Robotic Chewing Simulator for Dental Materials Testing on a Sensor-Equipped Implant Setup

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***Purpose*:** This study describes a mechanical chewing simulator that is able to reproduce mandibular movements in 3 dimensions and the forces exerted during mastication. The aim of this work was to validate the described device, which can be used to test the ability of different restorative materials to withstand stress. ***Materials and Methods*:** To validate the masticatory robot, 5 identical samples for each of 3 different restorative materials (an acrylic resin, a composite resin, and a glass ceramic) were created. Each sample underwent 5 minutes of chewing in the robot. The forces transmitted to the simulated peri-implant bone were collected. Two-way analysis of variance was used to evaluate the results. ***Results*:** There were significant differences between the materials, and internal comparisons also showed significant differences ($P < .0001$). ***Conclusion*:** The different elastic moduli of the restorative materials significantly affected stress transmission at the simulated bone-implant interface, and the masticatory robot was able to identify this difference. The very low levels of variation confirm the precision of the machine during data collection and validate the reliability of the method, showing effective repeatability of the tests.
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Several chewing simulation devices have been developed. In 1957, Cornell et al[1] described a chewing machine in which the maxillary teeth were mounted on a movable arm and the mandibular teeth were mounted on a rigid arm to determine the wear of denture teeth. In 1983 DeLong and Douglas[2] developed an artificial oral environment that used 2 servo-hydraulic actuators to control a clinically oriented force-movement cycle to simulate mastication. In 1995 Breeding et al[3] simulated a 3-unit posterior fixed partial denture supported at one end by an osseointegrated implant and at the other by a natural tooth fixed in a simulated mandibular arch. Three maxillary crowns were rigidly attached to the pistons in 3 pneumatic cylinders on the machine. The authors measured the effects of various prosthesis designs on the movement patterns of the tooth and implant and the force distribution within the implant. However, the 3 devices described cannot replicate complex chewing movements.

Instron machines are often used to test dental materials.[4] However, these mechanisms can only follow intermittent movements in 1 plane, and they cannot be used to reproduce the complex chewing movements in 3-dimensional space.

Because wear measurements in vivo are complicated, expensive, and time-consuming, many wear simulation devices have been developed. Among these, according to Heintze,[5] a good compromise with regard to costs, practicability, and robustness is the Willytec chewing simulator (Willytec), which uses weight as a force actuator and step motors for vertical and lateral movements. However, no information is available with regard to the force and force profile on the specimen and whether the forces and force profiles are identical in the 8 test chambers contained in the chewing simulator. Moreover, this system does not allow 3-dimensional simulation of masticatory movements and masticatory loads.

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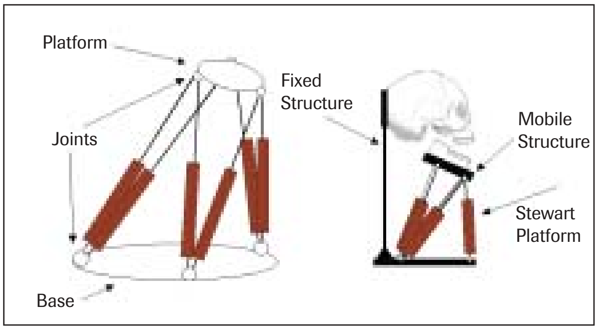

Fig 1 Schematic diagram of the masticatory robot.

Fig 2 *(right)* Sensor-equipped masticatory robot.

The chewing simulator described by Daumas et al[6] in 2005 is very similar to the one presented in this study. Daumas developed a mechatronic chewing device to reproduce human chewing behavior in 3 dimensions. The chewing movements are caused by 6 linear actuators placed between a simulated mandible (or the end-effector) and a simulated skull (or the ground), according to their respective biologic structure and functionality, resulting in a spatial mechanism of 14 links, 6 linear actuators, and 12 spherical joints. This device was created to evaluate new types of foods in terms of texture perception and was not provided with a sensor to record the loads transmitted, as was the chewing simulator described in the present study. Moreover, the present study simulates an implant setup.

