FACTORS EFFECTING PRIMARY STABILITY OF MINI-IMPLANTS *IN VITRO*

by

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Abstract

Objectives: Mini-implants (MIs) are now routinely used in orthodontic treatments; however, compared to conventional implants, MIs suffer higher failure. Achieving primary stability (PS) appears to be the most important factor predicting success of MIs. Factors such as implant diameter, length, and bone quality are known to influence PS in conventional implants; however, little is known of the effects of these factors on PS in MIs. Therefore, the aim of this study was to investigate the effect of MI's diameter, length and the presence of cortical bone in PS.

Methods: AbsoAnchor TAD design from Dentos with 1.5,1.7, and 2mm diameters; 6,8, and 10mm length were placed in Polyurethane bone blocks with densities of cancellous bone (GP-20). MIs were also placed in blocks were sandwiched with 1 or 2mm polyurethane sheets, which simulated cortical bone density. Four MIs in each group were placed using recommended procedures. PS of MIs was measured with Periotest and Osstell by three testers. The Cronbach Alpha inter-examiners reliability test was used to evaluate agreement among the testers. PS data were analyzed with multifactorial ANOVA to detect the significant influence of each factor in MIs' PS ($\alpha = 0.05$).

Results: Both Osstell and Periotest indicated significant increase in PS ($p<0.05$) when cortical bone sheet of 1 or 2 mm thickness were in contact with MIs. MIs' diameter had significant influence in PS, indicating that MIs with wider diameter (1.7-2 mm) had significantly higher PS ($p < 0.05$) in both cancellous and cortical sandwiched models.

There was no significant difference in PS when different lengths of MIs were used in cortical sandwiched models; however, an increase in MIs' length appeared to increase PS only in soft bone blocks, which simulated the hardness of the cancellous bone.

Conclusions: Important factors in achieving PS in MIs appear to be bone type and implant

diameter in heterogeneous bone (combined cancellous & cortical bone) often found *in vivo*. An increase in the length of the MIs only improves PS in homogeneous soft bone (cancellous bone). Recognizing factors improving PS would expect to decrease unnecessary trauma and failure rate in children and adolescence.

Lay Summary

Mini-implants (MIs) are becoming an integral part of the modern orthodontic treatments. In contrast to conventional implants, MIs are reported to have higher failure rate. It is documented that achieving primary stability (PS) is one fundamental requirement for MIs success. PS occurs immediately after MIs placement. There are several factors affect PS of conventional implants such as: implant design, surgical site, bone type and surgical protocol. There is little information available on the role of similar factors on MIs' stability. The simulation research reported in this thesis was conducted to investigate the effects of MIs design factors including the length, diameter, and the recipient bone quality on the PS of a commercially-available MI. The results indicated that both diameter of MI and cortical bone thickness appear to significantly improve PS. The length of the MI only contributes to PS in soft bone blocks, which simulated hardness of the cancellous bone.

Preface

This research project was designed and conducted by Dr. Hadeel Al-Ohali under the supervision of Dr. Babak Chehroudi and the guidance of Drs. Edwin Yen, N. Dorin Ruse, and Siamak Arzanpour. The data was collected at the laboratory of Dr. S. Arzanpour at the School of Mechatronic Systems Engineering at Simon Fraser University (SFU). The orthodontic mini-implants used in this study were donated by Dentos / AbsoAnchor. No ethics approval was needed or obtained for this study. The abstract was presented as oral presentation during the AADR meeting in March 2016, and as poster presentation during the Pacific Dental Conference, in March 2017.

Table of Contents

List of Tables

List of Figures

List of Abbreviations

PS	Primary Stability
TADs	Temporary Anchorage Devices
MI	Mini-implant
BMD	Bone Mineral Density.
BSBAs	Bracket Screw Bone Anchors:
MIT	Maximum Insertion Torque

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Dedication

I would like to dedicate this project to my Parents; your support and encouragement have allowed me to fulfill a dream of a lifetime.

Mom and Dad, thank you from the bottom of my heart for your unconditional love and commitment.

To my Beloved Brothers; Jarrah, Naif, Faisal and Ahmed: cannot imagine the world without you. I only know it would be a much different, much less comforting place.

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Chapter 1: Introduction

A fundamental concept in a successful orthodontic treatment is the application of principles of anchorage, which in simple term is defined as the degree of resistance to displacement. In orthodontic treatments it refers to the resistive value of posterior teeth toward mesial movement.(Wu, Kuang et al. 2009). Orthodontists have historically used a variety of appliances and strategies to enhance anchorage, particularly when minimal movement of the teeth providing the anchorage is desired. A popular strategy to achieve anchorage is to use anchorage-enhancing appliances such as a headgear. However, these appliances provide discontinuous anchorage only during the period of active wear, which is less than 12 hours a day. Most orthodontic retractive forces are expected to be continuous. A greater problem with headgears is achieving adequate levels of patient compliance and, lastly, it can be dangerous if it is worn during periods of physical activity. Generally, anchorage-enhancing appliances can be divided into extraoral, intraoral, skeletal, and temporary anchorage devices (TADS).

1.1 Extraoral appliances

The most popular example of extraoral devices is a face bow headgear or a J hook headgear. Headgears transmit forces to the maxilla through special attachments to the molars with bands and headgear tubes. The effect of headgear, whether orthopedic or dental, is largely dependant on how the appliance is used. The direction of force applied upon molars is determined by the headgear’s resultant force and the center of resistance at the attached molars. If the resultant headgear force is directed occlusally or gingivally from the tooth’s center of resistance then the crown will tip distally or mesially, respectively. In contrast, the bodily movement occurs if the resultant force is directed through the tooth’s center of resistance. Appropriate use of a headgear provides reliable extraoral anchorage and prevent mesial movement of the posterior teeth while retracting anterior teeth. The clinician should evaluate the specific anchorage needs of the system and adjust the force vectors of the headgear accordingly. Orthodontic headgear is often poorly received by patients with resultant poor compliance. (Jacobson 1979).Twelve years old or younger patients show greater compliance than older children (Weiss and Eiser 1977). The socioeconomic status was also found to be related to compliance with patients in lower-middle or lower classes displaying greater patient compliance (Starnbach and Kaplan 1975).

1.2 Intraoral appliances

These appliances also known as the pendulum appliance and/or the distal jet are anchorage devices and are designed to distalize maxillary molars and enjoy more patients' compliance (Fig. 1, 2, 3). They are consist of an anchorage unit, usually connected to premolars or deciduous molars and may also have an acrylic Nance button and a force-generating unit, which is responsible for moving molars distally.(Fortini, Lupoli et al. 2004). Generally, these appliances result in tipping distal movement of maxillary molars (Runge, Martin et al. 1999). Such distal tipping may also result in unfavorable reciprocal movement of other teeth, a similar situation to what is seen when anchorage obtained within the dental arch. These appliances also known as "noncompliant appliances", can also cause varying degrees of anchorage loss, which leads to incisor protrusion, as well as, upper lip protrusion (Fortini, Lupoli et al. 2004).

Figure 1 Image of a Nance appliance

Figure 2 Image of TPA Transpalatal Arch

Figure 3 Image of LLHA, Lower Lingual Holding Arch

1.3 Skeletal Anchorage

Skeletal anchorage provides absolute anchorage and has no adverse moving effects on anchored components. The concept of using implantable devices for skeletal anchorage has been around for the last fifty years. There are different forms of skeletal anchorages including conventional dental implant, endosseous titanium implants (onplant), mini-plate and mini-implant.

The earliest documented application of skeletal anchorage was reported by Gainforth and Higley in 1940. In their experiment, vitallium bone screws and wires were used for anchorage. Later in 1979, Smith reported that dental implants could act as ankylosed teeth and be used as anchorage for orthodontic movements. In 1988, Shapiro et. al. further established the use of dental implants for orthodontic anchorage. Midpalatal implants (Onplants) were later introduced by Block et. al (1995). They used hydroxyapatite-coated onplant in the palatal midline for orthodontic anchorage. Onplants are typically very short and placed at the midpalate to provide absolute anchorage. In contrast, larger-sized conventional dental implants, also used for anchorage, are restricted to limited areas because of anatomical limitation. (Roberts, Smith et al. 1984) (Turley, Kean et al. 1988)

Rigid fixation plates are another kind of skeletal anchorage devices that were introduced and used in orthodontic treatment by Umemori et.al.

Miniplate, is one example of a skeletal anchorage. It is secured to the bone with two or three fixation screws and have an extension arm designed to cross through the mucosa into the oral cavity. The arm, which measures 10.5-16.5 mm, serves as the point of anchorage for the orthodontic appliance. Miniplates can be placed in various locations, including the zygomatic buttress, periform rim, and the lateral border of the mandible(Garetto, Chen et al. 1995). A surgical flap is required to place Miniplates, and a lengthy healing period is recommended

(Daimaruya, Takahashi et al. 2003). A second surgical procedure is also required to remove the plates when they are no longer needed.

Miniplates can withstand heavy forces, but their main disadvantages are: complicated surgery, the need for a second surgery for removal and limited available anatomical sites.

Unfortunately, all skeletal anchorage devices require multiple invasive surgical procedures, have anatomical limitation, involve high cost and a lengthy healing period of 4 to 6 months for integration into the bone before loading.

1.4 Temporary Anchorage Devices (TADs)

TAD,s also called mini-screws (MS) or mini-implants (MI), are very small screw-like devices used widely in contemporary orthodontic treatments. These devices were introduced to orthodontics during the past two decades and their use quickly spread into clinical practice. TADs or MIs provide reliable anchorage, have low cost, and benefit from simplified surgical protocol.

In 1998, the MIs, which were 2 mm in diameter were first used in orthodontic treatments. MIs are, commonly, of cylindrical or conical shape, measure about 6 to 8 mm in length and 1.2 to 2.3 mm in diameter. MIs are also generally threaded, allowing either passive or self-tapping placement. As opposed to the conventional implants, MIs are placed at 90 or 45-degree angle to the alveolar bone.

A schematic example of a MI is given in Fig.4. (dentaire 2017)

Figure 4 Schematic example Mini-implant, MI, dentaire 2017

MIs have three components;

i. The head, that is designed to attach to several systems of traction (wires, coils, elastics, other elastomeric devices),

ii. The neck, designed often with a specific angle to facilitate insertion into the bone, and

iii. The body, often available with specific surface treatment to increase bone implant contact.

Current generations of MIs are generally made of Titanium alloy for strength and biocompatibility. MIs are becoming increasingly popular because of the low cost, simple surgical protocol , less invasive surgery , compliance and ease of removal at the conclusion of the orthodontic treatment. Therefore, this thesis focuses mainly on MIs and potential factors that may influence their clinical function.

1.5 MIs Applications, Advantages and Orientations

MI-supported anchorage is an excellent method for moving multiple teeth; en masse retraction; molars distalization or mesialization; molars intrusion or extrusion; correction of canted or tilted occlusal planes; moderate crowding; and vertical control (Lee, Kim et al. 2007).

As opposed to conventional implants, MIs are smaller, easier to place, less invasive (flapless surgery), have few anatomic limitations, can be placed in multiple sites, are more cost effective, can be loaded immediately, and offer less post-operative pain. (Lin and Liou 2003) (Melsen 2005). Also, a second implant exposure surgical procedure is not needed. (Costa, Raffainl et al. 1998) (Liou, Pai et al. 2004) (Melsen 2005).

MIs can be placed at both buccal or lingual bone plate in either diagonal or perpendicular direction (Kyung, Park et al. 2008). In diagonal or oblique orientation, MIs are placed 30~60 degrees to the long axes of the remaining teeth. This method is used when the inter-radicular space between the teeth is limited. This kind of orientations can reduce the risk of injuries to adjacent roots during placement. In perpendicular orientation placement method, MIs are inserted into the bone perpendicular to the alveolar bone surface. This orientation is used only when there is sufficient space present between the roots of the adjacent teeth.

