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Design of dynamic test equipment for the testing of dental implants

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Abstract

The market demand for dental implants is growing at a significant pace. There are mainly two common types of retention methods to fix the abutment to the implant. These are achieved by screw and taper locks. Screw loosening is a major concern and the taper lock system is relatively new and has many advantages over the screw system. This paper outlines a proposal for a novel test rig for dynamic testing of this taper-lock system. The test rig will simulate the magnitude and directions of the forces experienced in the oral cavity during mastication. The test rig will be used in a laboratory environment to investigate the loading conditions that cause the taper-locks to fail and how their location in the oral cavity can be adjusted to avoid failure conditions.

Keywords: Dental implants; Taper locks; Implant testing

1. Introduction

Dental implants are used in reconstructive oral surgery to replace single teeth or an array of teeth in either the upper or lower jaws. The two main components of a dental implant system are the Implant and the Abutment. In the case of replacing a single tooth, a ceramic crown is attached to the abutment whereas in the case of an array of teeth being replaced, a prostheses will be used onto which the ceramic crowns will be attached. The prosthesis will then be attached to a number of abutments. The number of abutments used depends on the size and location of the prosthesis in the oral cavity. Fig. 1 shows two methods of attaching the abutment to the implant and two methods for inserting the implant into the jaw bone.

Before insertion of the implant a hole is drilled into the bone and the titanium implant is inserted. The two insertion options are: (a) by self-tapping action or (b) by a press fit. In both cases the bone will grow around the implant and its serration through a biological process called osseointegration. On completion, the osseointegration process will provide a strong structural foundation for the implant. Failures of the implants are very rare [1] reported at 0.4% and 1.0% and so they can be considered as being permanent fixtures.

The abutment is attached to the implant by either (a) a screw lock or (b) a taper lock. In the case of a screw lock the screw will be tightened to a torque which will provide a pre-load on the components. The preload should be less than the strength of the materials of the various components but will be greater than the forces normally experienced by the components during mastication. Adherence to this tightening torque will significantly reduce the possibility for loosening of the screw [2]. There will generally be a feature on the abutment and implant to assist location. These features can also be used to help prevent rotational movement of the components that would assist screw loosening. Typical feature shapes are male/female hexagonal features or male/female conical features.

In the case of the Taper Lock, the central hole in the implant has a slight taper (1.5°). The protrusion on

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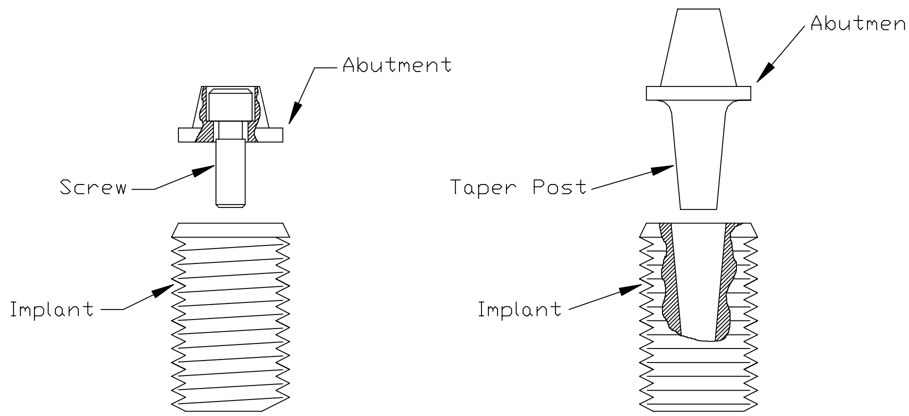

Fig. 1. Popular implant systems.

the abutment also has a taper of the same angle. When the abutment is inserted into the implant, any pure compressive forces acting on the components in a vertical direction will further close the taper lock. This locking mechanism is a function of the friction which exists between the surfaces. The abutment is removed by a twist and pull action so for this reason no features are present to prevent rotation of the abutment.