The aim of this study is to develop and validate a method for studying in vitro the stress transmitted to the bone-implant interface by the masticatory load applied on different restorative materials currently in use in implant dentistry. To evaluate the relationship between restorative materials and stress transfer at the bone-implant interface, a test system was needed that would simulate not only mandibular movement but also the force magnitudes and distributions recorded for the human masticatory system. For these reasons, a masticatory robot was built; this was given a parallel dynamic platform with 6 degrees of freedom, commonly called a “Stewart platform.” This mechatronic device is able to simulate human chewing in vitro, reproducing 3-dimensionally the masticatory movements and the loads exerted during mastication. The null hypothesis tested in this research was that the masticatory robot would not be a viable system to identify the transmission of different amounts of stress at the simulated bone-implant interface using restorative materials with different elastic moduli.

Materials and Methods

The Masticatory Robot

The robot (Fig 1) was built in collaboration with Società Graal Tech and was financed by MIUR (Ministry of University Instruction and Research, Italy) under the Research of National Interest Project (PRIN 2002). The masticatory robot is able to reproduce the mandibular movements in 3 dimensions and the loads produced during mastication.

The masticatory robot is composed of 2 distinct systems: The first is the system driving and controlling the robot, along with the robot itself; and the second system collects the data. The controller system is an industrial computer that gives orders to the movable part of the robot, ie, the Stewart platform, and controls the movements executed, thanks to feedback signals. The Stewart platform is a parallel mechanism made up of a rigid upper body, or moving platform (the end-effector simulating the mandible), which is connected to a fixed base by 6 identical kinetic legs, which are equidistant to each other and symmetrically arranged so as to form 2 equilateral triangles on a fixed base (Fig 2).

By varying the lengths of the legs, thanks to 6 linear actuators, it is possible to change the orientation of the platform in 6 degrees of freedom (3 degrees of freedom in rotation and 3 degrees of freedom in translation) and thus to replicate functional masticatory movements and forces. Each leg is made up of 2 steel cylinders (1 hollow, 1 solid) linked by a cylindric joint. Each leg is attached to the platform and fixed base through spherical joints at the 2 ends.

The robot motion is specified by the platform position in the x-, y-, and z-axes and platform orientation, defined as the angles around the x-, y-, and z-axes (roll,

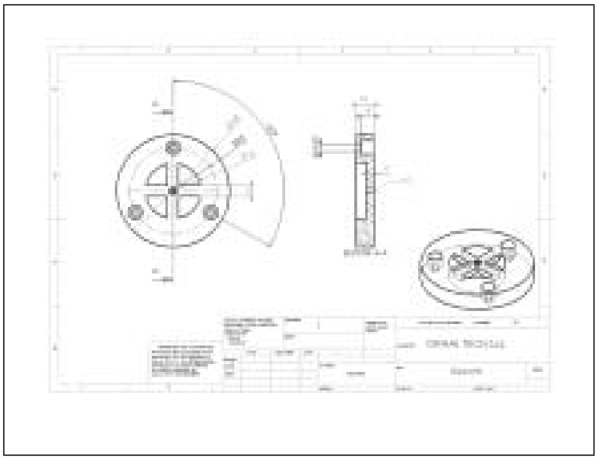

Fig 3 Scale drawing of the support.

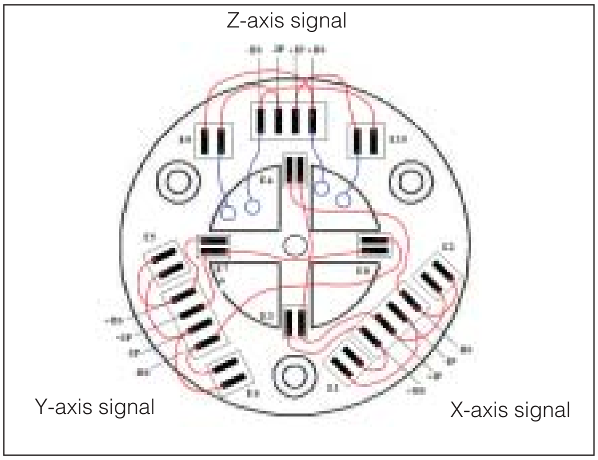

Fig 4 Upper face of the sensor-equipped base showing the wiring. Red line = Upper face connecting wires; Blue line = Wires connecting upper and lower faces; Dotted line = Wires connecting the sensor to the amplifier; +BS/–BS = Power supply to the bridge; +IP/–IP = Bridge output.

