)- and left (outlined dots)-side gum chewing tests, and the simultaneous differential left–right masseter (MM, *x*-coordinate) and temporal (TA, *y*-coordinate) activities were plotted. The relevant 90% standard (external) and confidence (internal) ellipses are also shown.

indices was observed: the activity index nearer to 0 (more balanced standardized masseter and temporalis anterior activities) was found in the control group and in patient group C, while patient groups A and B had, respectively, a prevalent temporalis (group A) and masseter (group B) standardized muscular activity.

Chewing frequency was similar in all four groups in both sides (Table 3). During chewing, the mean (masseter and temporalis) total muscle activities (both absolute activity, and 'standardized' activity) significantly differed among groups: they were higher in patient groups A and B for both sides. Overall, while control subjects chewed with approximately half of the muscular activity they used during MVC (standardized activity values: right side 52%, left side 48%), and patients in group C used approximately 70% of their MVC activity, patients chewing on occlusal surfaces unsupported by natural teeth used 90–110% of their MVC activity, which corresponded also to a significantly higher EMG amplitude.

In the right-side chewing, the confidence ellipse computed in the control subjects was smaller than those computed in the patient groups, with differences ranging between 127% and 234%. In the left-side chewing, the smallest ellipse was found in patient group C (approximately, 87% of the control group ellipses); the largest were found in patient group A (approximately, three times larger than in the control group). The differences were significant for left-side ellipses, but did not reach the 5% level of significance for the right side. No significant differences were found for the index of masticatory symmetry SMI.

Table 1. **Analyzed subjects, and percentage of interarch dental contacts as measured by shim stocks**

	Patient group A	Patient group B	Patient group C	Control group	*P*
Number of subjects	5	5	7	8	
Age (years)					
Mean	60.6	59.8	64	50.63	NS
SD	7.47	5.67	8.89	11.55	
Contact position (%)					
Right posterior	20	27.27	16.95	26.76	NS
Right anterior	30	24.24	28.81	23.94	
Left anterior	30	21.21	30.5	21.13	
Left posterior	20	27.27	23.72	28.17	

Patient groups: (A) maxillary and mandibular implant-supported fixed prosthesis; (B) mandibular arch with implant-supported fixed prosthesis, and maxillary arch with removable complete dentures; (C) one arch with implant-supported fixed prosthesis, and one arch with natural dentition or full arch tooth fixed prosthesis.

P, probability of Kruskal–Wallis test (age), or χ^2 test (made on the number of contacts); NS, not significant, $P > 0.05$.

Discussion

In the current investigation, patients with different kinds of prosthetic reconstructions were analyzed and compared with subjects with natural dentitions. All the patients were satisfied with their prostheses, and reported an adequate masticatory efficiency. The tests were performed at least 6 months after the completion of their prosthetic reconstructions, a time considered sufficient for the development of good muscle activities and force generation (Gartner et al. 2000; van Kampen et al. 2002).

Among the study limitations there is the use of a convenience sample: the patients were not randomly selected, and their prosthetic rehabilitations were chosen independently from the present investigations. Only well-satisfied patients were asked to undergo the EMG investigation. Therefore, the extrapolation of the present results to a wider population should be done with caution (Al-Omiri et al. 2005; Flanagan 2005; Feine & Lund 2006).

Also, no subjective evaluation of chewing performance was collected, and only objective measurements were used (Al-Omiri et al. 2005; Feine & Lund 2006). Even if EMG examination has

Table 2. **Maximum voluntary teeth clenching in patients and control subjects (mean and standard deviation)**