Retrievability of the abutment from the implant is very important as it allows the prosthedontist to remove the abutment to reshape or modify the prosthesis and to inspect the implant and gum or bone interface for infections. Retrievability has the problem that if something can be removed, there is a possibility that it will loosen and be removed unintentionally. A comparison can be made between the two abutment retention systems in terms of retrievability. To remove an abutment screw, access to the screw head must be provided. This can mean that a hole is left in the crown which can be undesirable. There is no abutment screw in the taper lock system thus the crown can be left complete. Various studies have been performed regarding the failure rate in terms of screw loosening over various periods of time. These rates are given in Table 1.

Only one study was retrieved which related to the lifetime of the taper lock joint and this showed for a population of 1757 implants, 1.5% of the abutments loosened over a four year period and 2.2% of abutments loosened over a seven year period [3].

There is a lack of research carried out into investigating the taper lock technique to date. Consequently the taper-lock technique is of primary concern to this study.

Table 1
Reported cases of loosened abutment screws over a variety of time periods

Reported loose screws (%)	Sample period (years)	Reference
22.2	$\geqslant 2$	[4]
28	3	[4]
40	Not specified	[5]
43	3	[6]
26	1	[6]
44.9	3	[6]

2. Forces in the oral cavity

Fig. 2 shows the various forces which are produced in the oral cavity and how they interrelate.

The most common force direction which occurs in the oral cavity is compressive and occurs during mastication (chewing).

Fig. 3 shows a crown with an oblique plane on which a compressive force (V) acts, producing a lateral force component (H). This lateral force component will cause a bending moment on the system which will be related to the distances 'a' and 'b' as shown.

Lateral forces can also be caused during normal chewing motions or through bruxism (teeth grinding). A lateral force which is applied to the crown or abutment at a distance from its central axis will produce a torsional force acting about that axis.

Fig. 4 shows how in a bridge supported on two or more implant systems, a compressive force can generate a tensile force. Depending on the interspatial distance between the implants and distance of the point loading to the implants, the magnitude of the forces on the implants relative to the magnitude of the applied load can be greatly increased.

When more than two implants are used to support a bridge, the magnification of the forces can be quite large as described by Skalak [4]. Many studies have been carried out to measure the compressive forces created in the oral cavity during mastication. The forces created through natural teeth tend to be significantly larger than

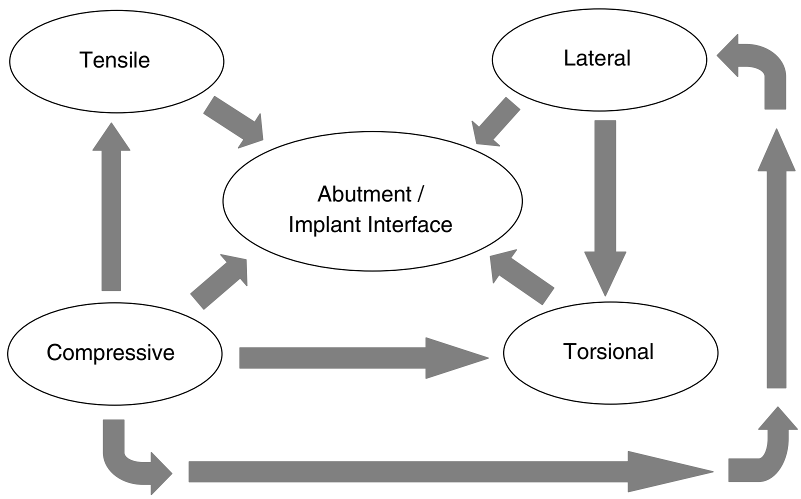

Fig. 2. Forces in the oral cavity which act on the abutment/implant interface and their interrelationship.

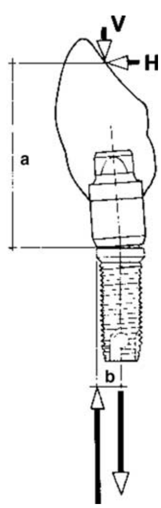

Fig. 3. Lateral force component produced from a compressive force on an oblique plane.