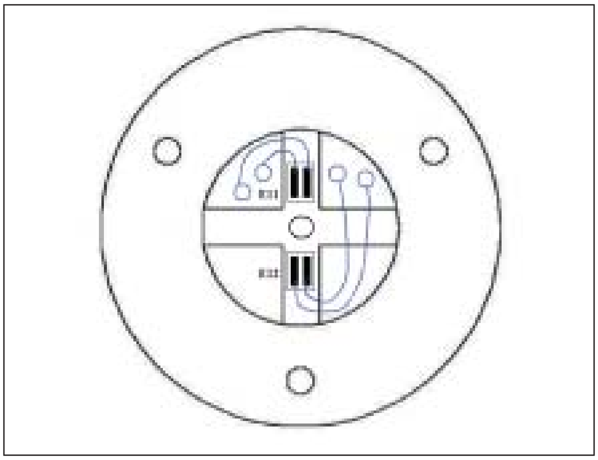

Fig 5 Lower face of the sensor-equipped base showing the wiring.

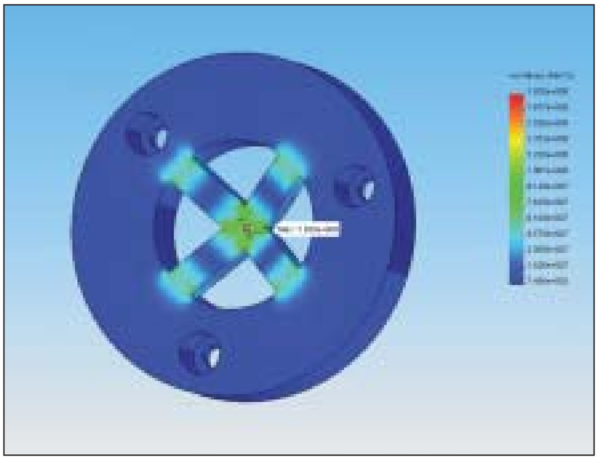

Fig 6 COSMOSXpress simulation of the behavior of the sensor-equipped base when loaded. The application of a force of 80 kg along the vertical z-axis was simulated to show the resulting deformation. The illustration highlights the zones of maximum stress on the structure and verifies that the model can support the maximum load.

pitch, and yaw angles, respectively). The x-, y-, and z-axes represent the laterolateral, anteroposterior, and vertical axes, respectively.

An encoder sensor for each of the 6 actuators evaluates the current position of the platform. As seen thanks to the encoder sensor records, the platform executes the movements requested with an accuracy of 0.1 mm. The described system allows control of the platform motion but not the application of pre-established forces. The forces are controlled indirectly thanks to a sensor-equipped base that is fixed to the mobile platform.

The structure has a support for the fixed upper portion (simulating the skull); to this, a chrome-cobalt reproduction of the maxillary arch can be attached. The chrome-cobalt maxilla may be removed from the fixed upper part of the robot to confer the ability to conduct tests of the sample crowns in occlusion with a flat cuspless steel surface. A sensor-equipped base (Figs 3 to 6) is placed on the moving platform (mandible) of the robot and records the degree of force being transmitted through the 3 axes (x, y, and z). Eight active strain gauges and 2 passive strain gauges are attached to the upper face of the base and other 2 active strain gauges are attached to its lower face to form a Wheatstone bridge. The Wheatstone bridge converts the resistance variations measured by the strain gauges in tension variations. The signals from the sensorized base are amplified and then acquired through 3 multiplexed

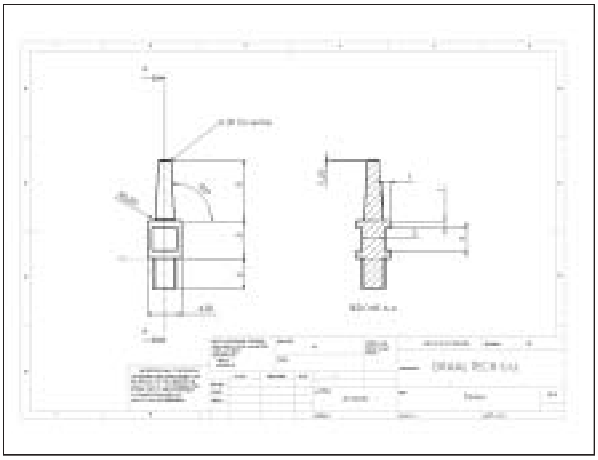

Fig 7 Scale drawing of the pin (simulating the implant-abutment system).

