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Fatigue Life Prediction of Commercial Dental Implants Based on Biomechanical Parameters: A Review

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Abstract

Dental implant is a surgical component that interfaces with the bone of the jaw to support a dental prosthesis. Dental implants are used to retain and support fixed and removable dental prostheses. Dental implants are subjected to continuous loading due to the mastication forces which makes it necessary to study the effect of fatigue life. Fatigue life depends on the implant design, different biomaterials as well as morphological characteristics of the patient.

The objective is to study the effect of different biomechanical parameters on the fatigue behaviour of commercially available dental implants. The effect of the surface roughness and surface coating techniques is being studied for the commercial dental implant. A study on the properties of the biomaterials available for the dental implants is carried out. The geometric parameters of the available commercial dental implants are varied and the effect on the fatigue life is observed on the basis of probabilistic method which predicts the failure probability of the implant. Finally an implant based on the biomechanical parameters is proposed owing to the maximum life in fatigue failure A brief study on the surface coating techniques is done for the commercial dental implant.

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Introduction

A dental implant is a Titanium alloy biomaterial used to replace the root of missing teeth achieving a strong, stable and long lasting interface with the surrounding bone in a process known as osseointegration [1,2] Dental implants are subjected to continuous loading due to the mastication forces which makes it necessary to study the effect of fatigue life. Fatigue life depends on the implant design, different biomaterials as well as morphological characteristics of the patient.

The tremendous success of dental implants has been tempered in some prosthetic applications by complications such as screw loosening, screw fracture, gold cylinder fracture, framework fracture, and infrequently, implant fracture [3]. In order to avoid such problematic and design a successful dental implant, the main objective should be to ensure that the implant can support bitting forces and deliver them safely to interfacial tissues over the long term [4].

The objectives of this study is to review the contemporary knowledge about the influencing biomechanical parameters affecting the fatigue life of dental implant as well as osseointegration process of dental implants, analyze the currently available implant surface modification techniques and their limitation, also discuss the future trends in surface bioengineering to enhance their biological performance.

Fatigue in Dental Implants

The main aim of design of dental implants is to ensure that the implant can support biting forces and deliver them safely to interfacial tissues over the long-term [5]. Dental implants are subjected to many loading cycles during their life, mainly those produced during mastication. Mastication forces act on a repeated or fluctuating manner and result in strains and micro motions that introduce fatigue failure of the dental implants and may cause them to break, with serious consequences from a clinical standpoint [6].

Factors affecting on fatigue Failure

Fatigue is the weakening of a material caused by repeatedly applied loads. It is the progressive and localized structural damage that occurs when a material is subjected to cyclic loading. Fatigue occurs when a material is subjected to repeat loading and unloading. Factors affecting on fatigue failure is mention below:

1. Cyclic stress state: Depending on the complexity of the geometry and the loading, one or more properties of the stress state need to be considered, such as stress amplitude, mean stress, biaxiality, in-phase or out-of-phase shear stress, and load sequence. The forces act on a repeated or fluctuating manner and result in strains and micromotions that can introduce fatigue failure of the dental implant.
2. Geometry: Notches and variation in cross section throughout a part lead to stress concentrations where fatigue cracks initiate.
3. Implant Material: Fatigue life, as well as the behaviour during cyclic loading, varies widely for different materials, e.g. composites and polymers differ markedly from metals.
4. Surface quality: Surface roughness can cause microscopic stress concentrations that lower the fatigue strength. Compressive residual stresses can be introduced in the surface by e.g. shot peening to increase fatigue life. Such techniques for producing surface stress are often referred to as peening, whatever the mechanism used to produce the stress. Low plasticity

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burnishing, laser peening, and ultrasonic impact treatment can also produce this surface compressive stress and can increase the fatigue life of the component. This improvement is normally observed only for high-cycle fatigue.

5. Residual stresses: Welding, cutting, casting, grinding, and other manufacturing processes involving heat or deformation can produce high levels of tensile residual stress, which decreases the fatigue strength.

6. Size and distribution of internal defects: Casting defects such as gas porosity voids, non-metallic inclusions and shrinkage voids can significantly reduce fatigue strength.

7. Direction of loading: For non-isotropic materials, fatigue strength depends on the direction of the principal stresses.