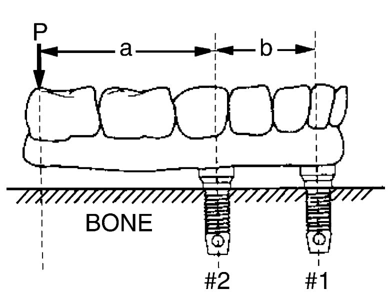

Fig. 4. A partial bridge supported on two implants.

those created through dental implant. The values recorded at the rear of the mouth (molar region) also tends to be larger than those recorded at the front of the mouth (incisor region).

Table 2 shows a variety of forces measured by authors for various locations in the oral cavity.

Table 2
Forces previously measured in the oral cavity

Location	Value (N)	Reference
Molar	300	[2]
Incisor	150	[2]
Varying (when chewing)	50.1	[8]
Varying (maximal)	144.4	[8]
Varying	113.2	[9]
Central incisor	140–250	[10]
First premolar	390	[10]
Molar and premolar	120–150	[11]

3. Failure modes in dental implants

At its simplest the loading of a dental implant can be seen as repeated cycles of different magnitudes having a combination of compressive, bending and torsional forces applied to a cantilever. These loading mechanisms in the oral cavity during mastication can eventually lead to fatigue failure of dental implants. More often than not the fatigue failure occurs in the metal abutment. Consequently a long held assumption that improvements in the ceramic implant material will result in improved clinical performance is invalid [5]. Ceramic restorations do not normally fail from lack of strength of the ceramic material. Flaw-free glass can be stronger than stainless steel [6]. However, dental ceramics are produced by techniques that induce microscopic defects known as Griffith's flaws [7] and such flaws can propagate under even minor occlusal loads and consequently fatigue failures are sometimes, though rarely, experienced [8,9].

Abutment screws are subjected to detorque after cyclic loading. A carousel-type fatigue testing device devised by Cibirka et al. [10] dynamically loaded implants with forces between 20 and 200 N for five-million cycles, equivalent to five years in vivo mastication. No longitudinal displacement of the implant-abutment interfaces or significant reduction in torsional strength were observed. Micromotion during mastication can induce fatigue failure in the abutment in apparently stable implant screw joints. This can lead to tissue inflammation and prosthesis failure. Micromotion and dynamic fatigue in dental implant screw joints was studied by Gratton et al. [11]. A compressive cyclic sine wave load was applied to contact points on implant crowns for a total of 100,000 cycles without any measurable fatigue damage.

4. Review of current test practices

As previously discussed, a range of research has been undertaken which investigated the reliability of different designs of implant systems. These investigations and tests have predominantly been carried out on systems that fix the abutment to the implant by a screw lock. Theoretical evaluations have been performed using finite element analysis (FEA) models whilst some test apparatus have been designed and built to physically test the components. The investigations are reviewed in this section.

Hoyer [12] applied off-centre cyclic loads (120 +/− 10 N) to 10 implant systems at 10 Hz for 103, 104, 105 and 5 × 105 cycles. The amount of movement of the joint between the implant and abutment was measured. The measurements were made using a strain gauge which was attached to both sides of the joint by means of a framework. The loads were applied through a prototype linear solenoid dynamic loading device which allowed for very fast cyclic loading. A schematic of the apparatus used by Hoyer in this investigation is shown in Fig. 5. Joint opening was consistently in the range of 0–30 mm for two diameters of 3.75 and 6.0 mm. There was no significant difference between the joint opening of both systems.

Cibirka et al. [13] used a carousel type fatigue tester to simultaneously test 10 samples for 5,000,000 cycles (≈5 years). The samples tested had a male hexagonal feature on the implant and a variety of modifications were made to this feature for testing. The test apparatus used a large bore cylinder and piston to deliver a force through individually adjustable springs to the loading styli as shown in Fig. 6.

The fact that the loading springs could be adjustable meant that the force applied to the styli varied depending on the off load length. The loads applied varied between 20 and 200 N. The implant systems were tested to observe any relative rotational movement between the abutment and implant after cyclic loading. This movement was measured by scribing a line between the two components along their common axis and inspecting for any offset of this line after cycling. Load cells were used to measure the load on each implant system. No relative rotational movement of the abutment and implant was observed after testing for any of the samples.