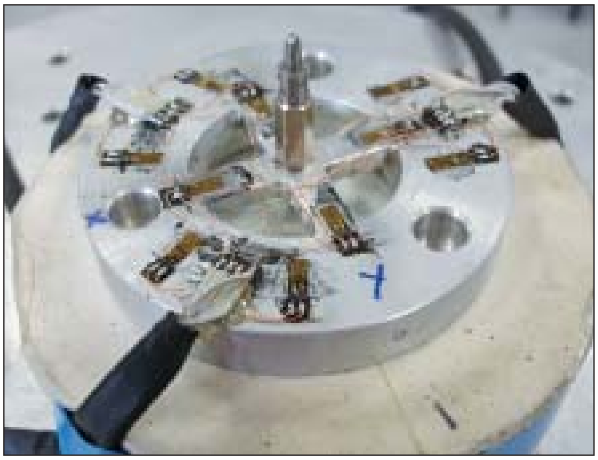

Fig 8 Sensor-equipped base with the pin for the sample crowns.

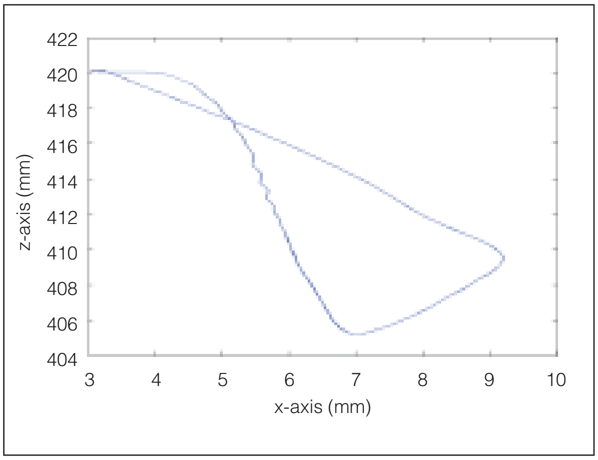

Fig 9 Trajectory followed by the masticatory robot in the frontal plane.

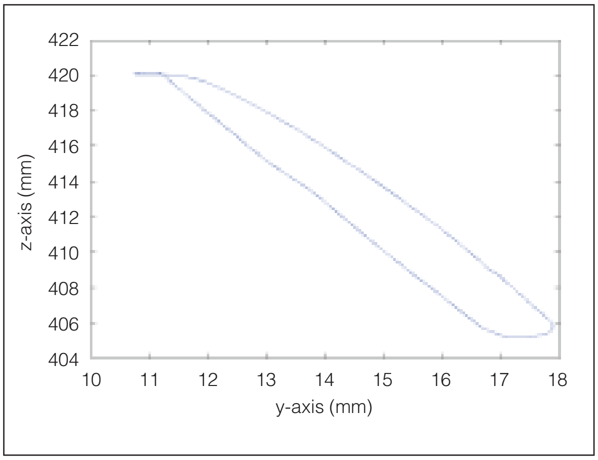

Fig 10 Trajectory followed by the masticatory robot in the sagittal plane.

channels by a computer (Windows NT4, Microsoft) equipped with an analog-to-digital conversion board (National, ISA) every 100 ms.

The base for the sensors was designed on a computer using computer-assisted design technology and underwent finite element analysis (FEA) using COSMOSXpress (SolidWorks) (Fig 6). FEA was performed to determine the appropriate location of the strain gauges (ie, in the regions where maximum stresses are concentrated for the active strain gauges, and in unstressed regions for passive strain gauges) and to verify that a maximum load of 80 kg would be applied along the vertical axis (z-axis) to keep the structure safely within the elastic range.

The sensor-equipped base supports a pin (Figs 7 and 8) that simulates the abutment-implant system; the samples being tested are attached to this and stressed in the various planar directions. A groove was made on the pin to match the ridge inside the sample crowns, such that the crown would sit precisely on the pin without any possibility of rotation or other movement during the test. The groove is 8 mm long and provides the antirotational property. The pin has a 6-degree conicity, which provides stability and retention forces to the crown-abutment system.

