An in vitro study evaluating the efficacy of a novel mount with torque control designed to tighten Osstell SmartPegs

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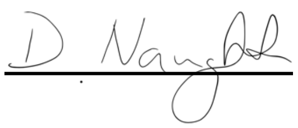

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Summary

This *in vitro* study aimed to evaluate the effect that different Osstell™ SmartPeg tightening methods might have on the implant stability quotient (ISQ) values of implants placed in artificial bone blocks. A secondary aim of the study was to determine the reliability of ISQ measurements when different SmartPeg tightening methods are used in implants with different abutment connection geometries placed in artificial bone blocks of varying densities.

Seven different types of implant, representing a range of different designs and connections, were placed in resin polyurethane blocks representing four different bone densities (D1, D2, D3 and D4). In total, 56 implants were placed in 8 bone blocks. Osstell SmartPegs were attached to each implant in four different ways: hand tightening with gauze, hand tightening with a plastic SmartPeg mount, hand tightening with the novel SmartPeg SafeMount and tightening to 6 Ncm with a calibrated torque wrench. Each SmartPeg tightening method was measured by two Osstell devices, from two directions and then repeated by a second operator.

Descriptive statistics were used to describe obtained ISQ values. Distribution of these values was visually represented using boxplots. Means of ISQ values by implant type were compared using a Kruskal-Wallis test when all bone densities were included and using an ANOVA when D4 was omitted from analysis. Intraclass correlation coefficients (ICC) were used to express reliability between the torquing methods, bone densities, operators and Osstell devices. Linear mixed effects regression was used to determine the effect of explanatory variables on ISQ readings. Descriptive statistics and ICC calculations were performed with IBM SPSS software v27. Linear mixed effects regression was performed with R (version 4.1.2) and R Studio.

The overall mean ISQ value was 65.58 ± 13.70. The control group, 6 Ncm of torque, had the highest mean ISQ and the lowest was observed in the hand tightening with gauze group. D1 and D2 had similar mean ISQ values, D3 had a reduction of approximately 6 ISQ values and D4 had a reduction of 31.5 ISQ values compared to D1. The difference in ISQ values between the 7 types of implants was not statistically significant when all bone densities were included but reached significance when D4 bone was removed ($p < 0.001$). All SmartPeg tightening methods had excellent agreement with the control group. The

highest agreement was seen with the SafeMount (ICC 0.994) and the lowest with the hand tightening with gauze group (ICC 0.978). There was excellent agreement between the two Osstell devices and between the two measurement directions. Overall, there was also excellent agreement between the two operators (ICC 0.993) however when data was analysed by bone density reliability between the two operators was very poor for D4 bone regardless of torquing method. The linear mixed effects model indicated that approximately 36% of the variation in ISQ values was due to the nested effect of the implant within bone density. The implant itself accounted for 11% and the operator accounted for 6%. The linear mixed effects regression also demonstrated the hand tightening with gauze group to have a statistically significant difference compared to the control group ($p < 0.001$), whereas the plastic SmartPeg mount group and the SafeMount group did not have statistically significant differences. Furthermore, there was a statistically significant difference in ISQ values obtained from D3 (p 0.006) and D4 ($p < 0.001$) bone when compared to D1 but no statistically significant difference between D1 and D2 bone.

These results demonstrate the novel SafeMount to be a valid tool to tightening Osstell SmartPegs. Hand tightening with gauze results in a statistically significant lower ISQ value compared to the control. However, the majority of the difference in ISQ values was observed from changes in bone density. Furthermore, while Osstell measurements are a generally reliable tool, they have very poor inter-examiner reliability for low ISQ values in soft bone.

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List of Abbreviations

BIC	Bone to implant contact
CBCT	Cone-beam computed tomography
CT	Computed tomography
CTG	Connective tissue graft
HA	Hydroxyapatite
HU	Hounsfield units
Hz	Hertz
ICC	Intraclass correlation coefficient
ISQ	Implant stability quotient
IT	Insertion torque
LDF	Laser doppler flowmetry
MBL	Marginal bone loss
PROM	Patient reported outcome measure
Q-Q	Quantile – quantile
RBM	Resorbable blast media
RFA	Resonance frequency analysis
RPM	Rotations per minute
SAE	Sandblasted acid-etched
SLA	Sandblasted, large grit, acid-etched

1. Literature review

1.1 Introduction

Since their introduction, dental implants have revolutionised treatment options for the replacement of missing teeth and become an integral part of dental practice. First reported in the 1960s, they were an experimental concept but in the early 1980s, they gained widespread acceptance (1). Since then, the scientific literature has continued to grow, resulting in a large data base validating their use. In a meta-analysis, Pjetursson et al. have reported implant survival rates of 95.6% at 5 years and 93.1% at 10 years (2). Improvements regarding implant therapy have focused on areas such as implant design at the macroscopic level, surface characteristics and peri-implant hard and soft tissue augmentation. Complications are relatively common with implants (2, 3). Most complications are technical and concern the implant crown and abutment. However, biologic complications also occur (3).

Implant stability can influence the overall treatment protocol and success. The ability to measure implant stability in an accurate, repeatable and non-traumatic way allows the implant surgeon and restorative dentist to guide treatment to a successful outcome.

This literature review aims to discuss concepts of relevance to implant stability and the use of resonance frequency analysis to measure it.

1.1.1 Osseointegration

The discovery in the 1960s that commercially pure titanium implants could achieve anchorage in bone was a breakthrough in tooth replacement. This was subsequently termed "osseointegration" and was defined as a direct functional contact between living bone and the implant (1). Davies expanded on early concepts of osseointegration by publishing histologic mechanisms by which implant osseointegration occurs (4). He reported three main healing phases: 1) migration of differentiating osteogenic cells to the implant surface, 2) *De novo* bone formation resulting in a mineralised interfacial matrix and 3) bone remodelling at the bone-implant interface.