8. Grain size: For most metals, smaller grains yield longer fatigue lives, however, the presence of surface defects or scratches will have a greater influence than in a coarse grained alloy.

9. Temperature: Extreme high or low temperatures can decrease fatigue strength.

Biomechanical Parameters

Bio-materials

Biomaterials are those materials that are compatible with the living tissues. The physical properties of the materials, their potential to corrode in the tissue environment, their surface configuration, tissue induction and their potential for eliciting inflammation or rejection response are all important factors under this area. The biomaterial discipline has evolved significantly over the past decades. The goal of biomaterial research has been and continued to develop implant materials that induce predictable, control guided and rapid healing of interfacial tissues both hard and soft [7].

Titanium has commonly been used for the manufacture of dental implants due to its properties such as low modulus of elasticity, low weight, high strength-to-weight ratio and easy shaping and finishing [8]. Dental implants are usually made from commercially pure titanium or titanium alloys. Pure titanium is generally used when corrosion resistance is of high importance than mechanical strength whereas for instances the alloy Ti-6Al-4V, is used when mechanical strength and fatigue resistance is required [9].

Materials used in medical devices are subjected to high stresses and high cycle loading. This very demanding condition coupled with the aggressive body environment leads to fatigue failure of metallic, polymeric and ceramic implants. A fatigue wear process involving fretting causes the generation of wear debris which invokes acute host–tissue reactions which tend to aggravate the fatigue problems of the biomaterial by producing enzymes and chemicals that are highly corrosive. The methods of fatigue evaluation for biomaterials must include wear debris morphology characterisation so as to understand the host–tissue reaction to wear debris and simulate as close as possible the imposed stress–strain and environmental conditions in vivo[10].

Surface Characteristics

Implant surface characteristics including topography, chemistry, surface charge and biological interface processes during early healing period. In fact, they play an extremely important role in the reconstruction of implant bone tissue. [11]

Surface roughness is the primary component of texture and refers to high frequency irregularities. In the case of dental implants, surface roughness consists of fine imperfections on the order of micrometer due to the cutting process or due to a surface treatment. In machined implants, roughness is closely related to the cutting tool and consists of a regular pattern of shallow grooves.

Surface waviness refers to the secondary component of texture upon which roughness is superimposed. It is as a series of regular deviations of approximately sinusoidal shape and a size on the order of millimetres. It is attributed to the deformations and vibrations of the machine and the part during manufacturing.

Surface form is some irregularity the general shape of the surface, neglecting roughness and waviness, which is frequently caused by errors in the machine tool guideway and deformations due to stress patterns in the component [12].

Surface Roughness

Surfaces of bone implants represent the site of interaction with the surrounding living tissue and are therefore crucial to enhance the biological performance of implants. Surface engineering aims to design implants of improved biological performance which are able to modulate and control the response of living tissue. Osseointegration is seen as the close contact between bone and implant, and the interest on surface engineering has to be understood as an important and natural trend. The bone response, which means rate, quantity and quality, are related to implant surface properties. The implant surface modifies molecular and cellular activity at the interface, so that high roughness surfaces allow greater cells and molecules adhesion [13, 14]

Generally, surface engineering includes modification of topographical (i.e., roughness) and chemical (i.e., coating) characteristics of a medical device. Topographical modifications of titanium and its alloys were aimed at increasing the roughness of implant surfaces, thus increasing the surface area of implants compared to larger smooth surfaces. The increased surface area increases cell attachment and augments the biomechanical interlocking between bone tissue and the implant. There are several methods used to modify implant surface characteristics with the main objective of improving the biomechanical properties such as removal of surface contaminants, improvement of wear and corrosion resistance on rough surfaces and stimulation of bone formation.[15]. Among several techniques the most common techniques used to improve fatigue life of dental implants are as below:

Machined or turned Surface

The dental implant is simply turned on machine to have a relatively smooth surface after being manufactured, and then it is submitted to cleaning, decontamination and sterilization procedures [16]. These surfaces are usually called “smooth” since scanning electron microscopy analysis showed that they have grooves, ridges and marks (Figure 1) derived from tools used for their manufacturing which provides mechanical resistance through bone interlocking [17].