	Unit	Patient group A	Patient group B	Patient group C	Control group	*P*
POC masseter	%	85.4	82.56	83.5	84.95	NS
		5.14	3.71	5.25	2.95	
POC temporalis	%	84.89	82.53	85.58	86.96	NS
		1.85	7.54	2.05	1.87	
APC	%	73.53	90.11	89.44	86.62	0.017
		16.71	2.17	3.15	5.02	
Activity index	%	− 20.8	15.83	− 3.04	− 4.89	NS
		24.17	20.81	8.06	12.28	
TC	%	89.25	91.01	91.08	90.44	NS
		2.05	0.54	1.59	1.25	
Activity standardized	μV/μV s %	78	77	95.43	87.75	NS
		18.29	15.43	23.56	27.53	
POC SCM	%	86.23	83.49	82.16	81.84	NS
		1.1	9.2	8.97	5.76	
Cervical load	%	16.58	10.31	23.79	13.38	NS
		7.24	4.91	17.06	8.27	

P, probability of Kruskal-Wallis test; NS, not significant, $P > 0.05$; POC, percentage overlapping coefficient (index of left–right muscular symmetry); TC, torque coefficient (potential lateral displacing component); APC, antero-posterior coefficient (relative activities of masseter and temporalis muscles); SCM, sternocleidomastoid muscle; Cervical load, contraction of SCM during MVC as % of standardization potentials.

***Table 3.* Unilateral gum chewing in patients and control subjects (mean and standard deviation)**

	Unit	Patient group A	Patient group B	Patient group C	Control group	*P*
Right side						
Frequency	Hz	1.32	1.24	1.38	1.25	NS
		0.17	0.17	0.27	0.17	
Total activity	μV s	2000.98	2101.64	1198.16	978.6	0.034
		591.75	882.55	676.97	425.14	
Activity standardized	μV/μV s %	100.58	111.14	69.97	51.85	0.011
		20.79	44.2	26.55	20.3	
Confidence ellipse	$\mu V^2/\mu V^2 \times 100^2$	2550	2679	1451	1144	NS
		1820	1199	1633	567	
Left side						
Frequency	Hz	1.48	1.3	1.45	1.24	NS
		0.22	0.1	0.33	0.33	
Total activity	μV s	1981.45	2012.1	1434.51	902.9	0.016
		580.94	878.22	460.1	312.4	
Activity standardized	μV/μV s %	89.4	101.92	68.5	48.41	0.021
		25.51	41.79	25.29	11.15	
Confidence ellipse	$\mu V^2/\mu V^2 \times 100^2$	2998	3144	935	1077	0.021
		1423	2192	694	607	
SMI	%	59.25	33.76	24.56	55.29	NS
		42.38	31.93	26.14	34.97	

P, probability of Kruskal–Wallis test; NS, not significant, $P > 0.05$; SMI, symmetric mastication index.

been reported to be time-consuming and to require special equipment, the current tests, performed during one of the periodic follow-up visits of the patients, lasted approximately 15 min for each patient and were made directly in the dental chair at a private dental office. With a minimal effort, the tests provided actual estimates of the energy spent by the patients (Feine & Lund 2006).

Functional activities of the stomatognathic apparatus require a stable tooth contact between the opposing dental arches. This position (maximum intercuspation) should be the position of maximum stability for the mandible (McDevitt & Warreth 1997; Owens et al. 2002). When a sufficient number of dental contacts provide a stable reference for the contraction of supramandibular masticatory muscles, both static (biting, swallowing) and dynamic (chewing) activities have been reported to be more efficient (Owens et al. 2002). Indeed, significant correlations between the EMG characteristics of masticatory muscles (amplitude of the electric potentials, duration of contractile activity) and the number of dental contacts have already been reported (Hidaka et al. 1999; Ferrario et al. 2002a).

The number of contacts between opposing teeth was measured with very thin shim stock strips (Anderson et al. 1993; McDevitt & Warreth 1997; Ferrario et al. 2002a). This method seems to be among the most precise, reliable and reproducible methods reported in the clinical and basic dental literature (Anderson et al. 1993; Ogawa et al. 1998). Overall, no significant differences in the number and position (anterior/posterior part of the arch, left/right side) of contacts were found among patient groups and control subjects. Accordingly, almost all static indices of muscular equilibrium measured in the MVC test, as well as the relevant EMG activity (muscle potentials over time), did not differ among the analyzed groups.