Berglundh et al. examined the phases of wound healing involved in osseointegration of 20 Labrador dogs (5). Custom made implants resembling solid screws with sandblasted, large grit, acid etched (SLA) surfaces were used. Compared to the equivalent standard Straumann commercially available implants, the implants in this study had a deep U-shaped trough within the thread region. The rationale was to provide a well-defined wound compartment. In total, histological healing was evaluated at 160 implant sites at various time points from 2 hours after implant insertion to 12 weeks. Histological samples from 2 hours after implant insertion revealed the peripheral portions of the implant threads to be in contact with the surrounding bone. This contact provided what is called primary stability of the implant. Initially, a coagulum was present between the threads of the implants. By day 4, this coagulum had been replaced by fibroblast-like cells. Immediately adjacent to the implant surface was a stroma of fibrin-like structures. At 1 week, a provisional matrix was observed in areas previously occupied by the coagulum and fibroblast-like cells. This was vascular and had areas of newly formed bone around the vascular units and in direct contact with some of the implant surface. At 2 weeks, large areas of woven bone had developed. The area surrounding the implant continued to be vascular and lined with osteoblasts. At 4 weeks, there was further marked formation of new bone. Bone remodelling was most prominent between the implant threads and by 6 weeks, almost all these regions had bone fill. Between 8 and 12 weeks, mature bone was visible and was often surrounded by bone marrow which contained blood vessels, collagen fibres and adipocytes. Overall, during healing, the bone initially responsible for primary stability resorbed and was replaced with newly formed bone. Implants, however, remained clinically stable throughout this process.

Lang et al. also assessed osseointegration at different time points using 49 Straumann chemically modified moderately rough implants placed in the mandibular retromolar region of humans (6). Both hydrophilic (SLActive) and hydrophobic (SLA) implants were used. After a designated healing time, the implants and surrounding tissue were removed with a trephine bur. The study reported that at 7 days after implant insertion, old bone was still present in contact with the implant providing stability. In a small number of specimens, new bone apposition with the implant surface could be seen in areas where the old bone was in close proximity to the implant. Where gaps existed between bone and implant, this was filled with a primitive matrix which contained various shapes and quantities of bone debris particles. By day 14, the bone to implant contact (BIC) had doubled from what was seen at day 7. New bone formation was limited to regions which displayed evidence of a prior resorptive process. Bone debris was surrounded by osteoid containing osteoblasts which resulted in trabeculae formation. By day 28, the BIC had increased threefold to approximately 30-50%. Large areas of the implants now had a bony coating. Newly mineralised trabecular bone extending into the provisional matrix was also observed. By day 42, the BIC continued to increase to approximately 60%. The bone coating on the implants had a remarkable increase in thickness and was frequently connected to the newly formed trabeculae. Both implant types showed similar bone healing but more osseointegration was observed for the hydrophilic SLActive implants compared to the hydrophobic SLA implants. It is possible that the hydrophilic surface allowed for more retention of a blood clot thereby promoting greater bone formation.

1.2 Implant stability

Implant stability is defined as the absence of clinical mobility (7). Stability is divided into primary and secondary stability. Primary stability is the biomechanical stability that occurs immediately after implant insertion. Secondary stability is that which occurs during the healing process and beyond. Primary stability is influenced by the design of the implant, the placement technique and the quantity, as well as, quality of bone (7-11). Secondary stability is influenced by the primary stability and bone remodelling as well as the micro- and macro- topography of the implant (12, 13).

1.2.1 Measuring implant stability

There are several methods of determining stability (12). Pre-operatively, computerised tomography (CT) is commonly used in association with implant planning and allows for a quantitative and qualitative evaluation of the cancellous and trabecular bone mineral densities. This is then used to infer the likely stability to be expected with subsequent implant placement. Intra-operatively, surgeon's perception of the implant's resistance to rotation upon insertion can be used to estimate implant stability. However, this has been shown to be poorly reproducible and can have a wide range of values away from the actual insertion torque (IT) (14). Percussion testing involves the tapping of an instrument handle against the implant carrier. A lack of ringing or the presence of a dull

ringing sound may indicate poor primary stability. A high pitched ring may indicate good primary stability. However, this is somewhat subjective, dependent on the instrument used to tap and generally considered to be a poor quality method (7). The maximum insertion torque required for implant placement is a more objective value. It is an indicator of rotational stability and provides some information on local bone quality (15).
Secondary stability can be measured by a number of techniques. The reverse torque test involves applying a reverse or unscrewing torque to the implant (16). Implants that rotate are considered failures however it has been shown that this test may itself cause a fracture in the areas undergoing osseointegration. The reverse torque test or, indeed, histological analysis are not clinically practical. Two dimensional radiographs allow identification of peri-implant radiolucencies and the level of the crestal bone. This is then used to infer implant stability. The diagnostic accuracy of this method is low, especially in populations with a low prevalence of implant instability (17).

Damping capacity analysis can be used to measure primary and secondary stability. The Periotest™ device (Medizintechnik Gulden, Modautal, Germany) was developed to assess mobility of teeth via an assessment of the damping characteristics of the periodontium. This has since been extensively used in the field of implantology. A metal electromagnet is tapped towards the head of the implant 16 times in 4 seconds. Upon contacting the implant, deceleration of the electromagnet occurs. High implant stability will result in a high damping effect of the peri-implant tissues. This will result in greater deceleration of the electromagnet. The contact time of the electromagnet on the implant is then calculated and expressed as a numerical value indicating the degree of stability.

Resonance frequency analysis can also be used to measure primary and secondary stability. It is described in detail below.