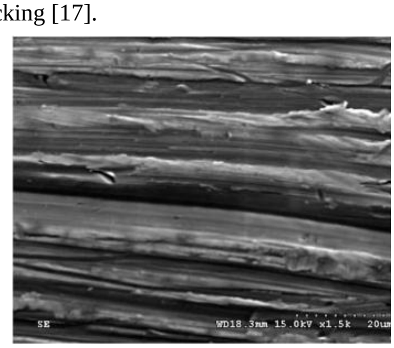

Figure 1: Scanning electron micrograph of a machined implant surface[22]

However, the main disadvantage regarding the morphology of non-treated implants is the fact that osteoblastic cells are prone to grow along the grooves existing on the surface, which in terms of clinical implications means a longer healing time required. The success rates of turned implants in challenging situations such as low bone density has been reported to be lesser than when placed in areas with good bone quality. Studies have shown lower primary stability for the turned implants, they demonstrated secondary stability values and clinical success rates similar to modified implants [18].

Grit Blasting

Grit-blasting, consists in the propulsion towards the metallic substrate of hard ceramic particles that are projected through a nozzle at high velocity by means of compressed air and leading to different surface roughness, depending on the size of the ceramic particles[19]. The grit blasting technique usually is performed with particles of silica (sand), alumina, titanium dioxide or resorbable bio-ceramics such as calcium phosphate [20]. Alumina (Al2O3) is frequently used as a blasting material, however, it is often embedded into the implant surface and residue remains even after ultrasonic cleaning, acid passivation and sterilization. It has been documented that these particles have been released into the surrounding tissues and interfered with the osseointegration of the implants. Moreover, this chemical heterogeneity of the implant surface may decrease the excellent corrosion resistance of titanium in a physiological environment. Titanium oxide (TiO2) particles with an average size of 25 µm can produce moderately rough surfaces in the 1–2 µm range on dental implants. Even though blasting introduced stress raisers, it improve the fatigue behaviour of Ti alloy. [20]

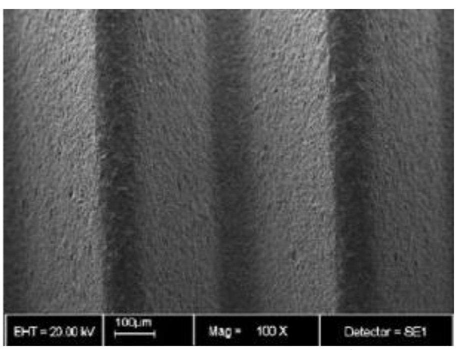

Figure 2 : Scanning electron micrograph of a Grit blasting Implant surface [20]

Anodic Oxidation

In order to alter the topography and composition of the surface oxide layer of the implants, micro- or nano-porous surfaces may also be produced by potentiostatic or galvanostatic anodization of titanium in strong acids, such as sulfuric acid, phosphoric acid, nitric acid and hydrogen fluoride at high current density or potential[21]. When strong acids are used in an electrolyte solution, the oxide layer will be dissolved along current convection lines and thickened in other regions which creates micro-or nano-pores on the titanium surface (shown in fig. 2). This electrochemical process results in an increased thickness and modified crystalline structure of the titanium oxide layer. However, it is a complex procedure and depends on various parameters such as current density, concentration of acids, composition and electrolyte temperature [18].

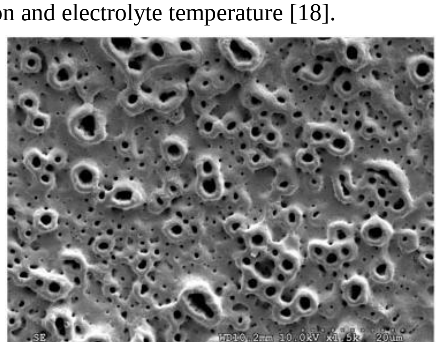

Figure 3 : Scanning electron micrograph of an anodized Implant surface [22]