The masticator was programmed to follow a trajectory (Figs 9 and 10) using as a base the mean displacement of the mandibular interincisal point in 3 dimensions and the median velocity of normal masticatory function for each phase of the masticatory cycle, with the trajectory drawn by kinesiographic tools.[7] The masticator traced this trajectory in all the tests described in this study. The 3-dimensional trajectory is defined by 19 pre-established points (specified by the position and orientation of the platform) that are timed at an interval of a tenth of a second. The entire cycle, therefore, is 2 seconds long, including the tenth of a second used by the platform to move from

Table 1 Elastic Moduli of the Sample Crown Materials

Trade name	Kind of material	Manufacturer	Elastic modulus (MPa)
Finesse	Glass ceramic	Dentsply	70,000
Signum	Composite resin	Heraeus Kulzer	3,500
Easytemp 2	Acrylic resin	DEI Italia	2,300

Fig 11 Pin and sample crowns. The pin (which simulates the abutment-implant system) shows the groove that matches the ridge made on the inside of the samples, so that the crowns fit snugly onto the pin without possibility of rotation during the test phase.

Figs 12a and 12b Each sample produced was measured on its main and smaller axes with a caliper to verify that all the crowns were identical.

the 19th point of the trajectory back to the starting position (position zero). For each masticatory cycle, 20 measurements were collected. The tests were carried out using the program LabVIEW 5.0 (National Instruments).

Sample Crowns

An acrylic resin (Easytemp 2, DEI Italia), a composite resin (Signum, Heraeus Kulzer), and a glass ceramic (Finesse, Dentsply) were used in the test. The elastic moduli of the test materials as obtained from manufacturer reported values are listed in Table 1.

Five identical metal-free crowns were made for each material tested (Fig 11). The 5 identical ceramic sample crowns were the first to be made. Duplicates in composite resin and acrylic resin were made using the printing technique for photopolymerizable materials with a transparent muffle. The sample crowns were fabricated by placing the composite resin in a transparent silicone mold and then photopolymerizing it inside the transparent muffle, which allowed passage of the beam rays. This technique was selected because it allows faithful reproduction of the morphology of the sample, and thus the creation of samples that are identical in size and shape for comparative testing.

To eliminate other variables and limit the risk of accidental breakage to the crowns as a result of accidental cusp contacts, it was decided to make the occlusal surfaces semispherical in shape (6.5 mm diameter). The main axis of the sample was 11 mm long. Each sample produced was measured on its main and smaller axes with calipers to verify that all the crowns were identical (Figs 12a and 12b).

The use of cement to attach the test crown to the pin is not necessary because of the strict friction coupling between the crown and the grooved pin. Moreover, the use of cement would introduce an additional variable, namely the cement thickness.

The samples were numbered from 1 to 15 for blinding, and the operator carrying out the tests and storing the resulting data was blinded to the type of material being tested. The specimens tested were chosen at random and not in a pre-established sequence. The material constituting each sample crown was revealed only after statistical analysis of the data.

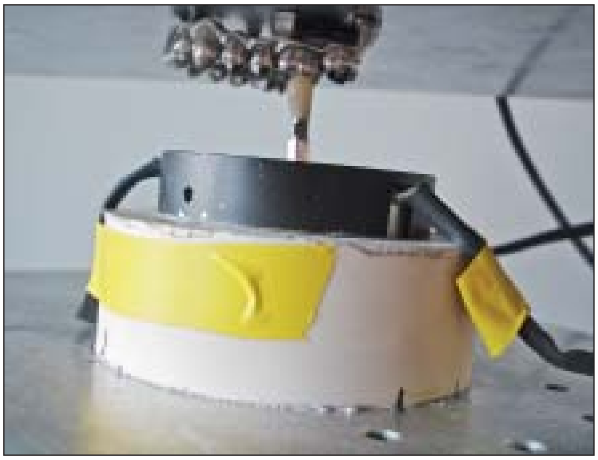

Table 2 Comparison (2-way ANOVA) of Materials and Samples in the Z-axis

Comparison	df	Mean square	F	*P*
Between materials	2	434,269.14	547,228.68	< .0001
Between samples	4	1.847	2.327	.0542
Interaction	8	1.350	1.701	.0933
Residual	2,385	0.794		

Fig 13 Sample crown in occlusion with the chrome-cobalt antagonist arch.