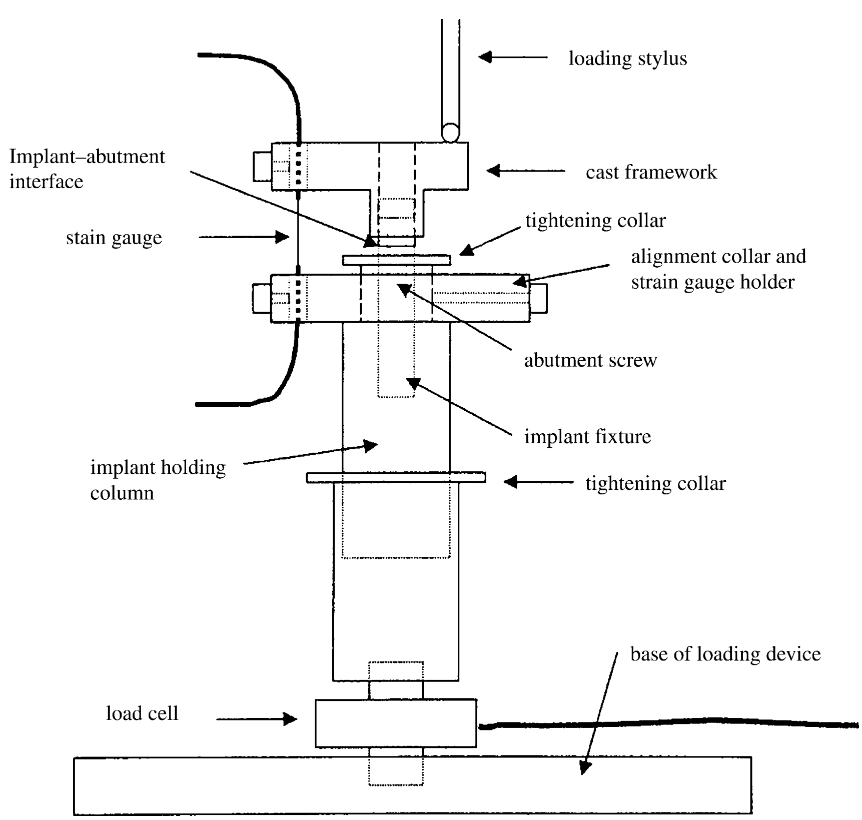

Fig. 5. Schematic of apparatus used by Hoyer.

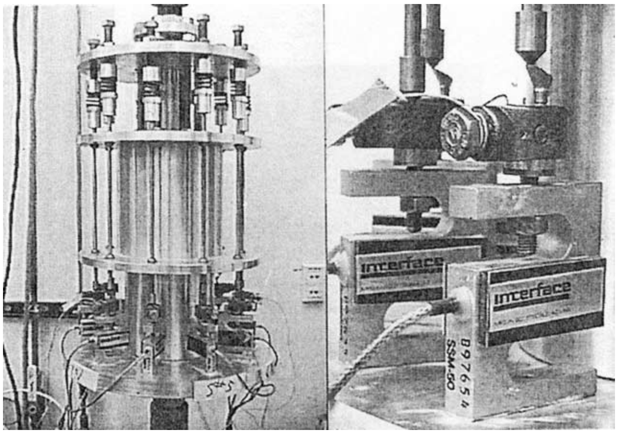

Fig. 6. Carousel apparatus used by Cibrka to simultaneously load 10 samples.

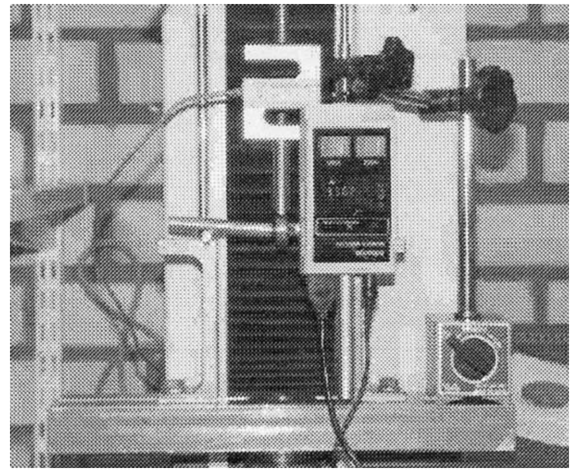

Fig. 8. 3-point bending apparatus used by Norton.