1.6 MIs stability

The clinical success of MIs depends on their stability at the insertion site. Generally, stability refers to the absence of mobility in the bone bed after MI placement. MI stability can be divided into primary and secondary stability. Primary stability (PS) refers to the degree of mechanical interlocking present immediately following MIs insertion. PS plays significant role in both short-term and long-term clinical function of MIs (Simon and Caputo 2002, Gapski, Wang et al. 2003). There are several factors that can influence PS of MIs; these factors include MI design, insertion technique, bone quality/quantity, and bone type at the insertion site.

Secondary stability, in contrast, is a biological term and relates to the degree of implant/bone osseointegration, which is a term coined by Branemark as the direct structural and functional connection between living bone and the surface of a load-carrying implant (Branemark 1983, Albrektsson and Johansson 2001)

Several histological studies have shown that titanium MIs osseointegration defined histologically as bone/implant contact, is less than half of that observed in conventional dental implants (Costa, Raffainl et al. 1998).

In an animal study by Bart Vande (2007), four bracket screw bone anchors (BSBAs) were inserted in the alveolar bone of the lower jaw in five male beagle dogs. The overall mean of osseointegration (bone/implant) contact of all mini-screws did not exceed 74.48 % and there was no significant difference with respect to loading time or site ($P > 0.05$). This partial osseointegration of titanium-alloy MIs is a distinct advantage in orthodontic applications because, while it provides effective anchorage, it can be easily removed following completion of the orthodontic treatment. (Vande Vannet, 2007) (Vande Vannet, Sabzevar et al. 2007)

The success rate of MIs refers to the satisfactory clinical function during the entire period of the active orthodontic treatment. (Reynders, Ronchi et al. 2009) reported that success rate of MIs with diameters of 1.0 to 2.3 mm ranged from 0% to 100%.

On the other hand, (Papageorgiou, Zogakis et al. 2012) in a meta-analysis of the risk factors for MIs failure, reported a mean failure rate of mini-implants of 13.5%, and the failure of MIs was related to the method of insertion, and placement site.

Achieving PS appears to be the most important factor predicting success of MIs. Therefore, measuring and monitoring MIs stability is very important and might predict the future clinical success.

The relationship of primary and secondary stability can be observed in the characteristic curves shown in (Fig.5). Orthodontists often observe clinically the overall stability, which is composed of both primary and secondary stability. Immediately after MI placement, all observed stability is due to PS (i.e., there is no secondary stability). Overall PS decreases rapidly at first, as secondary stability takes over. The point at which the primary and secondary stability curves cross is when

MIs are least stable, and it can be identified by the dip in the stability curve. The rate at which secondary stability increases begins to slow down after 4–5 weeks of healing. When healing has occurred and the bone has remodeled, overall MIs stability is primarily due to the secondary stability.

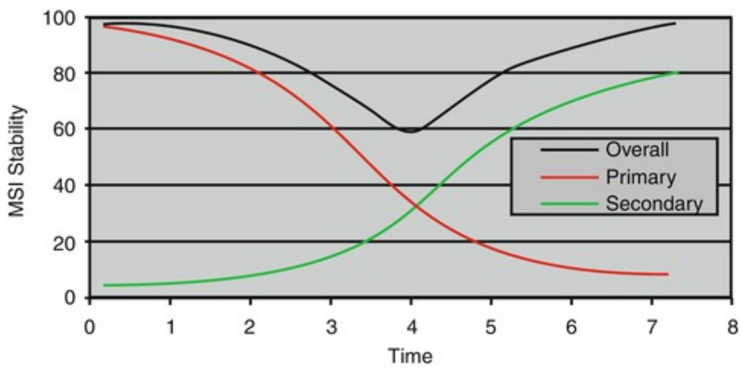

Figure 5 Overall primary and secondary stability curves of mini-implants as measured weekly by Osstell ISQ (dentistry 2017).

1.7 Methods of measuring the stability

Accurate measuring and monitoring of MIs stability is an important method of preventing MIs future failure. Generally, there are two available methods for measuring stability of MIs, which can be categorized as invasive and non-invasive.

1.7.1 Invasive Methods

These methods are perhaps the most objective methods of measuring stability; however, because of the destructive nature of the methods they often result in total loss of the MIs.

i- Histology

This technique estimates the implant's stability indirectly by examining the bone–implant interface using histological sections and microscopic techniques. Histomorphometry, is a quantitative method for measuring the percentage of bone to implant contact also known as BIC in the literature. In addition, the osteogenic cells and bone matrix can also be quantified as an indicator of implant success and stability. (Sakin and Aylıkcı 2013)

ii- Cutting torque resistance analysis

This method was originally developed by Johansson and Strid and then improved by Friberg et al . It estimates PS indirectly, through evaluation of bone hardness during surgery. It is based on the energy (J/mm3) required for an electric motor to cut a unit volume of bone during implant surgery. This energy has been shown to correlate significantly with bone density, an important factor influencing MIs stability.

iii- Removal torque analysis

This method was developed by Roberts et al. and then improved by Johansson and Albrektsson. It measures the critical torque threshold when the bone–implant contact is broken. Removal torque value provides indirect information on the degree of bone-to-implant contact in a given implant.

iv- Insertion torque analysis

This technique is favoured by the clinicians and basically measures the amount of force that is applied to the implant at the time of insertion. Initially, implant placement insertion torque is minimal, then increases rapidly when the cortical bone is fully engaged. This analysis estimates the quality of the bone that supports the implants. Many studies have reported that the insertion torque value increases as the cortical bone thickness increases. (Pithon, Figueiredo et al. 2013)

v- Pullout test

Pullout test is another indirect method of measuring MIs stability. It measures the required tensional force applied vertically to pull the implant out of the bone. The force is applied parallel to the long axis of the implant. Pullout tests have been mainly used to evaluate MIs different designs and the mechanical interlocking between bone and MIs.

1.7.2 Non-invasive Methods

Non-invasive methods are mostly applied clinically to constantly monitor MIs stability without interfering with the interface.

i- Radiographic analysis

Radiographic evaluation is a common clinical method applied to evaluate implants after placement. Radiographs can estimate the density and the physical properties of the surrounding bone. In fact, this method is more popular with conventional dental implants, because of their orientation difference compared to MIs. Dental implants are oriented with their long axis parallel to the long axis of the adjacent teeth, which make them suitable for radiographic observations. Conventional bitewing radiographs can be used to evaluate the height of crestal bone around dental implants. On the other hand, these radiographic techniques may not be useful to evaluate MIs because they are not oriented at the same plane as dental implants (Sakin and Aylıkcı 2013). More sophisticated radiographic techniques, such as computed tomography (CT) and Cone beam computed tomography (CBCT), can be used to evaluate bone density before and after MIs placement. CBCT can also be used to quantitate trabecular bone thickness, number, separation, bone volume density (BV/TV), bone mineral density (BMD), and cortical bone thickness. (Marquezan, Lima et al. 2014). These techniques, however, tend to expose patients to significantly higher radiation compared to the conventional radiographic methods.

ii- Finite element analysis, FEA

Finite element modeling is a theoretical approach and provides a computer-simulated analysis, based on known material properties, such as: Young's Modulus, Poisson ratio, and bone density. The main limitations of FEA is that it is essentially a static analysis that is difficult to apply in all clinical situations.(Sakin and Aylıkcı 2013).

iii- Percussion test

This technique is one of the simplest methods that can be used to estimate implant stability. Percussion test is usually done with a metallic instrument. A "dull" sound indicates no osseointegration, while a "ringing" sound indicates successful osseointegration. However, this method is very subjective and is difficult to standardize clinically. (Adell 1985, Sakin and Aylıkcı 2013).

iv- Pulsed oscillation waveform

This method is based on the frequency and amplitude of the implant vibration induced by a small pulsed force. However, the sensitivity and accuracy of the pulsed oscillation waveform test depends on load directions, positions, and implant location resulting in large data variation.

v-Impact hammer method

This method is an updated and more objective version of the percussion test. Originally, it was developed to measure increasing tooth mobility during progression of periodontal disease. However, it was found to be more reliable in measuring dental implant stability(Gulden-Medizintechnik, Bensheim an der Bergstraße, Germany) (Schulte and Lukas 1993) (Lukas and Schulte 1990).

The Periotest device, seen in Figure 6 (Gulden) measures the reaction of the peri-implant tissues to a known magnitude of percussive force applied to the implant. The Periotest uses an electromagnetically controlled metallic tapping rod located in a designated handpiece. The implant's response is measured by a small accelerometer incorporated into the head of the device.

Figure 6 Image of a Periotest Device (Medizintechnik Gulden)

The contact time between the test object and tapping rod is measured and then converted into a quotient, the Periotest value (PTV). The PTV ranges from −8 for low mobility to + 50 for high mobility.

Periotest values Interpretation: (Gulden)

- -8 to 0, Good osseointegration; the implant is well integrated and can be loaded.
- +1 to +9, Clinical examination is required; in most cases implant loading is not (yet) possible
- +10 to +50, Osseointegration is insufficient; the implant must not be loaded.

Several studies including Nienkemper et. al. 2013 and Marquezen et.al.2014 reported using Periotest successfully to evaluate MIs stability.

vi- Resonance frequency analysis, RFA

In 1994, Meredith introduced a vibration non- destructive testing method: resonance frequency (RF). Since 1999, this method of analysis has been commercially available as the OsstellTM equipment, which can be seen in Fig. 7 (Integration Diagnostics, Göteborg, Sweden).

Figure 7 Image of OsstellTM Device manufactured by Integration Diagnostics (Göteborg, Sweden)

The Resonance frequency (RF) technique is based on a small transducer that contains two piezoelectric elements and is screwed on top of the implant or its abutment (Meredith, Alleyne et al. 1996). The first element is excited in the range of 5-15 KHz thus transmitting a harmless vibration to the bone implant interface; the response to this vibration is then registered by the second element, transmitted through an output cable to a frequency/response analyzer which interprets the signal into an Implant Stability Quotient (ISQ). The whole operation is executed by piezoelectric transducers, called Smart Pegs, that are screwed to the implant. Osstell Smart Pegs (as seen in Fig. 8) are delicate measurement devices, made from a soft metal with a zinc-coated magnet mounted.

Figure 8 Schematic Osstell SmartPegs

The Osstell instrument vibrates the Smart Peg through magnetic pulses and measures the resonance frequency. A firm attachment to the implant or abutment is needed in order for the Smart Peg to function properly. An example of this attachment can be seen in Fig. 9.(Osstell).

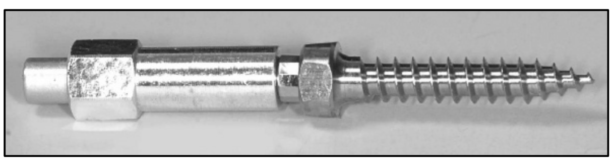

Figure 9 Osstell SmartPegs screwed to mini-implant

The OsstellTM transforms automatically the RF into Implant Stability Quotients (ISQ), which range from 1 to 100. The higher values indicate better implant stability. Implant Stability Quotient (ISQ) is an objective standard for measuring implant stability.

Osstell values Interpretation:(Osstell)

- >70 ISQ means high stability
- Between 60-69 ISQ means medium stability
- < 60 ISQ means low stability.

The clinical range of ISQ is normally 55-80 and higher values are typically observed in the mandible more than in the maxilla.

The clinical significance of the RF was extensively studied and it was found to be related to the stiffness of the bone implant interface and to the distance of the transducer from the first bone contact(Meredith, Alleyne et al. 1996).

While there is abundant literature that supports the use of Resonance frequency analysis, for evaluating dental implant stability, there is only limited literature available demonstrating its efficacy in measuring MIs stability. (Sakin and Aylıkcı 2013)

Nienkemper et al. suggested that RFA is a feasible method for measuring orthodontic MIs stability. As a consequence, it could be used for monitoring clinical stability of MIs. (Nienkemper, Wilmes et al. 2013). However, the mean ISQ value of mini-implants in this study was 35.40 ± 2.67, which is much lower than the ISQ value reported for stable conventional dental implants.