Also, no differences were found for the analyzed neck muscle: independently from the kind of occlusal support, the SCM had similar standardized symmetry and percentage of co-contraction during MVC. This result is in good accord with previous investigations: alterations in SCM activity were reported concurrently with alterations in occlusal surfaces (Kibana et al. 2002; Leiva et al. 2003; So et al. 2004; Sforza et al. 2006), while the patients analyzed is the current study had equivalent contact numbers and positions.

In contrast, differences in standardized masseter and temporalis activities were found (significant differences for APC index, a trend for activity index): subjects without any natural dental support (patient groups A and B) developed unbalanced standardized muscular potentials. In patient group A, the negative activity index showed a prevalence of temporalis muscle over masseter: this condition has already been reported to be determined from dental contacts in the anterior arch, with a larger load on the temporomandibular joint (Ferrario et al. 2002b; Flanagan 2005). Actually, even if the number and location of interarch contacts, as detected by shim stock strips, were not statistically different among study groups, this patient group appeared to have the largest percentage of contacts in the anterior part of the arch (Table 1). Similar morphological situations had an amplified effect on actual function, thus underlining the importance of functional tests together with conventional assessments (Gartner et al. 2000; van Kampen et al. 2002; Ferrario et al. 2004; Al-Omiri et al. 2005; van der Bilt et al. 2006; Feine & Lund 2006).

This alteration in the antero-posterior muscular balance during MVC was not reported by van der Bilt et al. (2006), who stated that their patients with implant-supported overdentures had masseter-to-temporalis activities comparable to those found in dentate subjects. The different kinds of prostheses (overdentures vs. fixed prostheses), the different sex composition (59% of patients in the current study were women vs. 6% in the study by van der Bilt et al. 2006) and mean age (the current patients were approximately 10 years older than those analyzed by van der Bilt et al. 2006) of the patients, together with some variations in data analysis (standardized indices vs. actual EMG amplitudes) should be taken into consideration.

In the current study, a larger number of significant differences was found in the dynamic chewing test, with larger ellipses (less repeatable alternate patterns of contraction of the masseter and temporalis muscles of the working and balancing sides) in patient groups A and B, who also contracted more their masticatory muscles to perform the same standardized chewing task (both in absolute terms and as a percentage of MVC), than in control subjects and in patient group C. Therefore, patients in groups A and B spent more energy for the same task than patients in group C and control subjects (Feine & Lund 2006).

Overall, the fraction of maximum contraction used by patients without natural teeth/roots while chewing was very similar to that recently reported for patients rehabilitated with implant-supported overdentures (van der Bilt et al. 2006). In that experiment, both natural and artificial foods were used, and unilateral chewing was not required. Therefore, even if unilateral gum chewing is an artificial situation that cannot be directly translated into actual food chewing, current results are in good accord with findings obtained in more ecological studies (van der Bilt et al. 2006; Feine & Lund 2006). Accordingly, similar chewing frequencies were recorded, independently from the occlusal support (Ferrario et al. 2004; van der Bilt et al. 2006). Chewing frequency seems to be centrally determined and to depend more on the kind of food than on the support of the occlusal surfaces (Ferrario et al. 2004; van der Bilt et al. 2006).

In contrast, neuromuscular coordination during chewing (alternate patterns of muscular contraction and inhibition) seemed to depend on the kind of support of the occlusal surfaces, in good accord with previous investigations (Ferrario et al. 2004). Overall, the patients in groups A and B seemed to use a wider group of muscles than control dentate subjects, with increased bilateral occlusion patterns as compared with the more frequent unilateral chewing of the dentate individuals (Ogata & Satoh 1995; Gartner et al. 2000; van Kampen et al. 2002). Both morphological (actual design of the prosthetic dental surfaces) and functional explanations should be considered: while the construction of dental prostheses should take both esthetics and biomechanics into account (Flanagan 2005), the patients must adapt their neuromuscular structures to obtain the best masticatory performance from the new occlusal surfaces supported by artificial roots. For instance, during unilateral chewing, patients with a superior performance contracted the masseter muscles of both working and non-working side, while patients with a lower performance had reduced muscular activities (Garrett et al. 1995). Accordingly, adult patients with unilateral posterior cross-bite (altered occlusal contacts) had altered chewing patterns (Rilo et al. 2007).