Screw loosening, deflection and rotation was investigated by Dixon et al. [14]. A constant load was applied to a sample at a distance of 2.5 mm from the centre and this load was traversed by a distance of 4 mm perpendicular to the 2.5 mm offset. The load applied to the abutments was 26.69 N (2.72 kg) and was cycled for 16,667 cycles. Proximity probes were used to observe any movement of the abutment relative to the implant in the form of either linear or rotational displacement. The equipment used and the arrangement of the proximity probes are shown in Fig. 7.

The detorque values required to loosen the abutment screws were compared to the torque applied when tightening the screws. No significant difference was observed between the samples used which comprised a variety of angles of inclination of the abutment, angle of inclination of implant and interface between abutment and implant. The maximum values recorded for the three characteristics were ~ Rotation, 0.47°; Deflection, 0.27 mm; detorque value −10.17 Ncm.

A 3-point bending test was adopted by Norton [15] in his work which compared the strength of the abutment-implant interface of two systems made by different manufacturers. This apparatus is shown in Fig. 8. With both systems, the abutment has a male conical protrusion which fits into a female conical cavity on the implant. The lower portion of the abutment is threaded and this screws into the implant. During the test, the abutment and implant were each attached to the end of a bar before assembly together. These bars were constrained like a simply supported beam and a load was applied to the system. The load was applied to the system at 4 mm from the interface by a screw driven testing machine and these loads were measured using a force cell. The displacement of the system was measured and bending moment versus displacement of the systems was recorded. The implant system which had a much longer length of conical surface could accept a bending moment nearly twice that of the system with a conical length of approximately half its own. Norton also shows in a previous report [16] that the conical interface is superior in strength to the butt joint interface.

Merz et al. [17] examined a conical interface between implant and abutment and a hexagonal butt interface. The hexagonal butt interface consisted of a male hexagonal feature on the implant with a corresponding female feature on the abutment. Finite element models were created and loads of 380 N were applied at angles of

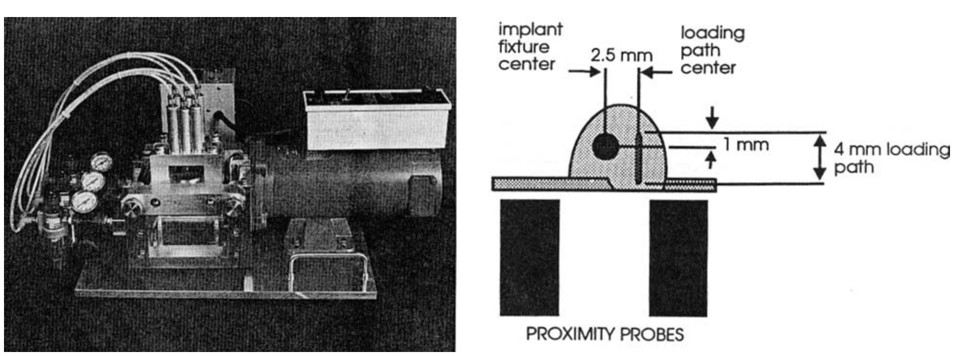

Fig. 7. Equipment use by Dixon to measure screw loosening, rotation and deflection.

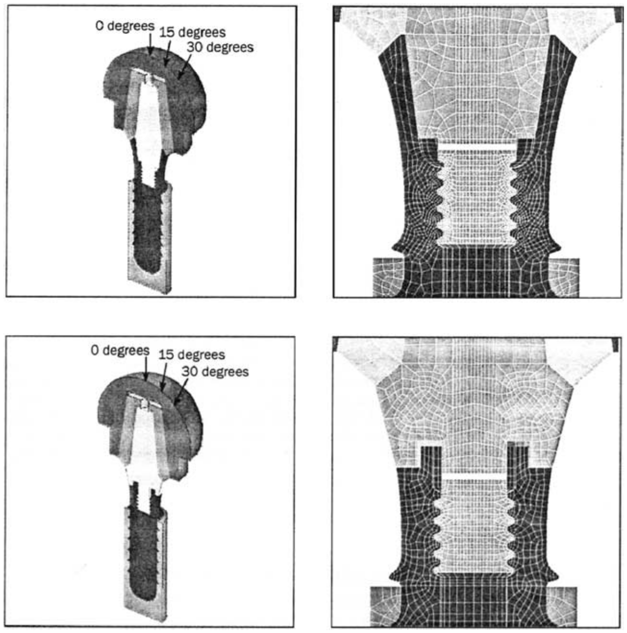

Fig. 9. Finite element models of conical and butt joints as used by Merz.