1.2.2 Resonance frequency analysis

Resonance frequency analysis (RFA) was described by Meredith in 1996 as an objective, non-invasive, method of determining implant stability (18). RFA is the measurement of the frequency with which a device vibrates. Integration Diagnostics Ltd. Company (Sweden) commercialised the use of RFA by launching a series of Osstell™ devices to measure RFA with implant-specific transducers, termed SmartPegs. The SmartPeg is attached to the implant and brought to vibration by magnetic pulses from the probe of the device. With high implant stability will be a high vibration frequency. If stability decreases, the vibration frequency also decreases. To date, manufactured devices include: Osstell Mentor, Osstell ISQ, Osstell IDx and Osstell Beacon. SmartPegs are inserted onto an implant with the aid of a supplied plastic wrench. Osstell recommend these should be tightened to 4-5 Ncm, which they describe as "finger tight". The Osstell device's probe is brought near the attached SmartPeg. The probe contains a piezoelectric element which emits a sinusoidal signal to make the implant vibrate. The implant's resistance to vibration is expressed as the implant stability quotient (ISQ) value. Although frequency measurements are usually expressed in Hertz (Hz), ISQ was deemed to be easier to communicate. ISQ is a scale ranging from 1-100. Stability increases with increasing ISQ. An ISQ value of 1 corresponds to approximately 1000 Hz and an ISQ value of 100 corresponds to approximately 10,000 Hz. ISQ values below 60 are associated with low stability, values of 60-70 are associated with medium stability and above 70 are associated with high stability. The ISQ scale corresponds to micro mobility in a non-linear manner. The micro mobility reduces by approximately 50% when the ISQ value increases from 60 to 70. The use of RFA is an indirect method of measuring osseointegration. It applies a bending or axial load to provide information about the stiffness of the bone to implant junction. Axial loading is the most common type of loading for a dental implant (7). The Penguin™ (Integration Diagnostics Sweden AB, Sweden) is a similar device which also uses RFA, expressing measurements as ISQ values and is used in a similar clinical manner to Osstell devices. However, the Penguin relies on re-usable transducers which require calibration as they are not specific to particular implants. Osstell, in contrast, relies on the connection of single use implant specific transducers.

The significant advantage RFA provides over other methods of assessing implant stability is that it can be repeated at various time points, is an objective measurement and is non-destructive. Periotest can also be used in a repeatable and non-destructive manner. In addition, Periotest also has the advantage that it can be used when there is already a single implant crown on the implant whereas the Osstell and Penguin devices require removal of the prostheses and attachment of a transducer. Periotest, however, is reliant on the positioning and angulation of the electromagnet. Changes in this can affect the stability measurement value. This is the main drawback over the Osstell and Penguin devices.

1.2.3 Importance of implant stability

In an animal model, Lioubavina-Hack et al. demonstrated that implants with very poor primary stability did not osteointegrate (19). Experimental implants were placed so that the implant was suspended from a capsule attached to the ramus of rats but not inserted into the bone. This ensured no primary stability. Control implants had their apex extending from the capsule into the bone. Assessments were made after 1 – 9 months of healing. At all time points, control sites showed a histologic increase in BIC. In contrast, the experimental group showed no BIC at all throughout the study and fibrous encapsulation in all implants of this group was observed. Human observational studies have reported that low primary stability is associated with higher implant failure rates but not 100% failure as reported by Lioubavina-Hack et al. (20, 21). The implants in this study were not rigidly attached thus significant micromotion of the implants could occur. This could explain the fibrous encapsulation of all the experimental implants. Micromovement of ≥100-150μm is enough to jeopardise healing (22). It was previously suggested that in order to achieve a predictable level of stability, bicortical stabilisation was necessary. However, in a retrospective study, it was reported that maxillary implants with bicortical stabilisation had a four times higher failure rate than monocortically stabilised implants (23). It was noted that in order to achieve bicortical stabilisation, a number of implants were placed in poor restorative positions. This lead to an increase in stress and bending forces causing a high number of these implants to fracture. Marginal bone loss was similar over the 15 year follow-up suggesting that the type of cortical anchorage did not have an influence on crestal bone levels. Overall, this concept has fallen out of favour.

Rodrigo et al. prospectively assessed over 4000 implants with a follow-up time of 6-36 months (20). Implants were clinically stratified as being stable by displaying no rotation when the healing cap was placed or having poor primary stability by displaying a light resistance or no resistance to rotation. Implants with poor primary stability had a 97.2% survival rate compared to 99.1% for stable implants. Furthermore, the implants with no resistance to rotation had a 94.1% success rate. The relationship between low stability and failure was statistically significant. All implants were placed using a two-stage approach.

Orenstein et al. reported on over 2600 implants placed in the early 1990s across multiple centres (21). Of the implants that displayed clinical mobility immediately after insertion, 93.8% of them displayed clinical stability at second stage surgery. Of the immobile implants at placement, 97.5% successfully integrated and were reported as stable at 2nd stage surgery. The results from these last two studies demonstrate that implants which are clinically mobile at placement can successfully integrate and gain clinical stability when they stay undisturbed during healing.

It has been demonstrated that there is a strong relationship between primary and secondary stability. Monje et al., in a systematic review which included 37 articles, reported a statistically significant association between primary and secondary stability (24). They determined that approximately 85% of the recorded variations in secondary stability was due to the initial primary stability.

Ivanova et al. also reported a high correlation between primary and secondary stability (25). Ninety implants were placed in fully healed extraction sites and stability was measured by RFA. Secondary stability was assessed four months after implant placement. Both primary and secondary stability were significantly associated with bone density as assessed by pre-op cone-beam computed tomography (CBCT) scans. Bone biopsies were also taken with a trephine bur immediately prior to osteotomy preparation. Statistical significance was demonstrated between the amount of new bone formation at the healed extraction sites and secondary stability.