1.8 Factors affecting MIs primary stability

PS, which can determine future success of MIs, can be easily influenced by several factors, including bone quality, surgical technique, anatomical restrictions, and MIs design.

1.8.1 Bone Quality

The quality and type of the host bone at the implantation site greatly influence PS. The quantity and quality of cortical bone are especially important to obtain mechanical support. However, extremely dense cortical bone is vulnerable to surgical trauma and may increase internal stress during MI placement, which results in necrosis of bone at the implant interface. Consequently, overall stability may be compromised. Trabecular bone density also may affect stability; dense trabecular bone is more favorable than low-density trabecular bone.

The quality of bone in the jaws depends on the location and position within the dental arches and alveolus respectively. The dense bone is found in the anterior mandible, followed by the anterior maxilla and posterior mandible. The least compact/dense bone is typically found in the posterior maxilla. Misch classified these bone densities into four categories, ranging from D1 through D4. (Misch 2008)

- D1 represents homogeneous cortical bone.
- D2 represents thick cortical bone with marrow cavity.
- D3 represents thin cortical bone with dense trabecular bone of good strength.
- D4 represents very thin cortical bone with low density trabecular bone of poor strength.

As the thickness of cortical bone increases, the maximum insertion torque also increases. An increase in cortical bone density enhances MIs primary stability. Cortical bone density may have more influence on primary stability than cortical bone thickness, when the latter is between 1 mm and 2 mm. (Holm, Cunningham et al. 2012).

1.8.2 Insertion Technique

MIs can be placed in pre-prepared (pre-drilled) sites or simply allowed to create its own pass during insertion. Higher PS can be achieved with free-hand placement compared to those MI that require pre-drilling. However, free handing of MIs can cause inadvertent injuries to adjacent teeth and may create additional internal stress in bone resulting in future bone necrosis.

1.8.3 Receptor site limitation

The available MIs site and anatomical restrictions can force placement in less desirable location or angle, which can affect PS. It is also possible that anatomical restrictions result in MIs placement far from the reach of the patient complicating hygiene and maintenance.

1.8.4 Mini-implant Design

Much of the information available from the implant design effects on stability are obtained from research on conventional dental implants. Generally, it appears that factors such as implants' taper, diameter, length, thread pitch, thread geometry, thread depth, thread helix angle, and width may all affect implant stability. Deeper, more aggressive threads seem to have an important effect on the stabilization in poorer bone quality but could result in excessive stress and necrosis in dense cortical bone. The addition of threads or microthreads up at the crest of an implant might also provide additional surfaces for bone contact and thus may increase stability(Abuhussein, Pagni et al. 2010).

Surface microtopography also appears to influence primary stability. Tabassum et al., in a simulated laboratory model, reported that implants with rough surfaces showed significantly higher primary stability compared to implants with smooth or machined surfaces (Tabassum, Meijer et al. 2010). However, Javed in their review of the literature, did not find a strong relation between PS and implant surface roughness in implants placed in patients. However, there was a general consensus that surface roughness increased overall implant success.(Javed, Almas et al. 2011)

The current research using simulation and clinical models indicate that similar factors that influence PS in conventional implants may also affect MIs' PS. Mini-implant macrodesign could alter PS as measured indirectly using the maximum insertion torque (MIT). It appeared that a significant increase of MIT was observed mainly in the taper type mini-implants. The 1.5 mm wide tapered and 2.0 mm wide cylindrical MIs achieved significantly greater primary stability than the 1.5 mm cylindrical design. (Lim, Cha et al. 2008). They concluded that an increase in MIs' diameter can efficiently reinforce the PS of MIs.

Pithon, Figueiredo et al(2013) reported that MIs' length did not increase the mechanical strength, but could improve PS. The interlocking surface area between bone and MIs can be increased with larger diameter, longer length, tapering effect, and double thread design, thereby increasing PS. (Hong, Lee et al. 2011). A contrasting view was expressed by Marquezan et.al. who reported a more pronounced influence of the diameter of MIs and not their length. They argued that the increased length of an MI only increases its contact with the trabecular bone, which may not improve PS to the same extent as it would with the cortical bone.(Marquezan, Mattos et al. 2014)

In summary, there seems to be solid evidence with conventional dental implants that factors such as implant diameter, length, and bone quality influence PS; however, there is insufficient data on the effects of these factors on PS of MIs. Therefore, the aim of this study was to investigate the effect of mini-implants' diameter, length and the presence of cortical bone in PS on MIs.

Chapter 2: Statement of the problem

Although there is convincing evidence in the literature that factors such as implant design, surgical site, bone quality and quantity, as well as surgical protocol can affect primary and secondary stabilities of conventional dental implants, there is little evidence if similar factors could also influence stability of MIs. Therefore, the laboratory research reported in this thesis was conducted to investigate the effects of mini-implant design factors including its length and diameter, as well as a simulated cortical bone thickness on the PS of a commercially-available Mini-Implant. The knowledge obtained from this experiment could provide valuable information for clinicians to formulate an optimal treatment plan, increase success rate of MIs and prevent unnecessary trauma to adjacent vital anatomical structure.

Chapter 3: Hypothesis

The PS of MIs can be affected by implant design-related factors, such as length and diameter, as well as by the density of the osteotomy site bone type. This hypothesis is derived from the data available from conventional dental implants where similar factors affect PS. The specific aims of this research were: 1) To determine the effect of MIs' diameter and length on PS, and 2) to investigate the effect of density (bone type) on PS of MIs.

Chapter 4: Materials and Methods:

4.1 Bone Blocks

Polyurethane-bone-blocks (Sawbones) with densities similar to cancellous-bone (GP20 - 20 lb./ft^3), were used to simulate softer trabecular (cancellous) bone. In order to reproduce the heterogeneous nature of the jawbone, 1 and 2 mm hard polyurethane sheets, which simulate the density of the cortical bone, were laminated over the GP20 bone block. In contrast to animal models or post-mortem cadaver bone models where bone demonstrates significant variation from sites to sites, artificial bone blocks have uniform density, which reduces large variation of stability measurements between implants. Simulated bone blocks are also significantly less costly, easy to maintain and allows large data collection without loss of any animals or use of hard-to-maintain cadaver bone.

4.2 Mini-implants

There are several designs of MIs available in the market, for all experiments of this thesis, MI provided by AbsoAnchor were used. These implants are made of titanium alloy (Ti6Al4Va) and have slight taper with aggressive thread pattern (SH 1312-05). They are also called "Joint Head(JH) Type" and are among the popular MI designs used in clinical orthodontic use in Asia and North America (Osstell). The particular joint-head design in this MI allows connection of magnetic smart pegs needed for ISQ stability measurement by Osstell.

A total of one hundred and eight AbsoAnchor MIs of three commonly-used lengths (6 mm, 8 mm and 10 mm) and three diameters (1.5 mm, 1.7 mm and 2 mm) were placed into synthetic bone blocks with densities of cancellous bone (GP-20).

Table 1 Experimental Design of MI in bony blocks.

Diameter	Length 6mm	Length 8 mm	Length 10 mm
1.5	4	4	4
1.7	4	4	4
2.0	4	4	4

MIs of similar length and diameters were also placed in blocks that were sandwiched with either 1 or 2mm polyurethane sheets, which simulated cortical bone density. Four MIs in each group were placed using manufacturer's recommendation. A Straumann torque wrench and a designated adaptor were used to place all MIs. In order to avoid excessive torsional forces during MI placement, the value of maximum insertion torque was recorded on random sample of MIs in each group.

4.3 Socket Preparations

Some manufacturers of MIs recommend free hand placement without pre-preparation of a osteotomy socket (pre-drilling). Since MIs placed this way would have more PS compared to those placed in pre-prepared sockets. Nevertheless, this method may lead to uncertain implant pass, which can cause un-necessary injuries to adjacent structures. The manufacturer of the AbsoAnchor provides designated pilot drills and recommends undersize pre-preparation of the implant bed prior to MI placement.

For all experiments of this thesis, MIs sockets were prepared 1 cm apart from each other using designated pilot drills and an automated Computer Numerical Control (CNC) Machine as seen in Fig. 10 (Simon Fraser University, SFU).

New MIs were then placed in each pre-drilled bed using a torque wrench (Straumann torque wrench) and a designated adaptor.

Figure 10 Image of the Computer Numerical Control (CNC) machine located at Simon Fraser University (SFU)

Each bone block received a total of 36 pre-prepared sockets in three rows of 12 sockets per row, as seen in Figures 11and 12. A designated implant driver was used by one operator to place MIs in groups of 4s of the same diameter and length. MIs were hand tightened first and then further tightened by the torque wrench till the head of the MIs became flush with the surface of the bone block.

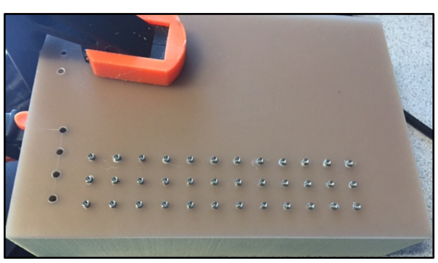

Figure 11 Occlusal View of bony blocks with inserted MIs

Figure 12 Lateral View of bony blocks with inserted MIs

4.4 Data Collection

PS values of all MIs were measured by three testers, including Periotest and Osstell. The clinical application of the Periotest device is straight-forward and the device generates one PTV value for each cycle of measurement. Periotest has a handpiece and an automated tapping device that touches the implant when it comes in close proximity of the implant surface. Erroneous readings are automatically ignored and the total average of 14 measurements is calculated at the end of each measuring cycle. The Periotest readings were obtained by holding the handpiece perpendicular to the long axis of MIs.

Osstell ISQ measures the RFA response at the MIs interface. It uses a prefabricated magnetic smart peg that has to be hand-tightened to the coronal threads of the implant. (Fig. 13). The smart pegs are magnetic and cannot be heat-sterilized, but can be re-used several times with the same patient. Osstell was originally designed to measure stability of the conventional dental implants that have wider coronal diameters than MIs. Unfortunately, we could not find any factory fabricated smart peg among the Osstell provided that could fit the inside threads of the AbsoAnchor MIs.

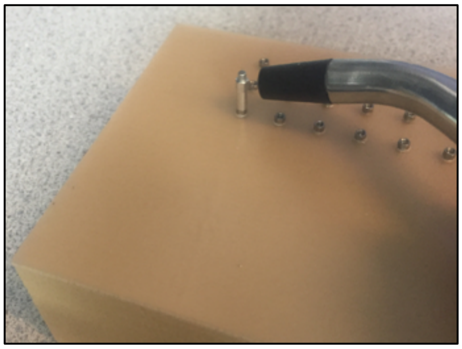

Figure 13 Customized Smart-peg Unit, OsstellTM device

In order to overcome this problem, customized smart pegs were fabricated by altering a current Osstell's small-diameter peg (Osstell) that closely matched AbsoAnchor's inner coronal thread. The customized smart pegs were successfully fabricated at the machining laboratory of the Mechatronic and Mechanical Engineering Department of SFU. This procedure involved removal of the existing connecting screw hold of the Osstell smart peg and replacing it with a new connecting screw that matched the MIs inside thread accurately. The accuracy of the ISQ readings of all customized smart pegs were tested on a sample MI that was secured in a controlled three-prong vice that provided maximum stability. The performance of the customized smart pegs was tested while one or two holding prong's blades was loosened, thus decreasing the maximum holding force. This method provided a controlled system in which the responses of each customized smart peg could be tested. The ISQ readings were plotted against the magnitude of the holding force reduction for each customized smart peg. Any customized pegs that did not show a direct reduction in ISQ in response to the prong blades loosening were discarded. A total of 10 customized smart pegs were fabricated that demonstrated similar performance at the 3-prong controlled stability setting. Customized pegs were discarded if they could not be securely hand-tightened to the inner threads of the MIs.