0°, 15° and 30° to the axis of the system as shown in Fig. 9.

Maximum stresses were experienced when the load was applied at an angle of 30° and the value for the butt joint interface were calculated as 1403 MPa, whereas the maximum stress calculated for the conical interface was 1176 MPa. Plastic deformation of the components was experienced in the hexagonal butt interface. This investigation supports Norton's experimentation [15].

5. Design of test rig for this investigation

The purpose of the test equipment described in this text is to simulate the magnitude and directions of the forces that occur in the oral cavity during mastication and applies these forces to a sample dental implant system.

There are four main elements to the design of the test rig and these are:

(a) Load generation and application;
(b) Mounting of sample;
(c) Control & Monitoring;
(d) Quantification.

5.1. Load generation and application

A variety of methods for applying a load to the dental implant system have previously been used. This test rig will use a pneumatic cylinder with a supply pressure of 0–5 bar. The force that the cylinder delivers is related to the diameter of the cylinder bore and the pressure of the supplied air (Force, N = Pressure, $N/m^2 \times$ Area, m^2). By controlling the supply pressure, the applied force can be controlled. The area of the cylinder bore will remain constant. The pressure will be controlled by a pressure control valve which delivers an output pressure proportional to an applied D.C. voltage (0–10 v delivers a pressure range of 0–10 bar). The supply voltage to the valve will be controlled through a PC. This technique will allow the force to be controlled in a variety of ways (sinusoidal, square wave, saw tooth, s.). The direction in which the cylinder acts will be controlled by a 5/2 directional control valve (DCV) which will also be controlled through a PC. Fig. 10 shows a schematic of the load generator.

The load generated is applied to the sample implant system through a hardened steel stylus. It is important that the actual force applied to the abutment and implant is accurately known as due to friction and pressure looses the force reduction may be up to 15% of the theoretical value. A piezo electric load cell is positioned behind the stylus to measure the force that the stylus applies. A schematic of the load application assembly is shown in Fig. 11.

The piezo electric load cell produces an electric charge proportional to the load applied, but the magnitude of this charge will be very small. A charge amplifier is used to magnify the charge to a more measurable

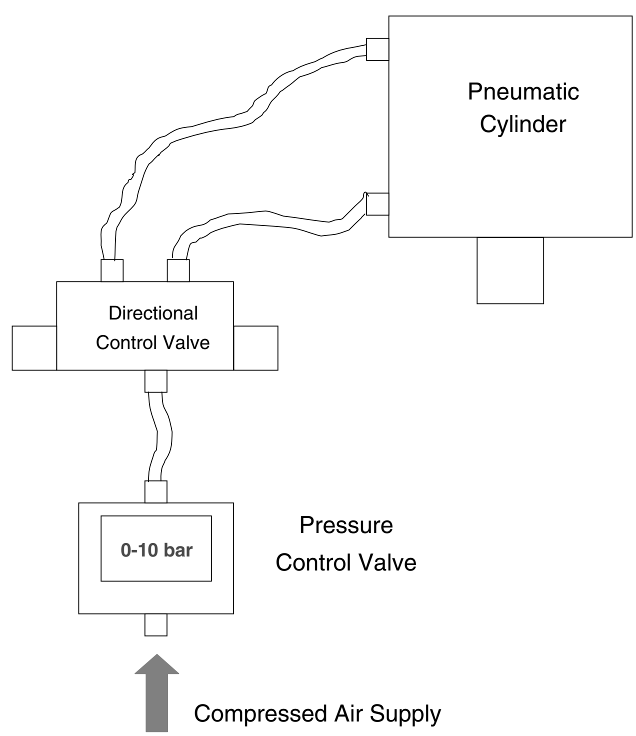

Fig. 10. Schematic of load generator assembly.