Secondary stability is significantly associated with implant survival (20). The majority of studies reporting on secondary stability are measuring stability at second stage surgery. Thus, these are generally of short term duration and not representative of a functional implant. Secondary stability can be subject to multiple confounding factors such as occlusal habits or prosthetic design that may impact the survival of the implant. This is usually not addressed as the main focus of many studies is often the change in stability from insertion to uncovering.

1.3 Immediate implant placement and loading

Historically, implants were submerged into healed extraction sockets and uncovered after 3-6 months (1). As techniques and implants have improved, a trend is seen towards immediate implant placement and restoration.

Immediate implants are defined as implants placed into fresh extraction sockets. Immediate restoration is defined as any restoration placed within 24 hours of the implant insertion. This is typically a non-functional loading whereby there is no contact with the opposing dentition.

The proposed advantages of immediate placement and provisionalisation protocols include an overall shorter treatment duration, less surgical visits and therefore, an overall improved experience for the patient. The gingival and osseous architecture may also be maintained thereby improving aesthetics compared to delayed placement and restoration (26-28).

The success of immediate placement and provisionalisation is dependent on several factors (26). Patient dependent factors include the quantity and quality of hard and soft tissues as well as the sagittal root position within the alveolar bone. Clinician related factors include the placement protocol, the three-dimensional positioning of the implant and the contour of the abutment and provisional restoration.

Many different protocols exist for immediate implant placement. A flapless approach has the advantage of a faster surgical time, maintaining the periosteum and the overall blood supply to the hard and soft tissues, and possibly reducing patient discomfort. However, it can be more technique sensitive and result in bony fenestration or dehiscence. A systematic review assessing flapless versus flapped procedures reported no significant differences between the two on implant survival and marginal bone loss (29). Therefore either approach is acceptable but a flapped approach may be more suitable for cases requiring extensive augmentation and a flapless approach for patient comfort (26).

The management of the gap between the implant and the facial bone plate has been subject to much investigation. Animal and human studies have generally shown the wider this gap, the less bone formation. Therefore, many advocate grafting when the gap is >1mm (26, 30). Gingival phenotype is also an important consideration for immediate implants. Patients with a thin gingival phenotype are at risk of gingival recession and are also likely to have thin labial bone which will result in less crestal peri-implant bone volume. A connective tissue graft (CTG) to thicken the peri-implant soft tissues can result in a more stable peri-implant soft tissue margin.

According to the consensus report of the XV European Workshop in Periodontology, immediate implants should be avoided in sites with >50% loss of one bony wall and where primary stability cannot be achieved without the implant being placed in the incorrect three-dimensional position (31). Additionally, if there is a need for an inappropriately wide implant in order to achieve primary stability, delayed implant placement should be selected.

1.3.1 Success rates of immediate placement and loading

Immediate implant placement and provisionalisation was first reported for the aesthetic zone by Wöhrle in 1998 (32). He published a case series of 14 single tooth implants in the aesthetic zone which were subject to immediate placement and provisionalisation. The concept then gained popularity due to its apparent success, shorter treatment times and aesthetic advantages.

In a prospective cohort study, Siebers et al. assessed 76 patients and 222 implants to compare immediate and delayed placement and loading protocols (33). After a mean observation period of 40 months, overall implant success was 97.7%. Delayed implant placement had greater success than immediate placement (99.4% vs 93.1%) and implants with delayed loading had better success than immediately loaded implants (100.0% vs 95.5%). Immediate loading, however, had better aesthetic scores, lower probing pocket depths and lower bleeding on probing scores. Immediate placement also had favourable marginal bone levels compared to delayed placement. However, while multiple trends were observed, the differences between groups were not statistically significant. Immediately placed and loaded implants were generally successful with some slight tendency towards higher failure.

In a recent systematic review, Aiquel et al. reported that all combinations of immediate or delayed placement and loading resulted in implant survival rates of ≥90% after ≥3 years of follow-up (34). While the study lacked data on immediate placement protocols, similar survival rates were observed for delayed implant placement with immediate and delayed loading. All studies were confined to single tooth implants or fixed partial dentures with non-functional loading. Smokers or those with a history of periodontitis were excluded from the majority of the included studies. Therefore, with careful patient selection, very good success was demonstrated.

In another recent systematic review, Gallucci et al. published data in agreement with previous reviews generally supporting the use of immediate placement and loading (35). All immediate and delayed protocols resulted in implant survival of >95% after follow-up of ≥1 year. Of note is the observation that more than half of the included studies did not provide information on the way the patients were assigned to the intervention (39 out of 69 studies). This can result in significant reporting bias for implants that were initially planned to be immediately placed or loaded but ultimately were not. The most common reported reasons for implants not to be immediately placed or loaded included lack of primary stability (32%) resulting in delayed loading, or a need for bone augmentation (32%) leading to delayed placement.

Khzam et al., reported that soft tissue aesthetics were generally very acceptable for single implants in the aesthetic zone which were subject to immediate placement and provisionalisation protocols (36). Within the first year <0.3mm of recession was noted. Papilla tended to rebound to their original levels after two years. However, 11% of cases showed ≥1mm of mid-facial recession despite having a thick gingival phenotype and adequate facial bone.

Cosyn et al. published a prospective cohort study with a 5 year follow-up assessing clinical outcomes of immediately placed and provisionalised single implants which also included implants in the aesthetic zone (37). Similarly to Khzam et al., all patients were considered to be at low risk of developing complications in that they displayed a thick gingival phenotype, intact facial bone, were periodontally healthy and had adjacent teeth. All surgeries, performed by an experienced periodontist, were flapless and had a bovine xenograft placed between the implant and the facial wall. Sites that displayed recession of >1mm or major alveolar bone changes at 3 months were treated with a CTG. Seventeen out of 22 patients attended for the 5 year follow-up. Implant survival was very good, marginal bone loss was minimal and papilla height increased between years 1 and 5. Despite this, five implants had early complications requiring a CTG and 3 had late complications. In total, 8 out of 17 implants had aesthetic complications. None of the late complications had been treated with a CTG in the early phase.