All data collections were conducted when blocks were secured to the bench with a holding wrench. Each measurement for ISQ and PTV were repeated three times by three testers. The average of the three measurements for each examiner were recorded in Excell spread sheet for statistical analysis.

4.5 Statistical Analysis

Data were exported and tested for significant differences using SPSS version 21 (IBM). Inter-examiner reliability for Periotest and Osstell were calculated using the Cronbach Alpha reliability test. Normal distribution of the data of each variable was tested using the "Explore" feature of the SPSS software, which applies Shapiro-Wilk Test and Q-Q plot to visualize the normality of the data. A multifactorial ANOVA was first conducted to investigate the effects of MIs' length, diameter and the cortical bone sheet. Finally, two-way ANOVA with Boneferoni post-hoc tests were performed to find out the trend of PS change in each bone block. The significant level value was set at $\alpha = 0.05$.

Chapter 5: Results

The uniform density of the Polyurethane blocks (Sawbones) offered less variation in contrast to the largely heterogeneous animal or post-mortem cadaver bone models. The artificial bone block method used in this research also successfully produced a controlled simulated model for two variations of heterogeneous bones with 1 and 2 mm cortical bone type.

Another source of variation in stability data collection could also occur if implant sockets are prepared manually. This was addressed by using a designated pilot drill and an automated Computer Numerical Control (CNC) Machine. The computer controlled drill created consistent implant osteotomy sockets exactly 1 cm apart. The integrity of each socket was inspected and confirmed with a magnifier (3X) prior to the MIs placement.

The three examiners were trained to use Periotest and Osstell as per manufacturer's instructions. The Cronbach Alpha inter-examiners reliability test was used to evaluate agreement among examiners. A strong correlation in the range of 0.98- 0.99 was found for the Periotest ($p<0.0001$). The range for Osstell had slightly more variation; nevertheless, demonstrated a clinically acceptable range of correlation between 0.75-0.97 among the examiners ($p<0.0001$). This indicated both devices were relatively easy to learn and apply in our model.

Table 2 Inter-Examiners Reliability of Periotest

Reliability Statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.995	.996	3

Item Statistics

	Mean	Std. Deviation	N
Periotest	-4.630	2.8076	108
Periotest	-5.290	2.9774	108
Periotest	-4.943	3.0687	108

Inter-Item Correlation Matrix

	Periotest	Periotest	Periotest
Periotest	1.000	.985	.991
Periotest	.985	1.000	.988
Periotest	.991	.988	1.000

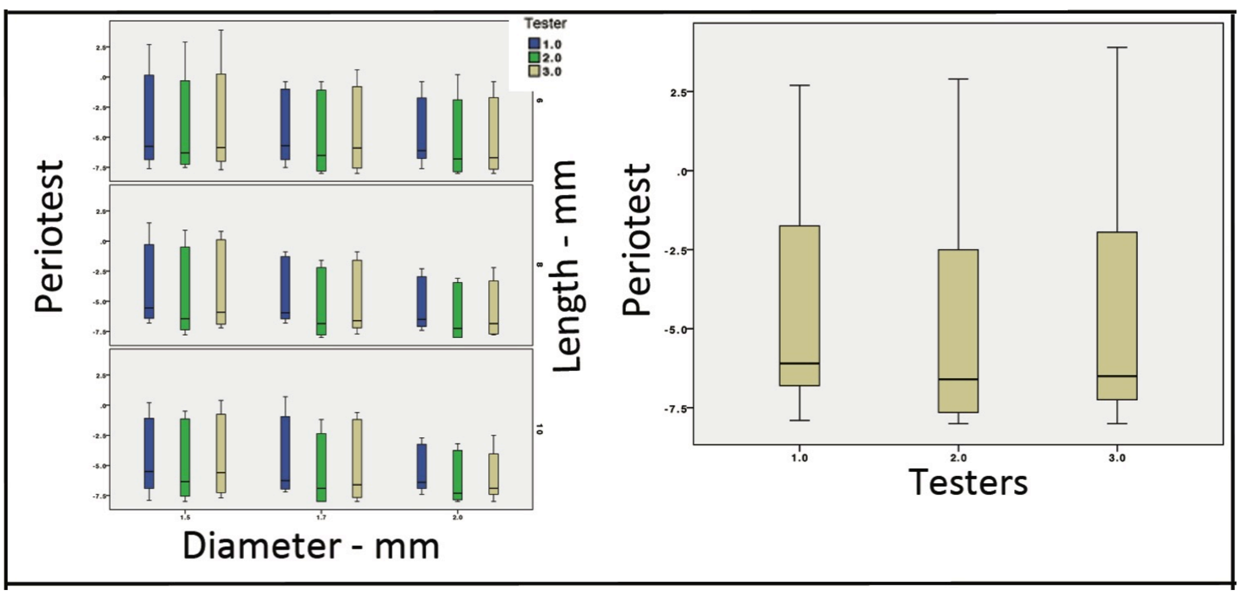

Figure 14 Inter-examiners Reliability of Periotest Box Plots

Table 3 Inter-Examiners Reliability of Osstell

Reliability Statistics

Cronbach's Alpha	Cronbach's Alpha Based on Standardized Items	N of Items
.917	.934	3

Item Statistics

	Mean	Std. Deviation	N
Ostell	51.343	11.0869	108
Ostell	51.315	11.1016	108
Ostell	38.972	14.8547	108

Inter-Item Correlation Matrix

	Ostell	Ostell	Ostell
Ostell	1.000	.986	.759
Ostell	.986	1.000	.731
Ostell	.759	.731	1.000

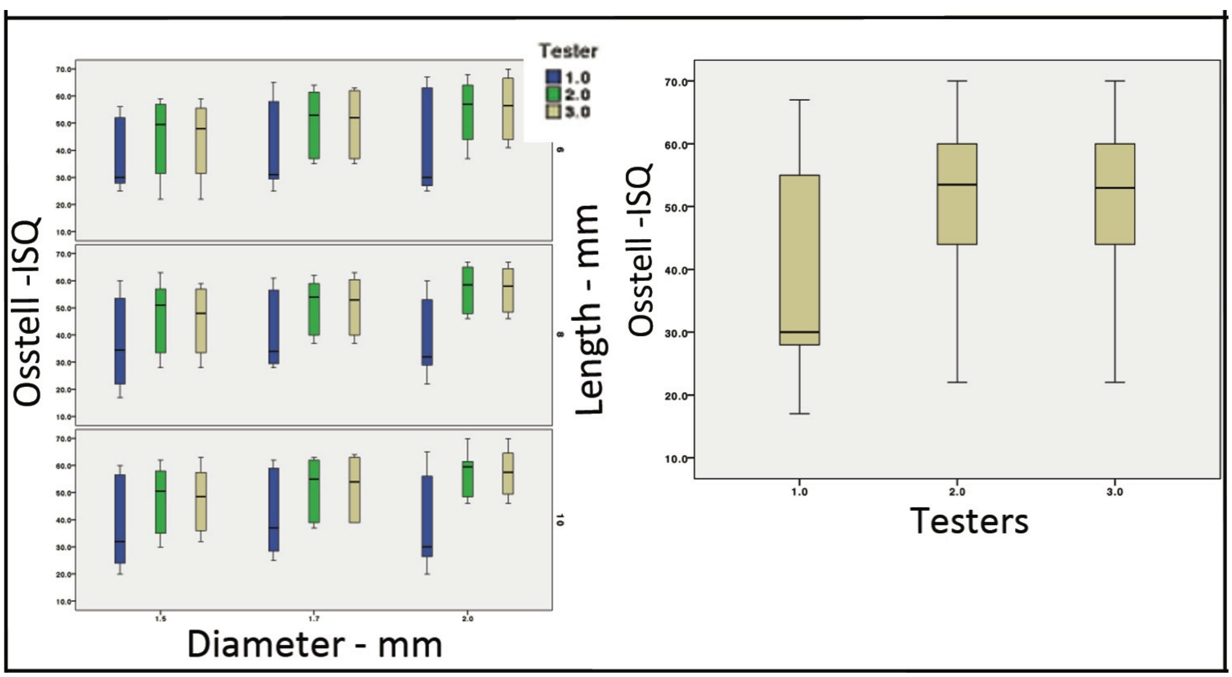

Figure 15 Inter-examiners Reliability of Osstell Box Plots

The Smart Pegs utilized for Osstell were originally recommended as the best fit choice for the inner threads of the head of AbsoAnchor MIs used in this study. However, the fit was initially found to be loose and became progressively looser after 1 or 2 times use. This resulted in low ISQ readings (≈15-30) in heterogeneous blocks. As a solution, custom-made Smart-pegs were made by press-fitting matching stainless steel screws to the magnetic body of the Smart-Peg. This resulted in an increase in ISQ values (≈ 50-65) in the previous blocks indicating that the custom-made pegs function better than the Original Smart-pegs. The three-prong test also indicated proportional loss of stability when one or two blades of the holding prongs progressively loosened.

All MIs were installed according to the manufacturer's recommendation. A Straumann torque wrench and a designated adaptor were used to place all MIs. The average final torque measurements were only recorded on half of the samples from each group of MIs. This was done to avoid excessive torsional forces that could distort or fracture the MIs during placement. The placement torque was consistent in each group of MIs placed and indicated different values only in different bone blocks and in MIs with different diameters. The mean final placement values are given at the following table:

Table 4 Torque Values of Mini-implants MIs.

MI Diameter - mm	GP20 / N-cm	GP20-1mmCB/N-cm	GP20-2mmCB/N-cm
1.5	5 ± 0.5	15 ± 0.8	25 ± 2
1.7	5 ± 0.8	20 ± 0.5	27 ± 1
2	6 ± 0.8	25 ± 0.8	32 ± 0.5

Data were analysed with Multifactorial ANOVA first to screen for statistical differences and potential interactions among variables. Both MI-related factors of length and diameter, as well as bone block type resulted in statistical significant differences in stability measurements with both Periotest and Osstell. Although there were significant interactions between both diameter and length and bone blocks, there was not any significant interaction between MIs length and diameter. This indicated that MIs length and diameter interacted with the bone block differently and in a unique manner. Then multiple two-way ANOVA were conducted for both Periotest and Osstell results in each bone block to identify the unique interactions of MIs diameter and length in different bone block.