Acid Etching

The immersion of a titanium dental implant in strong acids such as hydrochloric acid , sulfuric acid, nitric acid and hydrogen fluoride is another method of surface modification which produces micro pits on titanium surfaces with sizes ranging from 0.5 to 2 µm in diameter.[23] The resulting surface shows an homogenous roughness, increased active surface area and improved adhesion of osteoblastic lineage cells . Dual acid -etching consist in the immersion of titanium implants for several minutes in a mixture of concentrated HCl and H 2SO4 heated above 100°C to produce a micro-rough surface (Figure 4) that may enhance the osteoconductive process through the attachment of fibrin and osteogenic cells, resulting in bone formation directly on the surface of the implant.[24] On the other hand, acid-etching can lead to hydrogen embrittlement of the titanium, creating micro cracks on its surface that could reduce the fatigue resistance of the implants. Indeed, experimental studies have reported the absorption of hydrogen by titanium in a biological environment. This hydrogen embrittlement of titanium is also associated with the formation of a brittle hybrid phase, leading to a reduction in the ductility of the titanium which is related to the occurrence of fracture in dental implants. [20]

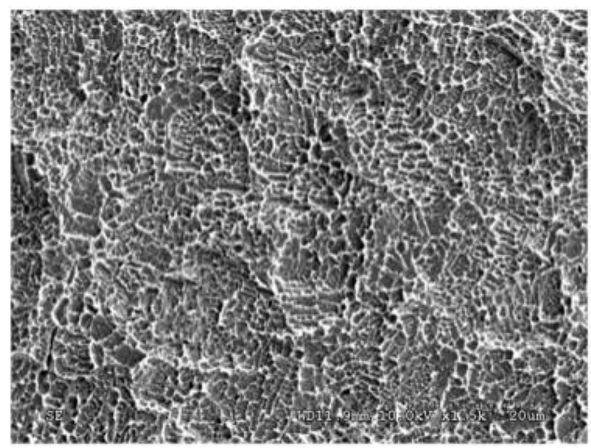

Figure 4: Scanning electron micrograph of an acid etching Implant surface [22]

Plasma Spraying

Titanium plasma-spraying (TPS) consists in injecting titanium particles into a plasma torch at high temperature. This particles are projected on to the surface of the implants where they condense and fuse together, forming a film about 30 µm thick (Figure 6) resulting in an average roughness of around 7 µm. The TPS processing may increase the surface area of dental implants up to approximately six times the initial surface area [25] and is dependent on implant geometry and processing variables, such as initial powder size, plasma temperature, and distance between the nozzle output and target.[26] One of the major concerns with plasma-sprayed coatings is the possible delamination of the coating from the surface of the titanium implant and failure at the implant-coating interface despite the fact that the coating is well-attached to the bone tissue. In a pre-clinical study using minipigs, the bone/implant interface formed faster with a TPS surface than with smooth surface implants presenting an average roughness of 0.2 µm. However, particles of titanium have sometimes been found in the bone adjacent to these implants.[27] However, while an increase of six times the original surface area may be a favourable scenario for bone growth and apposition it also becomes a risk factor when there is an exposure of the implant surface to the oral fluids and bacteria. In addition, a major risk with high surface roughness concerns difficulties in controlling peri-implantitis due to the intercommunication between porous regions facilitates migration of pathogens to inner bone areas, potentially compromising the success of the implant therapy.[28]

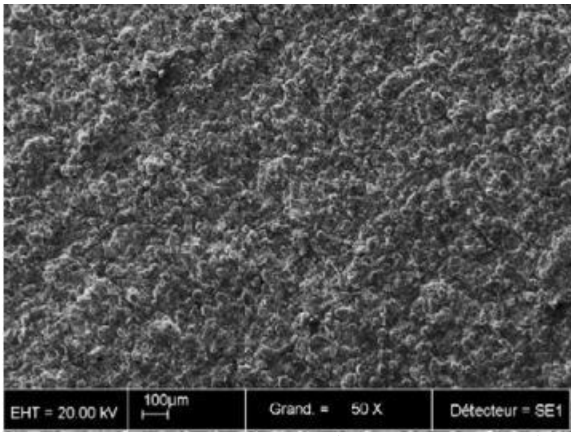

Figure 5: Scanning electron micrograph of a Plasma spraying surface [20]

Calcium phosphate coatings

Calcium phosphate (CaP) coatings, mainly composed by hydroxyapatite, has been used as a biocompatible, osteoconductive and resorbable blasting materials[29] . The idea behind the clinical use of hydroxyapatite is to use a compound with a similar chemical composition as the mineral phase of the bone in order to avoid connective tissue encapsulation and promote peri-implant bone apposition[30]. For this matter, the CaP coatings disclose osteoconductive properties allowing for the formation of bone on its surface by attachment, migration, differentiation and proliferation of bone-forming cells.