Testing

During the test, each crown was submitted to chewing cycles, with the starting position set to bring the sample into contact with the left first molar of the fixed chrome-cobalt reproduction of the maxilla (Fig 13). The vertical and transverse stresses transmitted to the simulated peri-implant bone were recorded.

Each sample was subjected to the same number of identical masticatory cycles, each starting from the same position. Thus, the only variable in the system was the material from which the crowns were made, and any difference in the force transmitted to the pin base was dependent entirely on the deformation capacity of the material. This capacity is represented by the elastic modulus of the material. It was decided to perform 160 cycles (which corresponds to 5 minutes of chewing of the masticatory robot) for each test and to use 5 samples for each of the 3 different materials to obtain enough measurements that were large enough to statistically validate the precision of the robot and the reproducibility of the tests.

The data were stored in a file and then translated into graphs using MATLAB 6.1 (MathWorks). With MATLAB 6.1, the maximum values of the forces recorded for each masticatory cycle were highlighted. These values underwent statistical analysis.

Statistical Analysis

Statistical analysis was performed with SPSS software (Version 13.0, SPSS Inc). Two-way analysis of variance (ANOVA) was used to compare transmitted stresses between the 3 different occlusal materials (ceramic, composite resin, and acrylic resin) and across the 5 sample crowns of each material. All tests were 2-tailed, and alpha was set at .05.

Results

Two-way ANOVA revealed highly significant differences between the forces transmitted using different materials. A comparison of transmitted stress between the 3 materials showed significant differences ($P < .0001$), whereas comparisons within each type of sample crown made for each material did not show significant differences (Tables 2 to 4).

The maximum force transmitted to the peri-implant bone on the vertical z-axis by the ceramic (mean, 52.087 kg) was greater than that transmitted by the composite resin (mean, 28.488 kg) and the acrylic resin (mean, 5.491 kg) (Table 5). On the laterolateral x-axis, the mean maximum stresses recorded at the base of the pin were 10.617 kg, 5.343 kg, and 1.504 kg for ceramic, composite resin, and acrylic resin, respectively. On the anteroposterior y-axis, the mean maximum stresses recorded at the base of the pin were 3.852 kg, 1.912 kg, and 0.339 kg for ceramic, composite resin, and acrylic resin, respectively.

The confidence intervals of variation were very small (Table 5).

Discussion

The differing elastic moduli of restorative materials significantly affected stress transmission at the simulated bone-implant interface, and the masticatory robot was able to identify these differences. The results demonstrate that the masticatory robot is a viable system to identify the different deformation capabilities of the tested materials, as the masticator always recorded the highest stress values using the ceramic samples, followed by the composite resin samples and finally by the acrylic resin samples, with significant differences between the groups ($P < .0001$); internal comparisons within samples of the same material did not show significant differences.

Table 3 Comparison (2-way ANOVA) of Materials and Samples in the X-axis

Comparison	df	Mean square	F	*P*
Between materials	2	16,746.70	97,463.01	< .0001
Between samples	4	0.321	1.870	.1129
Interaction	8	0.186	1.083	.3717
Residual	2,385	0.172		

Table 4 Comparison (2-way ANOVA) of Materials and Samples in the Y-axis

Comparison	df	Mean square	F	*P*
Between materials	2	2,478.11	27,223.03	< .0001
Between samples	4	0.159	1.743	.1377
Interaction	8	0.139	1.530	.1415
Residual	2,385	0.091		

Table 5 Comparison of Mean Maximum Occlusal Forces (in kg)