Slagter et al. also reported data with a 5 year follow-up comparing immediate placement and immediate provisionalisation to immediate placement and delayed restoration in the aesthetic zone (38). They reported no differences between groups despite their delayed restoration group receiving a CTG to cover the implant site. They also reported an approximately threefold increase in marginal bone loss at 5 years compared to Cosyn et al. Mid-facial recession at 5 years was 1.44mm in the immediate provisionalisation group and 0.81mm in delayed restoration group. Unlike the two previous studies, only mean values of recession were reported. No information was given on the number of patients who had more significant aesthetic complications. Facial bone thickness was assessed at various times points with a CBCT and overall, the immediate provisionalisation group preserved the facial bone better despite also showing more recession.

Seyssens et al., in a recent systematic review, evaluated immediate implants placed with or without a connective tissue graft (39). Both immediate and delayed loading protocols were included. Meta-analysis showed a difference of 0.41mm in vertical midfacial soft tissue change in favour of the CTG after 12-24 months of follow-up. The risk for developing ≥1mm of mid-facial recession was 12 times lower in the CTG group. Pink aesthetic scores and marginal bone levels were similar between groups. The differences in groups was most prominent for those with a thin gingival phenotype and <0.5mm facial bone thickness. A cross sectional analysis of 47 patients with loading times of up to 10 years and a mean of 4.2 ± 1.7 years, found similar levels of peri-implant disease when comparing immediate placement and provisionalisation to delayed protocols (40). No failures were seen in either group. Smoking status, a lack of facial wall integrity and ≤2mm of keratinised tissue were the significant factors associated with peri-implant disease rather than the placement and loading protocol.

Overall, most studies support the use of immediate implant placement and immediate provisionalisation in terms of achieving osteointegration and implant survival albeit with either equal survival rates of implants or a slight increase in implant loss in immediate placement or loading groups. Immediate placement does not prevent resorption of the facial bone and indeed hard or soft tissue grafting is often required. Even after adjunctive hard tissue grafting, soft tissue aesthetics can be an area of concern though existing literature does not have a significant amount of articles reporting medium to long term data.

1.3.2 Patient reported outcome measures associated with immediate loading

Patient perception should be a considered aspect of implant success. This should include perception of function and aesthetics during the healing phase and beyond. Measurement of patient reported outcome measures (PROMs) is commonly done through self-reported questionnaires. However, PROMs tend not to be the primary research question of the majority of implant studies (41). PROMs ideally should have scales rather than dichotomous answers but patient interpretation of these scales can be an issue. Likewise, patient recall, gratitude or bias can also influence results.

Gotfredsen et al. published a systematic review which included 15 studies on implant loading in partially edentulous patients (41). They reported that most studies did not show any PROM differences between different loading protocols. Of the studies that did show a difference, patients preferred immediate loading. Of note, several of the PROMs used were not oral specific and generally resulted in low scores. This may explain why little difference was seen between most groups.

1.3.3 Insertion torque required for provisionalisation

Most immediate implant protocols specify a minimum insertion torque that must be reached for an implant to be immediately provisionalised. In a recent consensus statement from the International Team for Implantology on placement and loading protocols, they reported that a threshold of ≥35 Ncm was the most common insertion torque value required for immediate provisionalisation in 12 of 24 studies (35). A threshold of ≥30 Ncm was reported in 5 studies, ≥15 Ncm in 3 studies, ≥40 Ncm in 2 studies and ≥20 Ncm and ≥45 Ncm in one study each. In general, it is universally accepted that primary stability is an absolute pre-requisite for achieving a successful outcome with an immediate provisionalisation (26). Micro-movement as a result of poor primary stability and loading can prevent osseointegration. Adequate stability is usually achieved by engaging the palatal wall and extending the osteotomy beyond the anatomical apex of the extracted tooth.

1.4 Clinical implications of RFA values

Osstell, through RFA, have sought to simplify the process of determining when an implant can be loaded. They advise that ISQ values upon implant insertion ≥70 can be immediately loaded, as per figure 1, whereas lower ISQ values may need closer monitoring or a 2-stage conventional approach.