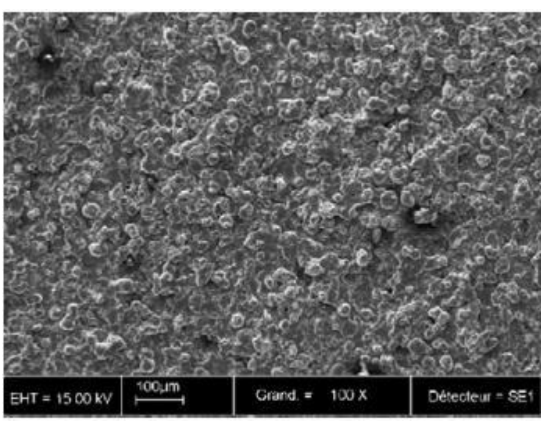

Figure 6: Calcium Phosphate coated Implant surface[29]

In the resorbable ones, following implantation, the release of calcium phosphate into the peri-implant region increases the saturation of body fluids and precipitates a biological apatite onto the surface of the implant.[31] This layer of biological apatite might contain endogenous proteins and serve as a matrix for osteogenic cell attachment and growth and therefore, improve osseointegration. [32]

Plasma Sprayed Hydroxyapatite (PSHA) coatings are the most commonly found among the commercially available calcium phosphate coatings. The HA ceramic particles are heated to extremely high temperatures and deposited at a high velocity onto the metal surface where they condense and fuse together forming a 20–50 µm thick film.[30] This resulting surface shows enhanced bioactivity observed at early implantation times, however, the mechanical resistance of the interface between the coating and titanium is considered to be a weak point, and some cases of implant failure have been reported. [25]Furthermore, it is recognized that regardless the resorbable blasting material, the release of particles of varied size from the surface may result in an inflammatory response detrimental to hard tissue integration. Despite the substantially for PSHA-coated implants, this type of implant has fallen out of favour in dental practice as studies have shown that coatings do not uniformly dissolve/degrade after long periods in function [30].

Implant Geometry

The geometric parameters of the available commercial dental implants are varied and the effect on the fatigue life is observed on the basis of probabilistic method which predicts the failure probability of the implant.

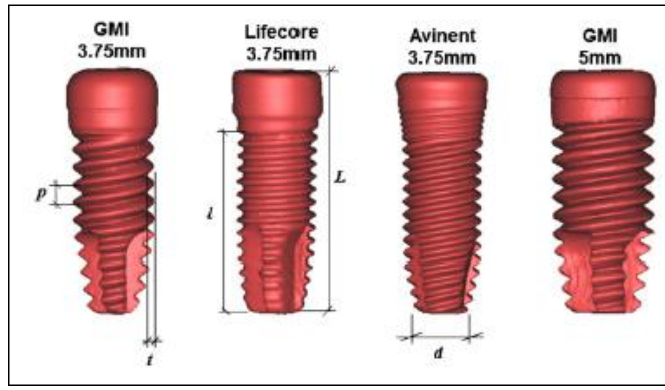

Figure 7 : Variation in geometric parameters in commercial dental implants [33]

In the above figure different dental implants are shown with variation in their geometric properties. Here, L is implant total length; l denotes bone-implant interface length; d indicates implant diameter; p is average thread pitch; t is average thread depth; angle of convergence is a physical property for the crown preparation it has to be as close to parallel as possible to attain adequate retention/resistance.

The probabilistic methodology proposed was applied to evaluate the failure probability of the different implant designs with the same implant diameter. The evolution of the failure probability was evaluated from one loading cycle to 12 million loading cycles, considering one million loading cycles as approximately one year of in vivo service [33].