Table 5 Significance levels and Interactions among Variables

Source	Dependent Variable	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	PerotestAverage	903.587[a]	26	34.753	134.972	.000
	OsstellAverageN	13831.798[b]	26	531.992	97.614	.000
Intercept	PerotestAverage	2650.562	1	2650.562	10293.992	.000
	OsstellAverageN	240707.424	1	240707.424	44167.056	.000
Diametermm	PerotestAverage	30.594	2	15.297	59.409	.000
	OsstellAverageN	1005.070	2	502.535	92.209	.000
Lengthmm	PerotestAverage	6.958	2	3.479	13.511	.000
	OsstellAverageN	34.755	2	17.378	3.189	.046
BlockCode	PerotestAverage	832.727	2	416.363	1617.031	.000
	OsstellAverageN	12538.730	2	6269.365	1150.357	.000
Diametermm * Lengthmm	PerotestAverage	1.464	4	.366	1.422	.234
	OsstellAverageN	5.084	4	1.271	.233	.919
Diametermm * BlockCode	PerotestAverage	19.508	4	4.877	18.940	.000
	OsstellAverageN	113.942	4	28.486	5.227	.001
Lengthmm * BlockCode	PerotestAverage	9.108	4	2.277	8.843	.000
	OsstellAverageN	44.016	4	11.004	2.019	.099
Diametermm * Lengthmm * BlockCode	PerotestAverage	3.229	8	.404	1.568	.148
	OsstellAverageN	90.200	8	11.275	2.069	.048
Error	PerotestAverage	20.856	81	.257		
	OsstellAverageN	441.444	81	5.450		
Total	PerotestAverage	3575.006	108			
	OsstellAverageN	254980.667	108			
Corrected Total	PerotestAverage	924.444	107			
	OsstellAverageN	14273.243	107			

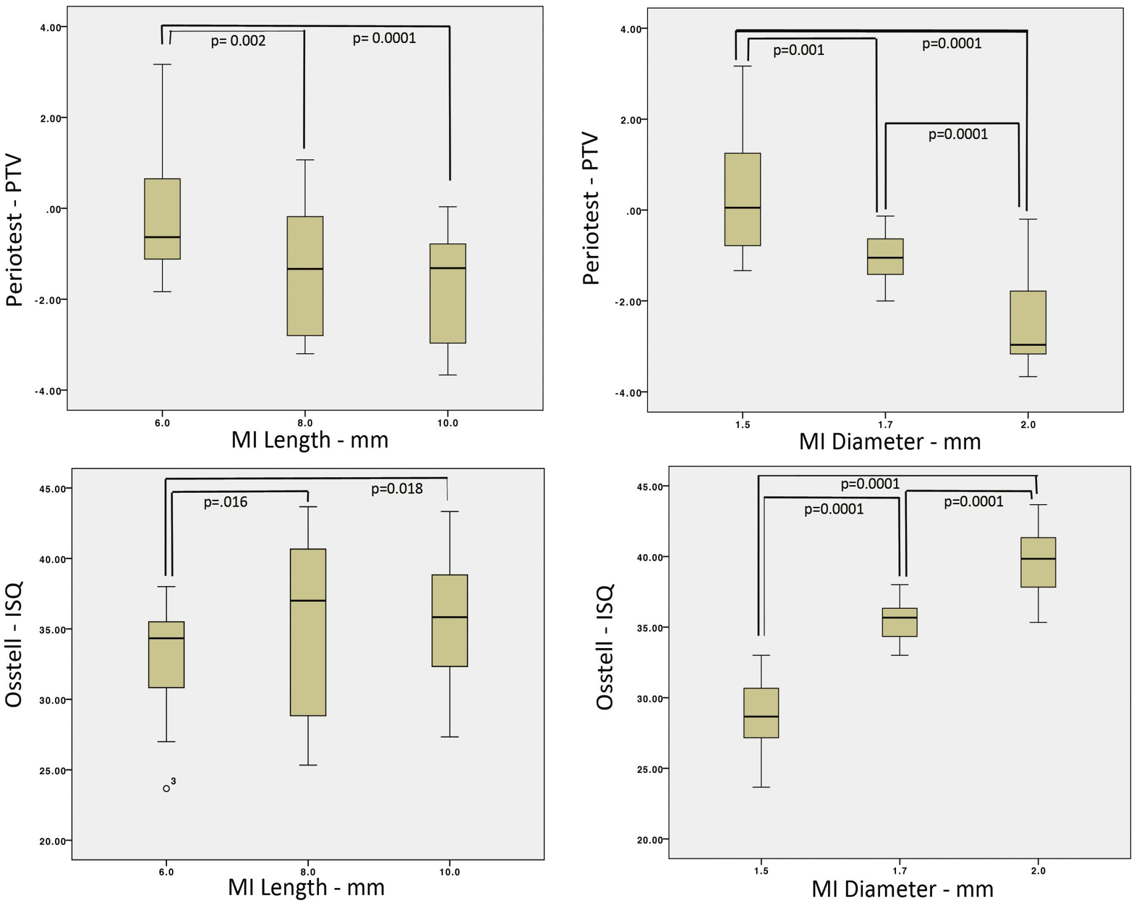

Figure 16 Box Plots of Periotest PTV and Osstell ISQ Values of different MI Lengths and Diameters in GP-20 (Simulated Cancellous Bone).

In GP20 (Cancellous bone), both Periotest and Osstell indicated significant differences for both increase in MIs diameter and length. However, the effect of PS was more pronounce in small diameter (6 mm) MI. When the same tests conducted on results obtained with Periotest and Osstell in sandwiched bone blocks (GP20-1mmCB & GP20-2 mmCB) only an increase in MIs diameter appeared to significantly increase PTV and ISQ. In these blocks, there was no significant difference in the measurement of stability when the length of MIs increased.

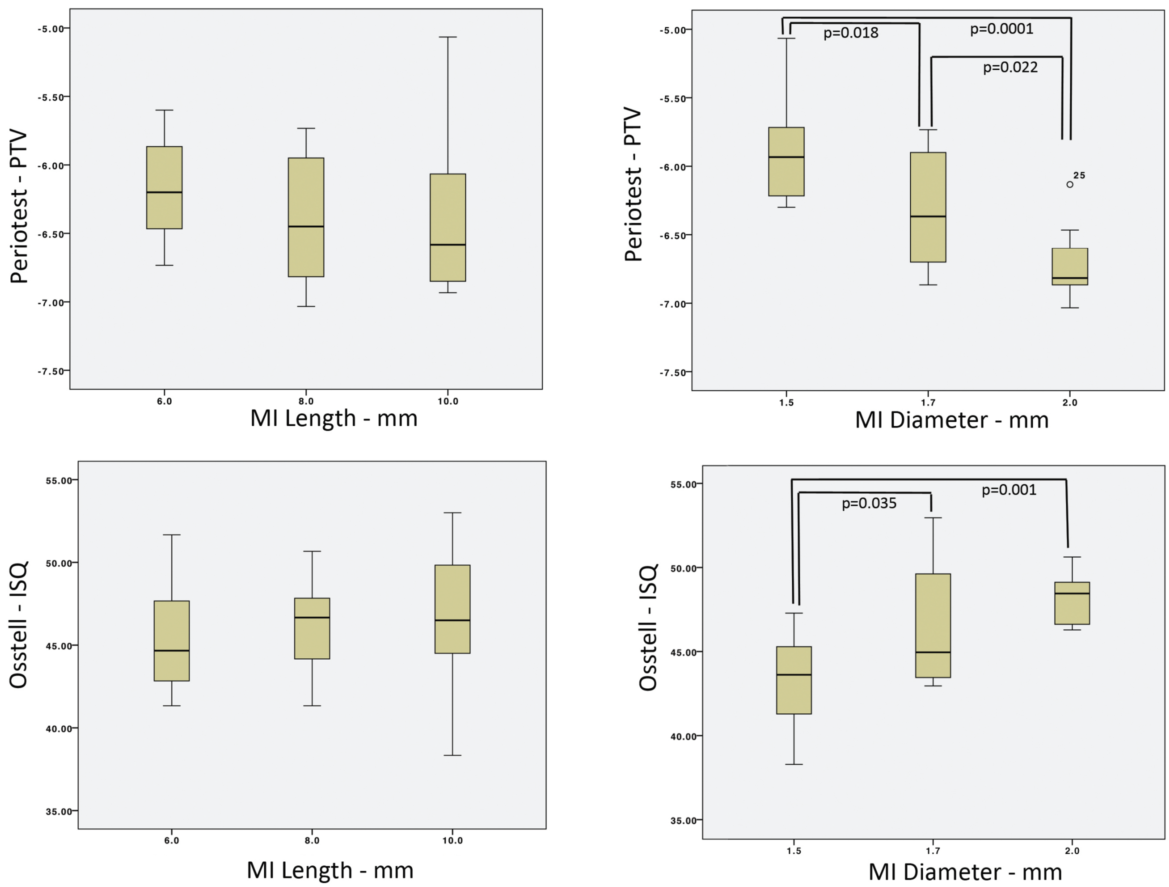

Figure 17 Box Plots of Periotest PTV and Osstell ISQ Values of different MI Lengths and Diameters in GP 20-1mm CB (Simulated Heterogeneous Bone).

Implant diameter and bone type appeared to be the most important factors in achieving optimal PS; whereas, MIs' length appeared to be only a contributing factor in PS in cancellous, soft bone.

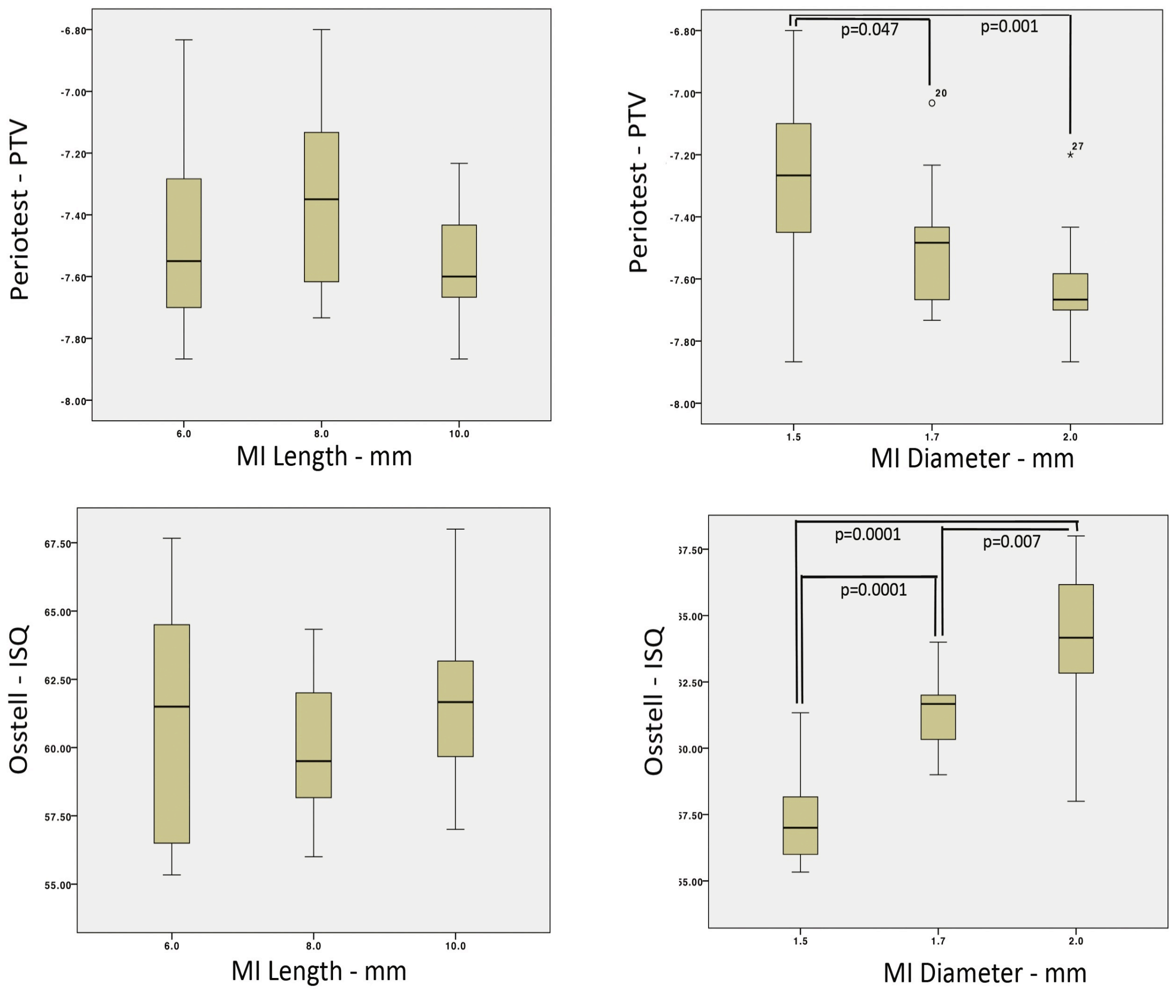

Figure 18 Box Plots of Periotest PTV and Osstell ISQ Values of different MI Lengths and Diameters in GP20- 2mm CB (Simulated Heterognous Bone)

Chapter 6: Discussion

Conventional dental implants have success rate of greater than 90% in favorable circumstances; however, because of their large diameter and unique abutment design, these implants are not favored for use as orthodontic anchorage. Alternately, MIs are becoming increasingly popular and are utilized in contemporary orthodontic treatments as a reliable and absolute anchorage strategy to resist unwanted tooth movements caused by the orthodontic loading forces. MIs are different than conventional dental implants as they are smaller, fabricated from strong titanium alloys, often have aggressive thread design, require simplified surgical protocols, are placed perpendicular to alveolar bone at interdental spaces, are loaded earlier, and can be removed easily after the completion of the orthodontic treatment. In contrast to conventional dental implants, MIs do not enjoy the same high success rate and may have to be replaced during the typical course of the orthodontic treatment. There is general agreement that a predictor of implant ultimate success is their degree of stability in the bone both at the time of placement, also called primary stability (PS), and during the function when bone healing completed, also known as secondary stability or biological stability (Adell, Lekholm et al. 1981, Meredith 1998, Balleri, Cozzolino et al. 2002). In particular, PS appears to be the most important predictor of future success in MIs (Norton M 2013 , Butchter *et al*. 2005). Therefore, the laboratory research reported in this thesis was conducted to investigate the effects of MIs design factors including its length, diameter, as well as bone type on the PS of a commercially-available MI. The results obtained indicated that both diameter and cortical bone thickness appear to significantly improve PS in MIs placed in polyurethane simulated bone blocks.