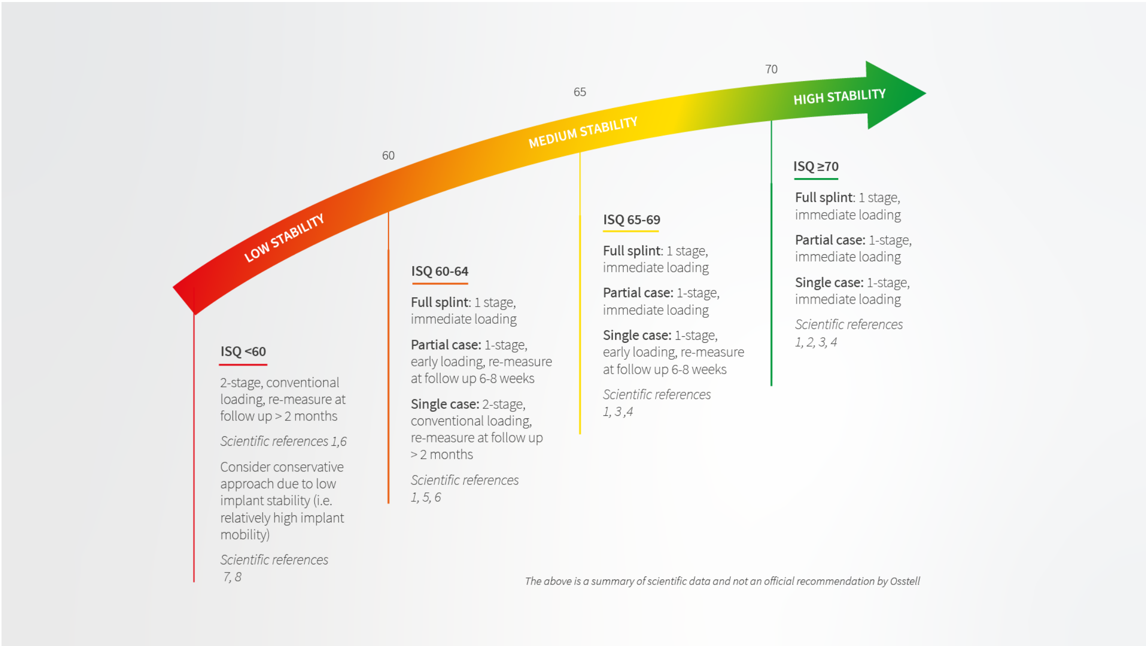

Figure 1: Osstell loading protocols

These values are based on a combination of authors' opinions derived from their clinical experience and on the results of several clinical trials. Rather than taking ISQ values in isolation, a useful tool is the ability to track changes in ISQ over time. An implant undergoing osteointegration should increase in ISQ.

In a prospective clinical study, Krafft et al. aimed to assess whether a specific ISQ threshold at implant placement correlated with successful osseointegration (42). Four hundred and ninety five Straumann implants of varying diameter and length were included in the study. After 6-8 weeks of healing, implants were torqued forward at 35 Ncm, which is the torque the implants would be subjected to when the crown was placed. If the patient felt discomfort they were allowed a longer healing time. Overall, 8 implants failed at this stage and 55 required further healing. There was a statistically significant difference in ISQ values, at placement and after healing, between successful implants and those which failed or required further healing. However, ISQ values between different groups overlapped significantly meaning that no specific ISQ threshold could be demonstrated to be predictive of successful osseointegration.

Nedir et al., in a cohort study, placed implants in healed extraction sites and carried out immediate and delayed loading of implants (43). Grouping was determined by patients' treatment needs such as their sensitivity to aesthetics, regardless of their ISQ values. Over 98% of the implants were splinted implants. At the 1 year follow-up, one implant in each group was mobile and removed. The lowest ISQ value recorded from a clinically successful implant was 47. The two clinically mobile implants had an ISQ value of 43 and 46 before removal. Therefore, the authors report that ISQ values <47 are not a reliable indicator of stability. They also reported several splinted implants in both groups had ISQ values in the 50s, were loaded and performed successfully.

Bornstein et al. reported on 56 implants placed in fully healed sites in the posterior mandible and were subject to early loading at 3 weeks (44). Two implants had no resistance to rotational movement at the 3 week follow-up and were allowed to osteointegrate for a further 3-4 weeks. All loaded implants reached an ISQ of ≥ 70 and were clinically successful. In agreement, Valderrama et al. also reported implants subjected to early loading, with ISQ values of ≥ 65, were clinically successful (45). For implants with ISQ values less than this, they were successfully loaded following a period of extended healing.

Although the most pertinent use of RFA in clinical practice is to guide the loading protocol, many studies which include ISQ values do so to determine statistical significance between various study groups. Indeed, very few studies exist assessing success rates of implants with poor-moderate ISQ values which are loaded. Given that multiple studies show failed implants to have generally low ISQ values, it is unlikely these types of studies would ever be ethical to conduct. Currently, there are suggestions that implants may be loaded potentially sooner, at lower ISQ values, than Osstell recommend. Studies on this are lacking however. Indeed, the Osstell protocol has been shown to generally be successful.

1.5 Factors affecting RFA values

1.5.1 Insertion torque

The relationship between peak insertion torque and ISQ values have been investigated with mixed results by many. Degidi et al. reported a poor correlation between the two in a sample of over 500 implants (14). While implants with a high insertion torque tended to have a high ISQ value, the overwhelming majority of implants with a low insertion torque had a medium or high ISQ value. Levins reported a very poor correlation between IT and ISQ of immediate implants (46). He reported that there was no significant correlation between IT and ISQ at time of insertion or at up to 14 weeks later. Souze et al. reported a moderate positive correlation between insertion torque and ISQ on the day of implant placement but no correlation between insertion torque and ISQ after 6 months (47). Cassetta et al., however, reported a strong correlation between IT and ISQ at time of implant placement but not at 2, 6 or 12 months (48). Furthermore this was maintained regardless of implant design (presence or absence of microthreads) and arch. In a systematic review, Lages et al. concluded that IT and RFA were independent and incomparable with no statistically significant correlation between the two (49). While 12 studies were included in the analysis, the overall quality of the evidence was low. In agreement with Degidi et al., multiple cases of high IT and low ISQ or vice versa were reported. Acil et al. have postulated that one possible reason for the lack of correlation between IT and ISQ is that when implants are placed at a certain IT, some degree of osseous relaxation occurs immediately after placement reducing the ISQ value (50). This is dependent on the viscoelastic behaviour of the bone. In a retrospective cohort study, Bavetta et al. concluded that IT values alone were more reliable than ISQ values for decision making on immediate provisionalisation of immediate implants (51). All implants that met the study inclusion criteria had an IT of >30 Ncm. Several of these implants were provisionalised despite having an ISQ of <60 with no reported failures or complications.

1.5.2 Bone density

The influence of bone density on ISQ ideally would involve recording ISQ values and then immediately assessing bone density histologically but this is not ethically possible.