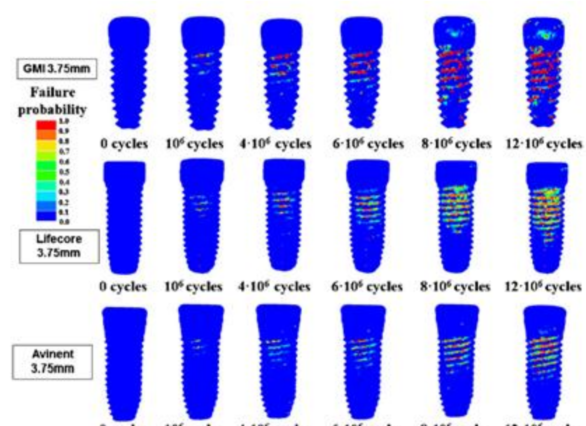

Figure 8 : Failure Probability of different dental implants due to change in geometric properties[33]

The contours of the evolution of the failure probability were represented for the GMI, Life core and Avinent implants with a diameter of 3.75 mm and for the GMI 5 mm diameter implant versus the GMI 3.75 mm diameter implant In all cases, the highest failure probability was located at the upper screw-threads, which was expected because stress concentrations appeared around these regions. Failure probabilities were similar among the implants with the same diameter. Lifecore and Avinent implants, both with a diameter of 3.75 mm, had local failure probabilities of 0.3 and 0.4, respectively, after 6 million of cycles (Figure 8).[33]

Bone Quality

Human Jaw Bone quality plays a significant role in determining the fatigue life of the implant as they retain and transfer the continuously variable and changing masticatory forces acting on implant. The bone density available for implant placement reflects a number of biomechanical properties, such as strength and modulus of elasticity and highly influences the implant design utilized, treatment planning and healing time required [34].

Misch separates bone quality and volume into distinct classifications. Especially bone quality is classified into four groups D1, D2, D3 and D4 as mention below:

1. D1 type of bone -Dense Cortical Bone
2. D2 type of bone-Dense-to-thick porous Cortical and Coarse trabecular Bone
3. D3 type of bone-Thin porous cortical and fine trabecular bone
4. D4 type of bone- Fine trabecular bone

The interplay of bone quality and volume has a direct influence on the success rate of dental implants. [37]

Implant Stability

Primary stability has been regarded as a prerequisite for osseointegration of dental implants. The primary stability of dental implants can be regarded as the mechanical stability obtained immediately after insertion. Primary stability affects the strength, rigidity and resistance to movement of the implant before tissue healing and increases with increasing resistance to implant insertion.

Secondary stability is provided by osseointegration and requires a direct contact between implant and bone without the interposition of connective tissue. From a theoretical standpoint, as the implant stability increases, micro movements decrease and the success rate of implantation increases [35].

Assessment Techniques for Implant Stability

Dental implants are widely used clinically and have allowed considerable progresses in oral and maxillofacial surgery, to restore missing teeth. However, implant failures, which may have dramatic consequences, still occur and remain difficult to anticipate. The implant stability is determined by the quantity and biomechanical quality of bone tissue around the implant. Assessing the implant stability is a difficult multiscale problem due to the complex heterogeneous nature of bone and to remodeling phenomena [35].

Conclusions

The success in implant dentistry depends on the biomechanical parameters play an important factor in predicting the fatigue life of the dental implant. Various factors affecting the fatigue life of the dental implants are studied in various sections. Biomaterials used for making the dental implants also have an effect on the fatigue life. Various biomaterial properties were studied for and titanium and its alloys were found out to be the most promising biomaterials for the clinical applications.

A large amount of studies compare a specific rough surface with machined surfaces, it is widely acknowledge that rough surfaces have better performance than machined or turned surfaces. Surface finish has an effect on the bone implant interface and finally contributing to the fatigue life of the implant. Despite the importance of roughness in osseointegration, there is no standard for the roughness of dental implants. Over the past decade, several techniques were used to evaluate the implant stability still no definite method is established to evaluate implant stability.

Although titanium is used extensively as a biomaterial, there are still doubts about the procedure to obtain the best biological response. Special relevance is the study of commercially pure titanium dental implant osseointegration. The strategy to improve dental implant osseointegration is to alter the biocompatibility of titanium implant surfaces, modifying the surgical technique and changing the implant design. Clinical trials comparing different commercially available implant surfaces under similar clinical situations are rarely disclosed, making the outcome assessment between different surfaces quite difficult. The low quality and quantity of bone tissue can be partially compensated using thicker and longer implants.

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