Common clinical methods for determining stability of dental implants may include palpation, tapping, patient sensation, placement torque, imaging techniques such as radiography, X-ray computed tomography (CT), panoramic and intra-oral radiography (Salvi and Lang 2004, Almeida, Maciel et al. 2007, Atsumi, Park et al. 2007, Shalabi, Wolke et al. 2007). These techniques, however, have been criticized for their inaccuracy, complexity, lack of objectivity, high cost, and overall safety (Sunden, Grondahl et al. 1995, Pattijn, Jaecques et al. 2007). The Periotest and Osstell are commercially-available, non-invasive and objective implant stability measuring devices that were developed to measure damping (Periotest) and vibration (Osstell) characteristics of the bone implant interface (Schulte and Lukas 1992). Both systems have been extensively used in research and clinical practice to record stability of conventional dental implants and more recently utilized to measure PS of MIs. Their application in measuring stability of MIs has not been researched as extensively as that of the conventional implants; nevertheless, published studies indicate consistent and repeatable measurement of stability of MIs for both devices. We used both systems in out experiment to measure PS of MIs in different bone blocks. Both devices were in agreement in recording PS increase when MIs diameter increased or when 1 and 2 mm simulated cortical bone layers were added to the porous polyurethane blocks.

Osstell suffers from a design restriction and requires an electromagnetic exciter probe and a dedicated smart peg, which must be screwed into an implant (Meredith 1998). This way, the vibration characteristics of the bone implant interface can be measured from its resonance frequency (Meredith 1998, Pattijn, Jaecques et al. 2007). Most MIs are not designed with inner threads at the coronal part to receive smart pegs; however, we selected AbsoAnchor's design, which has a unique coronal design that can receive different orthodontic brackets as well as Osstell's smart peg. Unfortunately, the type 1 smart peg that was recommended by Osstell for AbsoAnchor MIs did not function as expected and loosened after the first attempt to install into the inner threads of the AbsoAnchor MIs. The ISQ measurements were therefore inconsistent and not repeatable. Therefore, we modified smart pegs by replacing the existing connecting screw hold with a new stainless steel screw that matched the MIs inner coronal threads precisely. The smart peg modification has been performed in other studies as well to improve accuracy (Uysal, Ekizer et al. 2012) (Nienkemper, Wilmes et al. 2013); however, details of such modifications were not explained clearly. It is feasible that a mismatch of threads between smart peg and AbsoAnchor was responsible for early loosening of the pegs. It is also possible that the differences of material hardness between the soft metal of smart pegs and the hard titanium alloy (Ti-6Al-4V) of AbsoAnchor caused premature wear of the peg threads. In agreement with the later possibility, Osstell also acknowledges that smart pegs are made from a soft metal with a zinc-coated magnet mounted on top. The smart pegs will therefore rapidly wear after being opened (Osstell Web site). Our modification method produced a hybrid smart peg by using a custom precise-fitting screw-hold that allowed the magnetic portion of the smart peg to vibrate. The consistency of these modified smart pegs were successfully tested before use in a three-prong vice hold and showed predictable reduction of ISQ values as individual vice arm loosened sequentially.

Many clinicians rely on the more convenient means of measuring maximum implant insertion torque (N-Cm) to estimate PS of an implant. This often performed by a mechanical torque wrench with limited accuracy, which measures the mechanical friction force applied between the implant and bone. Mathematical formula also has been proposed, which applies coefficient of friction, surface area, implant height and diameter to quantitate PS (Norton 2013).This hypothetical approach has been criticised by Norton (Norton 2013) who questioned if implant insertion torque is an appropriate way of quantifying PS. He further pointed out that measuring axial stiffness, with vibration analysis is more reflective of true PS than measurement of the frictional rotational resistance. High insertion torque also has been shown to apply excessive lateral forces to the surrounding bone, which could result in microcracks and premature osteogenic cell death at the implant interface and loss of the implant (Buchter, Kleinheinz et al. 2005). In our study, we monitored maximum insertion torque in samples of MIs mainly to prevent build-up of excessive frictional forces that could cause inadvertent implant or bone block fracture.

There is convincing evidence with conventional implants that both implant design factor and bone type can increase PS (Balleri *et al* 2002 , Atsumi M *et al* 2007 , Adell R *at al* 1981) However, the extent of the same factors in stability of MIs is not fully understood. Holm et al (Holm, Cunningham et al. 2012) in their study of 260 different MIs design concluded that MIs diameter, tapering , thread design and cortical bone thickness can influence PS. They did not find any significant difference in PS between MIs with 6 mm and 9 mm length. In a systematic review and meta-analysis, (Marquezan, Mattos et al. 2014) reported a positive association between cortical bone thickness and MIs stability; however, they also acknowledged a lack of well-designed clinical trials to investigate PS. Our data indicated that MIs diameter is important designs factor that influences PS in all types of simulated bone tested. Cortical bone thickness also was associated with increased stability of MIs. We also found that increased length of MIs increased PS of MIs only in soft cancellous type bone. Length did not have any significant affect on PS in heterogeneous 1-2 mm cortical sandwiched bone blocks.

Within the limitation of this in vitro study, the results of this investigation have demonstrated that PS of orthodontic MIs can be affected mainly by the increase in diameter as well as the type and density of the contacting bone. The length of the MIs only contributes to PS in soft cancellous bone. Recognizing factors improving PS would be expected to decrease unnecessary trauma, premature MIs failure and costly retreatments in recipients of these implants, who are mainly children and adolescence. Although MIs are smaller than conventional dental implants, they have to be placed in anatomically restricted areas between posterior teeth. Careful planning with advanced imaging tools such as cone-beam computed tomography (CBCT) should assist mapping anatomical complexity and available bone type. The result of this simulated study should provide a guideline for selecting optimal MIs for available anatomical space and bone type that results in maximum primary stability.

Chapter 7: Conclusion

The research reported in this thesis investigated the effects of MIs design factors including its length and diameter, as well as bone type on the PS of a commercially-available Mls. Within the limitation of this in vitro study, the results have demonstrated that PS of AnsoAnchor orthodontic MIs can be affected mainly by the increase in diameter as well as the type and density of the contacting bone. The length of the MIs only contributed to PS in soft cancellous bone. The result of this simulated study should provide a guideline for selecting optimal MIs for available anatomical space and bone type in order to maximize primary stability.

Chapter 8: Future Directions

The research reported in this thesis was conducted using a simulated model that may not represent true *in vivo* situations. Although, simulations models are excellent to study a concept, more systematic well-designed *in vivo* animal experiments are needed to investigate the effects of MIs and bone factors on PS. Detail diagnostic and quantitative imaging tools, such as micro and cone-beam computed tomography, are required to map the bone of the recipient sites for MIs.

There is general agreement among researchers that PS is a prerequisite for achieving secondary stability in dental implants. However, this concept has been questioned recently, at least in conventional dental implants, where implants with rough surfaces can integrate in bone despite poor PS at the time of placement (Norton M, 2013) . The current available evidence on MIs, strongly suggests that achieving PS is a fundamental requirement for successful clinical function by MIs. Nevertheless, this concept has not been systematically studied. More well-controlled animal and human studies are needed to establish the factors that interact and control both primary and secondary stability of MIs.

Periotest and Osstell the two devices that we used in this study are the only objective, non-invasive stability testing devices that are commercially available. These devices were originally designed for conventional dental implants and would be difficult to use on recipients of MIs who are often children and adolescents with possibly restricted mouth opening. New dedicated stability measuring devices are needed that are specifically designed for measuring PS of MIs.

In our study we only investigated the effects of length and diameter of the MIs on PS. The influence of other parameters of MIs, such as thread design, pitch size , tapers , surface topography , and different materials on PS should also be studied in details.

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Dental measuring instrument for implantology and high-quality dentistry. M. Gulden and M. o. t. periotest.

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Appendix

Appendix contains details of Statistical Analysis for each Bone Block.

Appendix 1

i- Two-way ANOVA for Periotest PTV results in GP-20 (Cancellous Bone) – Effects of Diameter & Length of MIs in PS.

Dependent Variable: PerotestAverage

Diametermm	Lengthmm	Mean	Std. Deviation	N
1.5	6.0	1.2167	1.87073	4
	8.0	.2583	.62561	4
	10.0	-.6750	.50580	4
	Total	.2667	1.33477	12
1.7	6.0	-.5750	.33040	4
	8.0	-1.4667	.36209	4
	10.0	-1.0667	.52705	4
	Total	-1.0361	.53512	12
2.0	6.0	-1.1667	.76836	4
	8.0	-2.9833	.30490	4
	10.0	-3.2917	.37847	4
	Total	-2.4806	1.08827	12
Total	6.0	-.1750	1.50508	12
	8.0	-1.3972	1.44260	12
	10.0	-1.6778	1.27797	12
	Total	-1.0833	1.52221	36

Dependent Variable: PerotestAverage

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	64.624[a]	8	8.078	13.239	.000
Intercept	42.250	1	42.250	69.244	.000
Diametermm	45.324	2	22.662	37.140	.000
Lengthmm	15.324	2	7.662	12.557	.000
Diametermm * Lengthmm	3.977	4	.994	1.630	.196
Error	16.474	27	.610		
Total	123.349	36			
Corrected Total	81.099	35			

a. R Squared = .797 (Adjusted R Squared = .737)

Dependent Variable: PerotestAverage

Bonferroni

(I) Diametermm	(J) Diametermm	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1.5	1.7	1.3028*	.31890	.001	.4888	2.1167
	2.0	2.7472*	.31890	.000	1.9333	3.5612
1.7	1.5	-1.3028*	.31890	.001	-2.1167	-.4888
	2.0	1.4444*	.31890	.000	.6305	2.2584
2.0	1.5	-2.7472*	.31890	.000	-3.5612	-1.9333
	1.7	-1.4444*	.31890	.000	-2.2584	-.6305

Dependent Variable: PerotestAverage

Bonferroni

(I) Lengthmm	(J) Lengthmm	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
6.0	8.0	1.2222*	.31890	.002	.4083	2.0362
	10.0	1.5028*	.31890	.000	.6888	2.3167
8.0	6.0	-1.2222*	.31890	.002	-2.0362	-.4083
	10.0	.2806	.31890	1.000	-.5334	1.0945
10.0	6.0	-1.5028*	.31890	.000	-2.3167	-.6888
	8.0	-.2806	.31890	1.000	-1.0945	.5334

ii- Two-way ANOVA for Periotest PTV results in GP20-1mmCB (Heterogeneous Bone)- Effects of Diameter & Length of MIs in PS.