Therefore, most studies rely on assessing bone density through radiographic Hounsfield units. The Hounsfield unit (HU) is a relative quantitative measurement of radiodensity.
In a systematic review, Marquezan et al., assessed the influence of bone density on implant stability (52). Bone density was assessed radiographically from pre-operative CBCT images while stability was assessed by a range of measures including insertion torque, RFA and Periotest values. Although included articles were generally of low or moderate methodological quality, a positive association was demonstrated between bone density and primary stability. Correlations between bone density and ISQ values specifically ranged from a moderate to high correlation. Of note, the studies with lower correlations tended to assess the trabecular bone only whereas studies that considered trabecular and cortical bone as one unit had higher correlations. Turkyilmaz & McGlumphy retrospectively assessed 300 implants to determine the influence of local bone density on implant stability (53). Bone density was again determined by measuring Hounsfield units from CT images and stability through ISQ values. Bone density demonstrated a statistically significant association with implant stability at placement. ISQ values at 6 months were also significantly associated with baseline ISQ values. More recently, and in agreement with Turkyilmaz & McGlumphy, Merheb et al. also reported ISQ values to be significantly correlated to Hounsfield units (54). They assessed the influence of trabecular bone density and, separately, cortical bone density on implant stability in a prospective study using stereolithographic implant guides. In contrast to the systematic review by Marquezan et al., a higher correlation between density and ISQ value was demonstrated for trabecular bone than for cortical bone. During the healing phase, as osseointegration progressed, the influence of trabecular bone density on stability became non-significant however cortical density maintained significance. The stereolithographic implant guides used in this study allowed for accurate implant placement relative to the pre-operative CBCT scan, thereby allowing an accurate measure of Hounsfield units in the actual region the implant is placed rather than estimating where the implant is. This is noteworthy as bone density can change over very small distances (54). The relationship between ISQ and lateral micromotion of implants was assessed in vitro by Pagliani et al. They reported a significant inverse correlation between implant micro-motion and ISQ values (55). Both of these were also significantly influenced by the bone density.

Overall multiple studies of different design and of different implant type have shown relationships between bone density and primary implant stability (55-61). In contrast, some studies have reported no association between bone density and ISQ values (62). In a randomised control trial, Schnutenhaus et al. also sought to assess, as a secondary aim, whether bone density influenced primary stability (63). They reported no association between the two. Of note, the CBCT images were taken 2 months after extraction and 1 month before implant placement. Therefore the actual bone density at time of implant placement was not known as healing was still occurring when the CBCT was taken.
Overall, the influence of bone density on ISQ appears to be most significant for primary stability and decreases in importance for secondary stability.

1.5.3 Bone-to-implant-contact and ISQ

Whereas three-dimensional imaging strongly correlates with histological results of alveolar bone density (64), there are mixed outcomes on studies evaluating the relationship between BIC and ISQ. It is important to note that the type and quality of bone is of importance for stability rather than just the presence or absence of bone as is reported with BIC. Ito et al. found no correlation between ISQ and BIC in hydroxyapatite-coated implants inserted in the tibiae of mini-pigs with a 4 week follow-up (65). Park et al. also investigated the relationship between ISQ values and BIC (66). Using four rabbits, 16 implants in total were placed in tibiae. Initial ISQ values at implant insertion did show a significant correlation with BIC. However, in agreement with Ito et al., by 4 weeks there was no longer any correlation. Manresa et al. assessed the relationship between BIC and ISQ in Beagle dogs (67). At 0, 1, 2, 4, 5 and 8 weeks after implant insertion, no correlation between the two was observed.
Overall, there have been conflicting results in outcomes of studies investigating BIC and ISQ. Several animal and human cadaver studies have shown no correlation (10, 62, 68, 69) and several have shown some correlations (50, 70-74). These studies tend to have significant differences between them in terms of implant types, follow-up times, adjunctive use of biomaterials and other methodological differences.

1.5.4 Implant design

1.5.4.1 Macroscopic

The design of an implant can also have an influence on ISQ values. Merheb et al., reporting on 195 implants, concluded that longer and wider implants reached higher primary stability than shorter or narrower implants (54). This is in agreement with others in terms of wider implant diameters having higher ISQ values (10, 56, 75). However, some clinical studies do not show a statistically significant relationship between ISQ and implant length of 8-14mm (76), between 10 and 11.5mm (75) and between 7.5 and 14.5mm (77). Of note, none of these studies adjusted for differences in implant diameter, position within the arch or bone density when comparing different implants. Farronato et al. reported, in an vitro study, an increase of 1.0 ISQ units for every millimetre increase in implant length (78).

Akkocaoglu et al. compared ISQ values of Straumann tapered and standard implants in cadavers (10). The ISQ value for the tapered implants was statistically significantly higher than for the standard implants. Of interest, the 4.1mm diameter tapered implants had approximately the same ISQ as the 4.8mm diameter standard implants. Commuzi et al. also reported tapered implants to have higher ISQ values than parallel walled implants in-vitro (79). González-Serrano and colleagues compared 30 implants with a tapered body and single thread design to identical implants with a double thread design placed in a bovine rib of D3 bone (80). Bone quality was assessed from CT scans. The double thread design had statistically significant higher ISQ values. Yamaguchi et al., using artificial bone blocks, reported that the implant thread length and pitch had a statistically significant association with ISQ values (81). In agreement, Gehrke et al. also reported a difference in ISQ values between implants of different thread pitch and design (82).