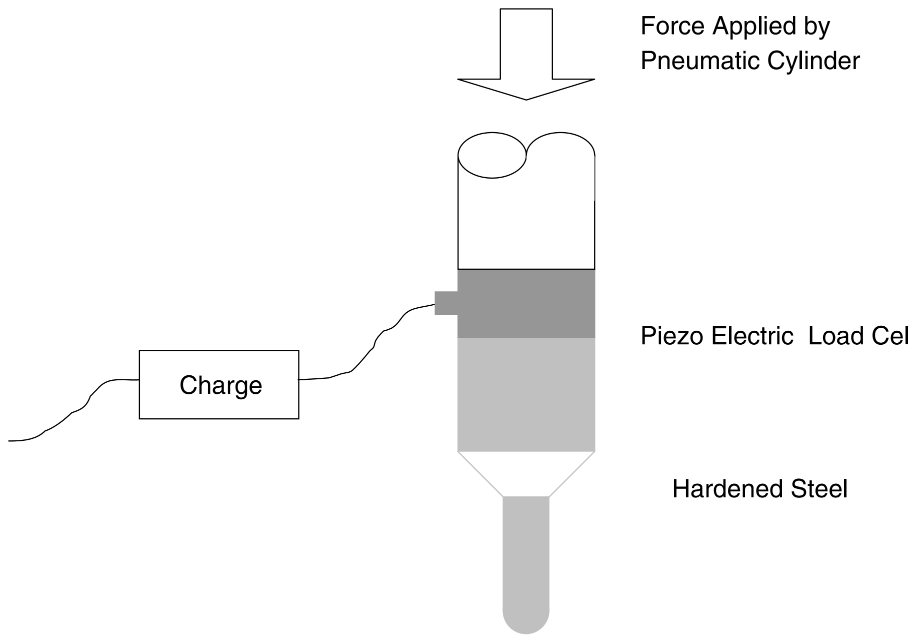

Fig. 11. Schematic of load application Stylus.

scale. The signal produced by the charge amplifier is received by the control PC.

The orientation of the stylus is adjustable so that it can rotate about the sample abutment and implant to best simulate the direction of the forces which exist in the oral cavity.

5.2. Mounting of sample

To best simulate the transfer of forces through the abutment and implant into the surrounding bone, it is important that the implant is mounted in a material that has similar properties to the bone that exists in the maxilla and mandible. The implant should be fixed to this material in a manner similar to that achieved by osseointegration to ascertain identical load transfer properties. This is achieved with a light polymerising resin composite that has an elastic modulus of 10.5 GPa, which is similar to that of the bone that exists in the mandible [15]. The test sample mounted in a block of this resin will be of a standard size and will be located and rigidly held in a repeatable position on the test apparatus.

5.3. Control and monitoring

A PC with data acquisition hardware and software is used to control the test rig and to monitor the measurable variables which are:

- Number of cycles.
- Frequency of cycles.
- Magnitude of applied force (control and measure).
- Linear and rotational displacement of abutment relative to implant.

The associated software package is required to perform many calculations and construct graphical representations relating to the following:

- Calculate component forces if load is applied at an angle.
- Graph deflection/rotation relative to magnitude of loading.
- Graph deflection/rotation relative to number of cycles.
- Actual and estimated number of cycles to cause failure of interface.
- Actual and estimated magnitude of loading to cause failure of interface.

5.4. Quantification

The status of the interface between the abutment and the implant is quantified with relation to the deflection of the abutment and of any rotational displacement which may be experienced during testing. These parameters are measured with non-contact proximity sensors.

6. Conclusion

This test apparatus is now capable of performing complex force simulations on a variety of dental implant system configurations. The configurations are defined by implant diameter, length, angle of insertion, abutment length and angle of inclination. The configurations which tests show as more suitable to specific loading conditions will be recommended for use in the oral cavity where the specific loading conditions exist. This will result in a Wöhler (S–N) curve for a particular implant configuration.

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