Dependent Variable: PerotestAverage

Diametermm	Lengthmm	Mean	Std. Deviation	N
1.5	6.0	-5.9167	.29123	4
	8.0	-6.0083	.12874	4
	10.0	-5.7833	.57639	4
	Total	-5.9028	.35717	12
1.7	6.0	-6.1083	.31195	4
	8.0	-6.3667	.52634	4
	10.0	-6.4833	.41141	4
	Total	-6.3194	.41838	12
2.0	6.0	-6.4583	.24702	4
	8.0	-6.8583	.13710	4
	10.0	-6.8583	.05693	4
	Total	-6.7250	.24787	12
Total	6.0	-6.1611	.34811	12
	8.0	-6.4111	.46652	12
	10.0	-6.3750	.59512	12
	Total	-6.3157	.47991	36

Dependent Variable: PerotestAverage

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	4.880[a]	8	.610	5.178	.001
Intercept	1435.989	1	1435.989	12189.165	.000
Diametermm	4.057	2	2.028	17.217	.000
Lengthmm	.438	2	.219	1.860	.175
Diametermm * Lengthmm	.385	4	.096	.818	.525
Error	3.181	27	.118		
Total	1444.050	36			
Corrected Total	8.061	35			

Bonferroni

Bonferroni		Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
...m	(J) Diametermm				Lower Bound	Upper Bound

(I) Lengthmm	(J) Lengthmm	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
6.0	8.0	.2500	.14012	.257	-.1077	.6077
	10.0	.2139	.14012	.416	-.1438	.5715
8.0	6.0	-.2500	.14012	.257	-.6077	.1077
	10.0	-.0361	.14012	1.000	-.3938	.3215
10.0	6.0	-.2139	.14012	.416	-.5715	.1438
	8.0	.0361	.14012	1.000	-.3215	.3938

iii- Two-way ANOVA for Periotest PTV results in GP20-2mmCB (Heterogeneous Bone)- Effects of Diameter & Length of MIs in PS.

Dependent Variable: PerotestAverage

Diametermm	Lengthmm	Mean	Std. Deviation	N
1.5	6.0	-7.2500	.31798	4
	8.0	-7.0750	.23154	4
	10.0	-7.5000	.26527	4
	Total	-7.2750	.30752	12
1.7	6.0	-7.5833	.14011	4
	8.0	-7.2917	.20069	4
	10.0	-7.6167	.12910	4
	Total	-7.4972	.21008	12
2.0	6.0	-7.6167	.28996	4
	8.0	-7.6583	.06872	4
	10.0	-7.5750	.09954	4
	Total	-7.6167	.16787	12
Total	6.0	-7.4833	.29284	12
	8.0	-7.3417	.30021	12
	10.0	-7.5639	.17024	12
	Total	-7.4630	.27031	36

Dependent Variable: PerotestAverage

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	1.356[a]	8	.170	3.811	.004
Intercept	2005.049	1	2005.049	45071.878	.000
Diametermm	.722	2	.361	8.110	.002
Lengthmm	.904	2	.152	3.414	.480
Diametermm * Lengthmm	.331	4	.083	1.859	.147
Error	1.201	27	.044		
Total	2007.607	36			
Corrected Total	2.557	35			

Bonferroni

(I) Diametermm	(J) Diametermm	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
1.5	1.7	.2222*	.08611	.047	.0024	.4420
	2.0	.3417*	.08611	.001	.1219	.5614
1.7	1.5	-.2222*	.08611	.047	-.4420	-.0024
	2.0	.1194	.08611	.530	-.1003	.3392
2.0	1.5	-.3417*	.08611	.001	-.5614	-.1219
	1.7	-.1194	.08611	.530	-.3392	.1003

Bonferroni

(I) Lengthmm	(J) Lengthmm	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval Lower Bound	95% Confidence Interval Upper Bound
6.0	8.0	-.1417	.08611	.335	-.3614	.0781
	10.0	.0806	.08611	1.000	-.1392	.3003
8.0	6.0	.1417	.08611	.335	-.0781	.3614
	10.0	.2222	.08611	.480	.0024	.4420
10.0	6.0	-.0806	.08611	1.000	-.3003	.1392
	8.0	-.2222	.08611	.480	-.4420	-.0024

iv- Two-way ANOVA for Osstell ISQ results in GP-20 (Cancellous Bone) – Effects of Diameter & Length of MIs in PS.

Dependent Variable: OsstellAverageN

Diametermm	Lengthmm	Mean	Std. Deviation	N
1.5	6.0	28.0833	3.88134	4
	8.0	27.9167	1.72938	4
	10.0	30.4167	2.47019	4
	Total	28.8056	2.83006	12
1.7	6.0	34.2500	.99536	4
	8.0	36.9167	.99536	4
	10.0	35.3333	1.12217	4
	Total	35.5000	1.48051	12
2.0	6.0	36.6667	1.36083	4
	8.0	41.5833	1.42400	4
	10.0	40.5833	2.18369	4
	Total	39.6111	2.69618	12
Total	6.0	33.0000	4.37394	12
	8.0	35.4722	6.06107	12
	10.0	35.4444	4.70189	12
	Total	34.6389	5.08803	36

Dependent Variable: OsstellAverageN

Source	Type III Sum of Squares	df	Mean Square	F	Sig.
Corrected Model	797.944[a]	8	99.743	24.904	.000
Intercept	43194.694	1	43194.694	10784.804	.000
Diametermm	713.907	2	356.954	89.124	.000
Lengthmm	48.352	2	24.176	6.036	.007
Diametermm * Lengthmm	35.685	4	8.921	2.227	.093
Error	108.139	27	4.005		
Total	44100.778	36			
Corrected Total	906.083	35			

Bonferroni

(I) Diametermm	(J) Diametermm	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1.5	1.7	-6.6944*	.81702	.000	-8.7799	-4.6090
	2.0	-10.8056*	.81702	.000	-12.8910	-8.7201
1.7	1.5	6.6944*	.81702	.000	4.6090	8.7799
	2.0	-4.1111*	.81702	.000	-6.1965	-2.0257
2.0	1.5	10.8056*	.81702	.000	8.7201	12.8910
	1.7	4.1111*	.81702	.000	2.0257	6.1965

Bonferroni

(I) Lengthmm	(J) Lengthmm	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
6.0	8.0	-2.4722*	.81702	.016	-4.5576	-.3868
	10.0	-2.4444*	.81702	.018	-4.5299	-.3590
8.0	6.0	2.4722*	.81702	.016	.3868	4.5576
	10.0	.0278	.81702	1.000	-2.0576	2.1132
10.0	6.0	2.4444*	.81702	.018	.3590	4.5299
	8.0	-.0278	.81702	1.000	-2.1132	2.0576

v- Two-way ANOVA for Osstell ISQ results in GP20-1mmCB (Heterogeneous Bone) – Effects of Diameter & Length of MIs in PS.

Dependent Variable: OsstellAverageN

Lengthmm	Diametermm	Mean	Std. Deviation	N
6.0	1.5	42.6667	1.44016	4
	1.7	45.5833	4.13096	4
	2.0	47.6667	1.12217	4
	Total	45.3056	3.18601	12
8.0	1.5	44.5000	2.45704	4
	1.7	45.6667	2.50924	4
	2.0	48.2500	1.95078	4
	Total	46.1389	2.66082	12
10.0	1.5	42.8333	3.96746	4
	1.7	48.3333	4.52974	4
	2.0	48.8333	1.55158	4
	Total	46.6667	4.31347	12
Total	1.5	43.3333	2.69305	12
	1.7	46.5278	3.70765	12
	2.0	48.2500	1.51174	12
	Total	46.0370	3.40381	36

Dependent Variable: OsstellAverageN

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	179.895[a]	8	22.487	2.691	.026	.444
Intercept	76298.716	1	76298.716	9131.046	.000	.997
Lengthmm	11.302	2	5.651	.676	.517	.048
Diametermm	149.377	2	74.688	8.938	.001	.398
Lengthmm * Diametermm	19.216	4	4.804	.575	.683	.078
Error	225.611	27	8.356			
Total	76704.222	36				
Corrected Total	405.506	35				

Bonferroni

(I) Diametermm	(J) Diametermm	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1.5	1.7	-3.1944*	1.18011	.035	-6.2066	-.1823
	2.0	-4.9167*	1.18011	.001	-7.9289	-1.9045
1.7	1.5	3.1944*	1.18011	.035	.1823	6.2066
	2.0	-1.7222	1.18011	.468	-4.7344	1.2900
2.0	1.5	4.9167*	1.18011	.001	1.9045	7.9289
	1.7	1.7222	1.18011	.468	-1.2900	4.7344

Bonferroni

(I) Lengthmm	(J) Lengthmm	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
6.0	8.0	-.8333	1.18011	1.000	-3.8455	2.1789
	10.0	-1.3611	1.18011	.777	-4.3733	1.6511
8.0	6.0	.8333	1.18011	1.000	-2.1789	3.8455
	10.0	-.5278	1.18011	1.000	-3.5400	2.4844
10.0	6.0	1.3611	1.18011	.777	-1.6511	4.3733
	8.0	.5278	1.18011	1.000	-2.4844	3.5400

vi- Two-way ANOVA for Osstell ISQ results in GP20-2mmCB (Heterogeneous Bone) – Effects of Diameter & Length of MIs in PS.

Dependent Variable: OsstellAverageN

Diametermm	Lengthmm	Mean	Std. Deviation	N
1.5	6.0	55.9167	.78764	4
	8.0	57.3333	1.05409	4
	10.0	59.3333	2.32538	4
	Total	57.5278	2.02239	12
1.7	6.0	61.9167	1.50000	4
	8.0	60.0000	1.41421	4
	10.0	62.0000	.54433	4
	Total	61.3056	1.47339	12
2.0	6.0	66.0000	1.78471	4
	8.0	62.5000	1.93410	4
	10.0	63.5833	4.15777	4
	Total	64.0278	2.98974	12
Total	6.0	61.2778	4.51224	12
	8.0	59.9444	2.59305	12
	10.0	61.6389	3.10249	12
	Total	60.9537	3.47613	36

Dependent Variable: OsstellAverageN

Source	Type III Sum of Squares	df	Mean Square	F	Sig.	Partial Eta Squared
Corrected Model	315.228[a]	8	39.404	9.879	.000	.745
Intercept	133752.744	1	133752.744	33533.058	.000	.999
Diametermm	255.728	2	127.864	32.057	.000	.704
Lengthmm	19.117	2	9.559	2.396	.110	.151
Diametermm * Lengthmm	40.383	4	10.096	2.531	.064	.273
Error	107.694	27	3.989			
Total	134175.667	36				
Corrected Total	422.923	35				

Bonferroni

(I) Diametermm	(J) Diametermm	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
1.5	1.7	-3.7778*	.81534	.000	-5.8589	-1.6967
	2.0	-6.5000*	.81534	.000	-8.5811	-4.4189
1.7	1.5	3.7778*	.81534	.000	1.6967	5.8589
	2.0	-2.7222*	.81534	.007	-4.8033	-.6411
2.0	1.5	6.5000*	.81534	.000	4.4189	8.5811
	1.7	2.7222*	.81534	.007	.6411	4.8033