Material/ sample	Mean force (95% Confidence Interval)		
	z-axis	x-axis	y-axis
Finesse			
1	52.181 (52.029–52.334)	10.603 (10.520–10.685)	3.805 (3.721–3.890)
2	52.173 (52.008–52.337)	10.583 (10.491–10.675)	3.809 (3.738–3.880)
3	52.237 (52.001–52.473)	10.545 (10.487–10.603)	3.918 (3.852–3.984)
4	51.897 (51.642–52.151)	10.668 (10.537–10.799)	3.884 (3.803–3.966)
5	51.949 (51.676–52.222)	10.684 (10.548–10.820)	3.845 (3.748–3.942)
Signum			
1	28.471 (28.308–28.635)	5.344 (5.339–5.349)	1.933 (1.928–1.938)
2	28.443 (28.359–28.526)	5.341 (5.327–5.356)	1.893 (1.887–1.900)
3	28.561 (28.530–28.591)	5.338 (5.333–5.342)	1.916 (1.911–1.920)
4	28.553 (28.529–28.577)	5.348 (5.343–5.354)	1.925 (1.917–1.934)
5	28.414 (28.381–28.448)	5.346 (5.341–5.350)	1.892 (1.884–1.900)
Easytemp 2			
1	5.569 (5.422–5.517)	1.524 (1.488–1.560)	0.336 (0.328–0.344)
2	5.495 (5.448–5.542)	1.525 (1.479–1.570)	0.346 (0.340–0.351)
3	5.521 (5.487–5.556)	1.462 (1.433–1.491)	0.343 (0.338–0.349)
4	5.506 (5.486–5.525)	1.482 (1.440–1.524)	0.334 (0.327–0.341)
5	5.463 (5.412–5.514)	1.525 (1.478–1.573)	0.335 (0.319–0.351)

Other studies have analyzed the force transmitted to peri-implant bone by different occlusal materials using photoelasticity models,[8,9] FEA,[10–16] or Instron machines.[4] The main limitation of these studies is the fact that none of them accurately reproduce the mandibular kinematics. The first 2 tests are static and virtual, respectively, whereas the Instron machine can only follow intermittent movements along a single plane. This does not come close to reproducing the masticatory cycle, which operates within 3 dimensions and was replicated in this study by using a masticatory robot with a kinematic parallel structure. With regard to FEA, the validity of the mathematical model is difficult to estimate objectively, and the assumptions made in the use of FEA in implant dentistry must be taken into account when interpreting the results. Comparisons of FEAs are made difficult by the different assumptions made in building different models. During the modeling process, in fact, some assumptions greatly affect the predictive accuracy of FEA. These include assumptions involving model geometry, material properties, applied boundary conditions, and the bone-implant interface.[17,18]

Some experiments have been conducted using animals, such as beagle dogs.[19] Such a model would not allow for controlling the forces applied and obviously would not accurately simulate the human masticatory cycle. Other studies[20–22] have measured in vivo the masticatory forces transmitted by various restorative materials. These tests use sensors and memory boards for data collection that are placed in the oral cavity. These devices make chewing more difficult for subjects, and more importantly, they lead to cortical control of masticatory function, with possible alterations in the results of the experiment. Moreover, under these conditions, the experimental cycles need to be shorter, and it is impossible to create identical masticatory cycles. Finally, strains can be recorded only where the strain gauges are bonded or embedded. It is therefore impossible to measure the stresses transmitted at the bone-implant interface.

The creation of a masticatory robot with a kinematic parallel platform was an attempt to overcome these limitations. With this device, a situation was created (*1*) that precisely replicated the mandibular kinematics in a way that was always the same and (*2*) in which the loads transmitted by an occlusal surface through the implant to the peri-implant bone (simulated by the sensor-equipped base) were able to be recorded.

Because only a limited number of occlusal materials were tested, the results can not be generalized to other restorative materials. While the work presented in this paper is preliminary, it does provide a viable jaw mechanism model to use for testing dental materials.

The very narrow confidence intervals found in the statistical analysis of the data demonstrate that the masticatory robot is able to reproduce, several times over, identical masticatory cycles. They also confirm the precision of the machine during data collection, therefore validating the reliability of the method. In fact, the small variations found show that the tests are also repeatable and effective under lengthy testing.

Acknowledgments

The construction of the masticatory robot was financed by MIUR (Ministry of University Instruction and Research, Italy) under the auspices of the Research of National Interest Project (PRIN, 2002). The authors wish to thank Professor Giuseppe Casalino and engineers Fabio Giorgi, Tommaso Bozzo, Andrea Caffaz, and Alessio Turetta at Graal Tech, Genoa, who built the masticatory robot. We are especially thankful to dental technician Paolo Pagliari for the laboratory support.

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Erratum: In *IJP* issue 3, 2008, in the article by Etman et al, on page 246, the second sentence of the first full paragraph in the second column should read as follows: “At this visit, an oral examination was conducted, patient concerns were addressed, independent assessors completed the case report form, and crown adjustments were made, finished, and polished.” The publisher regrets this error.