The null hypothesis of the current study could, therefore, be rejected for those patients who had no more supporting dental roots in their maxilla and mandible: the lack of parodontal receptors modified the performance of both the dynamic (chewing) and the static task (MVC). In contrast, the patients in group C, who maintained a dental arch with natural dental support (even if not all of them had a complete set of natural occluding surfaces), performed similarly to control subjects. Considering that no differences were found in the morphological assessment (interarch contacts), the main difference among groups seems to reside in the nervous information from the oral cavity (Garrett et al. 1995; Jacobs 1998; Abarca et al. 2006; Jacobs & van Steenberghe 2006; Van Steenberghe & Jacobs 2006). Patients without dental roots lack all receptors of the periodontal ligament, and this deficit should be compensated by the extero-receptors embedded in the gingiva, alveolar mucosa and bone (Jacobs 1998; Abarca et al. 2006; Jacobs & van Steenberghe 2006; Van Steenberghe & Jacobs 2006). Indeed, tooth extraction, similar to limb amputation, provokes degeneration of a substantial amount of afferent nerve fibers (Jacobs 1998; Abarca et al. 2006; Jacobs & van Steenberghe 2006; Van Steenberghe & Jacobs 2006): in the mandibular arch, tooth extraction may provoke a 20% reduction in the myelinated fiber content of the inferior alveolar nerve (Jacobs & van Steenberghe 2006).

On the other hand, recent histological investigations found some kind of nervous regeneration in correspondence of the bone surrounding osseointegrated implants (Jacobs 1998; Jacobs & van Steenberghe 2006). Also, masticatory forces applied to osseointegrated implants are directly transferred to the maxillary and mandibular bone: bone deformation may provoke receptor activation in the peri-implant bone and in the neighboring periosteum, and may also activate remote proprio-receptors through transmission of vibrations via the facial bones (Gartner et al. 2000; Jacobs & van Steenberghe 2006). All together, these sensory inputs may explain the best performance of implant-supported than of bone-supported prostheses; the phenomenon is not limited to dental prostheses, but it has been described also for limb prostheses (Abarca et al. 2006; Jacobs & van Steenberghe 2006). The term 'osseoperception', a conscious perception of external stimuli transmitted via a bone-anchored prosthesis by activation of neural endings and/or receptors in the peri-implant environment, has been recently proposed (Abarca et al. 2006). Nevertheless, the new receptors do not completely restore previous afferents, and neurophysiological tests found variations in the oral/dental innervation and reflexes (Jacobs 1998; Jacobs & van Steenberghe 2006; Van Steenberghe & Jacobs 2006). From a more global perspective, in the chewing test performed in the current study, the sensory compensation did not appear to be completely satisfactory, and both a lower coordination (larger ellipses) and a higher energy (larger muscular activities) were found in patients without periodontal ligament receptors. The larger muscular activities may derive from a lack in inhibitory feedback from the teeth-supporting structures (Jacobs 1998; Abarca et al. 2006; Jacobs & van Steenberghe 2006). Overall, when a larger energy is spent for the same effort, efficiency decreases, and muscles may become fatigued earlier.

In conclusion, the present surface EMG analysis of a static (clenching) task showed that the analyzed prostheses were functionally equivalent to natural dentition, apart from the relative increment of temporalis activity. In contrast, neuromuscular coordination during chewing (dynamic task) was larger in patients who maintained their teeth or dental roots than in patients with osseointegrated implants or removable dentures, independently from the number of dental contacts.

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