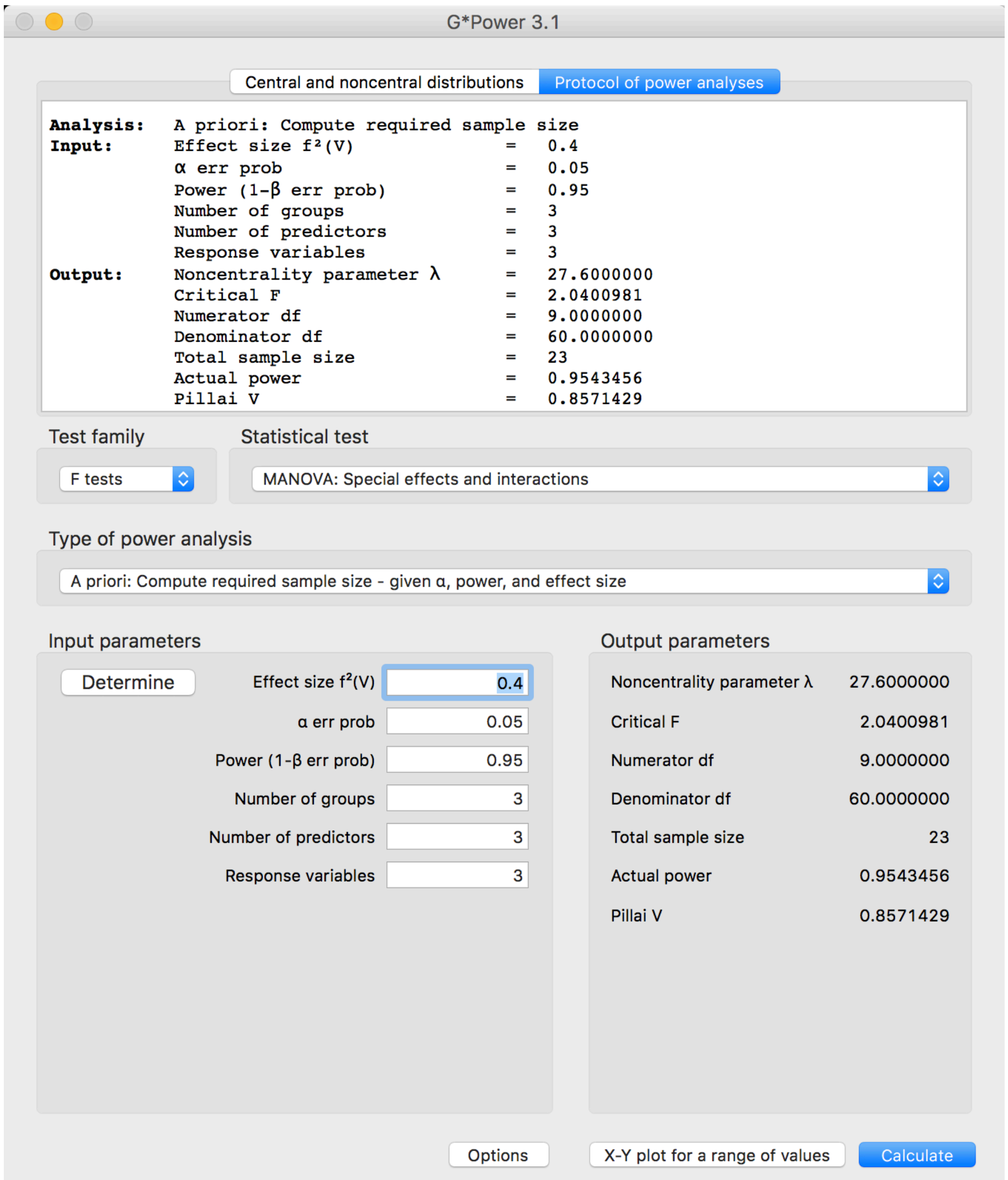
Bonferroni

(I) Lengthmm	(J) Lengthmm	Mean Difference (I-J)	Std. Error	Sig.	95% Confidence Interval	
					Lower Bound	Upper Bound
6.0	8.0	1.3333	.81534	.341	-.7478	3.4145
	10.0	-.3611	.81534	1.000	-2.4422	1.7200
8.0	6.0	-1.3333	.81534	.341	-3.4145	.7478
	10.0	-1.6944	.81534	.142	-3.7756	.3867
10.0	6.0	.3611	.81534	1.000	-1.7200	2.4422
	8.0	1.6944	.81534	.142	-.3867	3.7756

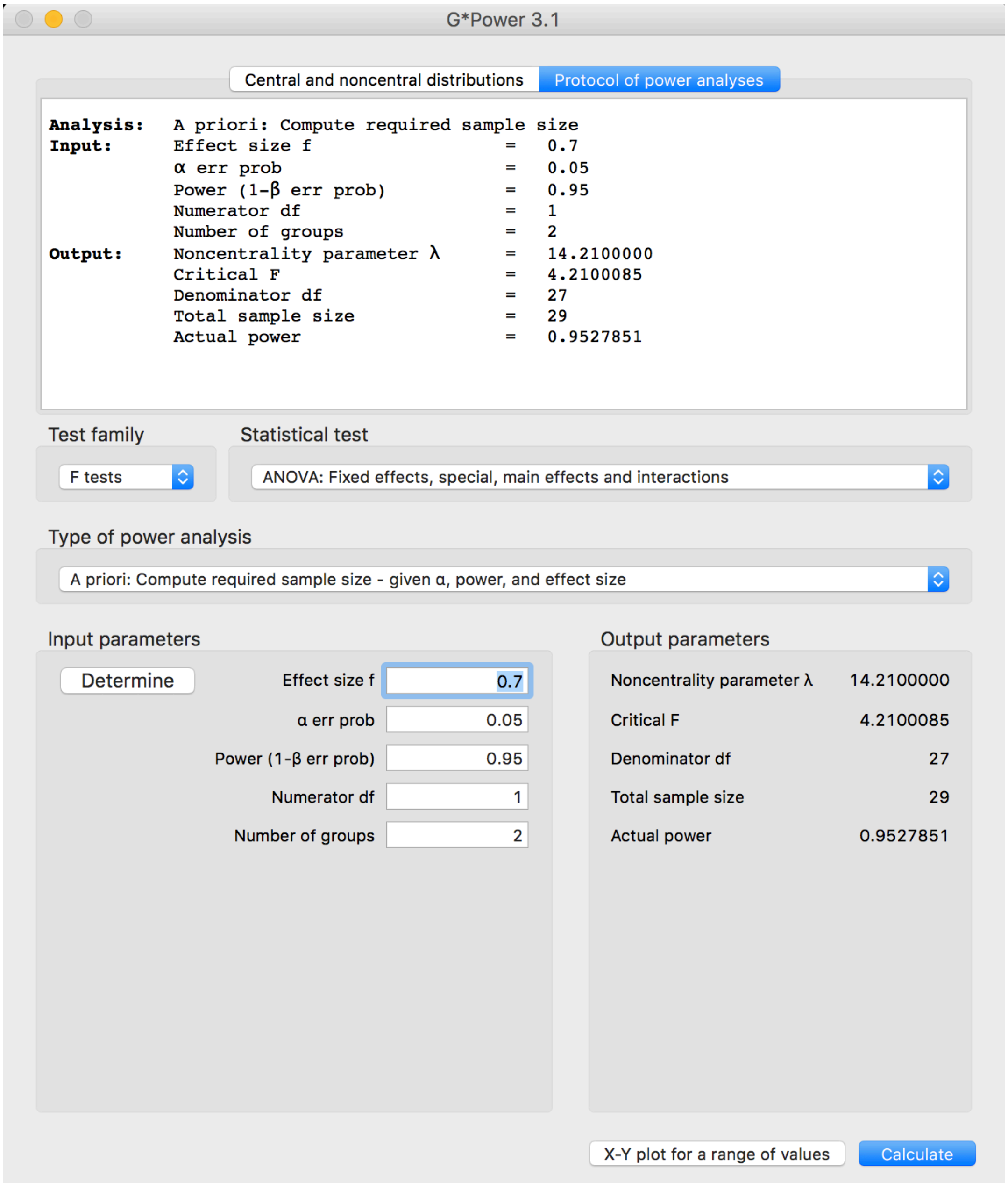
Appendix 2

Sample size calculation using G*Power 3.1 software.

i- Sample size estimation for Multifactorial ANOVA with three independent variables using effect size of 0.4 obtained from previous similar experiments with conventional implants. Total sample used in this experiment was 108, 36 in each group.



ii. Sample size estimation for ANOVA with two independent variables (Length and Diameter) using effect size of 0.7 obtained from previous similar experiments with conventional implants. Total sample size used in each of these tests was 36.



Appendix 3

Publications:

1- H. AlOhali, B.Bahrani, E. Yen, S Arzanpour, and B Chehroudi, "Factors effecting primary stability of mini-implants or TADs *in vitro*", *American Assiociation of Dental Research Annual Meeting,* Los Angles, Calif, March 16-19, 2016.

Abstract
OBJECTIVE: Mini-implants or Temporary Anchoring Devices (TAD) are now routinely used in orthodontic treatments; however, compared to conventional implants, TADs suffer higher failure. Achieving primary stability (PS) appears to be the most important factor predicting success of TADs. Factors such as implant diameter, length, and bone quality are known to influence PS in conventional implants; however, little is known of the effects of these factors on PS in TADs. Therefore the aim of this study was to investigate the effect of TAD's diameter, length and the presence of cortical bone in PS. MATERIAL AND METHODS: AbsoAnchor TAD design from Dentos with 1.5,1.7, and 2mm diameters; 6,8, and 10mm length were placed in Polyurethane bone blocks (Sawbones) with densities of cancellous bone (GP-20). TADs were also placed in similar blocks that were sandwiched with either 1, or 2mm polyurethane sheets, which simulated cortical bone density. Four TADs in each group were placed using recommended procedures. PS of TADs were measured with Periotest and Osstell by two testers. Results were analysed by multifactorial ANOVA to detect the significant influence of each factor in TADs' PS ($p \leq 0.05$). RESULTS: Both Osstell and Periotest indicated significant increase in PS ($p<0.05$) when cortical bone sheet of 1 or 2 mm thickness were in contact with TADs. TADs diameter also appeared to have significant influence in PS, indicating that TADs with wider diameter (1.7-2mm) had significantly higher PS ($p<0.05$) in both cancelous and cortical sandwiched models. There was no significant difference in PS when different lengths of TADs were used in both cancelous and cortical sandwiched models.CONCLUSION: Important factors in achieving PS in TADs appear to be bone type and implant diameter and not its length. Recognizing factors improving PS would be expected to decrease unnecessary trauma and failure rate in children and adolescence who are main recipients of TADs.

2. B Bahrani, H. Alohali, B Chehroudi and S Arzanpour, “Comparison of a novel low-cost implant stability measuring system with commercially-available devices”, *International Assiociation of Dental Research Annual Meeting,* San Francisco, Calif , 2017.

Abstract

OBJECTIVE: An important prerequisite for the success of dental implants is to achieve and maintain stability. Continuous and objective measurement of implant stability is needed to predict long-term success. Commercially-available systems for measuring stability are expensive, technique-sensitive, and show high degree of variations. The aim of the present study was to assess the reliability of a low-cost novel device for measuring damping characteristics of dental implants in vitro. MATERIAL AND METHODS: Polyurethane blocks (Sawbones) with composition and densities to simulate cancellous, cortical and combined (sandwiched bone) were used. Straumann (10mm,ø3.3mm), and AbsoAnchor mini-implants with 1.5,1.7, and 2mm diameters; 6,8, and 10mm length were placed into the sites prepared using an undersized technique. In Straumann group, an incrementally increasing crestal defect was created by preparing a 1.5 mm diameter socket at 0, 90, 180, 270 degrees at the periphery of the main socket. A total of four implants per groups were used. Implant stability was assessed with Osstell, Periotest, and the new device by 3 investigators. Inter & intra class correlation analyses for repeated measurements were performed to assess reliability. Multifactorial ANOVA analyses were used to detect the significant influence of bone and implant type, as well as failure mode on devices’ quotient. RESULTS: There were strong correlation between investigators ($r=0.7-0.9$) and repeated measurements with all devices tested. All devices demonstrated significant ($p=0.05$) increase in stability in both type of implants placed in blocks with the greatest density. The diameter appeared to have greatest influence on the primary stability of mini-implants. The sensitivity of devices in measuring crestal defect varied greatly with defect location and depth. The new experimental device appeared to be more sensitive in detecting loss of stability in this model. CONCLUSION: This study demonstrated that the new experimental device for measuring damping characteristics of dental implants is a highly reliable tool for measuring stability in artificial bone.