1.5.4.2 Microscopic

In a randomised control trial, Novellino et al. evaluated the ISQ values of implants placed in the posterior maxilla with either a hydrophobic sandblasted acid-etched (SAE) surface or a hydrophilic SAE surface (83). All 64 implants had the same macroscopic design. While the survival rate of both groups was 100% after one year, the hydrophilic implants reached an ISQ of ≥70 2.24 times faster than the hydrophobic SAE implants. Velloso et al. undertook a similar study, comparing the same implants in a double blind RCT but in the mandible rather than the maxilla (84). They reported similar outcomes where the hydrophilic SAE surface treated implants increased ISQ values quicker and obtained a higher ISQ value to a statistically significant degree. Yoon et al. compared four different implant surface treatments in dogs: resorbable blast media (RBM), hydroxyapatite (HA), hydrothermal-treated HA, and SLA (85). Implants were of the same diameter, length and manufacturer throughout (Dentis Inc, Korea). While the SLA implants showed the highest ISQ values directly after insertion, at 2 weeks, RBM implants had the highest stability though this was not statistically significant. By 4 weeks, the HA coated implants had a significant difference over the hydrothermal-treated HA implants. Han et al. compared different Straumann implant surfaces and diameters to determine differences in ISQ values in-vivo (86). Of a total of 25 implants, no difference was reported between the SLA and SLActive implant surfaces. Of interest, they also reported no statistically significant correlation between ISQ and implant diameter however, only a small number of 4.8mm diameter implants were included compared to their standard 4.1mm implant.

1.5.5 Supracrestal height of implant components

The height of the supracrestal component of the implant complex may influence the bending force of the implant and therefore the lateral stability and ISQ. Lages et al. reported that the supracrestal height of the implant connection had a negative correlation with ISQ (87). They assessed 31 identical implants in-vivo. ISQ values from a standard SmartPeg were compared to those from abutments of varying height to which identical SmartPegs were sequentially attached. There were statistically significant and clinically relevant decreases in ISQ values with increasing abutment height. All abutments were tightened with a standardised force and all SmartPegs were attached with 4-6 Ncm of force. Of interest, this is one of the few studies in the Osstell literature that comment on the tightening torque of SmartPegs.

1.5.6 Osteotomy protocols

Saleem et al. oversized implant osteotomy preparations in the posterior maxilla to determine the resulting effect on ISQ (88). In the experimental group an extra osteotomy drill was inserted to half the length of the osteotomy and was 0.2mm wider than the implant to be placed. The experimental group had a statistically significant lower initial ISQ than the control group. However, the experimental group had a faster increase in ISQ and a significantly higher ISQ from weeks 2 to 12.

Turkyilmaz & Tozum assessed the outcome of undersizing implant osteotomy preparations on ISQ. Forty-eight implants were placed in 6 cadavers with three different groups based on their final drill diameter of 3mm, 3.4mm or 3.8mm (61). The mean difference between the 3mm and 3.8mm group was 18 ISQ units. This is in agreement with other studies showing a significantly higher ISQ in undersized osteotomy preparations (89, 90).

The influence of osteotomy drilling speeds have been theorised to impact the biological response at the bone-implant interface. Therefore some have sought to ascertain if measurable difference in ISQ values exist as a result of different drilling speeds. Romanos et al. most recently assessed this (91). They demonstrated no statistically significant difference in ISQ values when implant osteotomies were performed with drilling speeds of 800 and 2000 rotations per minute (rpm). Three hundred and sixty osteotomies were carried out in dense artificial bone blocks. These results are in agreement with Almedia et al. who also sought to assess if drilling speed had an influence on primary stability using RFA (92). Drilling speeds of 800 and 1500 rpm resulted in no significant difference in ISQ values in polyurethane bone blocks simulating D2 and D4 bone. Of note, these two studies are in artificial bone blocks, therefore the biological response has not been assessed, only the mechanical influence of the drilling speeds.

Osteotomy preparation in terms of osseodensification also plays a role in ISQ values. In a recent meta-analysis, it was reported that osseodensification had a statistically significant impact on ISQ values. Osseodensification resulted in a mean ISQ value increase of 13.1 at implant placement (93). Furthermore, osseodensification also resulted in a statistically significant increase in ISQ at follow-up periods. This is in agreement with a recent prospective clinical trial which also reported a statistically significant higher mean ISQ at all investigated time points (94).

1.5.7 Tightening torque of SmartPegs

Given that one of the advantages of RFA is the ability to repeat measurements at different time points, it is of importance to be able to standardise any variables which are not of clinical interest. In particular, the influence of the tightening force of the SmartPeg on the resulting ISQ has been only scantly reported in the literature.

Geckili et al. reported that insertion of SmartPegs using different torques did affect ISQ values (95). They recommended a range of 5-8 Ncm. This study was carried out in bovine ribs, the rationale being to attempt to imitate human edentulous bone in terms of cortical and cancellous bone composition. Four examiners hand tightened SmartPegs onto 30 Trias implants (Servo-Dental GmbH & Co. KG, Hagen, Germany) and this was compared to a standardised torque value ranging from 1 to 11 Ncm. No negative consequences of torquing to higher than 8 Ncm were reported. While the torque values of the hand tightening group were not known, this group did result in some statistically different ISQ results compared to the standardised group and compared to the other examiners. This suggests the need for a standardisation of the applied SmartPeg torque.

Kästel et al. conducted a study with similar design to the previous study (96). Bovine ribs were again used with a specified bone density of D1. Thirty implants (XiVe S, Dentsply Sirona Implants, Bensheim, Germany) were inserted into the bone. They reported a wide variation in hand tightening insertion torque ranging from 2 to 11 Ncm between different examiners. The control group was tightened to 5 Ncm with a calibrated torque wrench. Insertion torques were assumed to be the same as the amount of force needed to remove the SmartPeg. Overall, they reported no significant impact on ISQ with differing insertion torques. In contrast to Geckili et al., they suggested that hand tightening was acceptable and there was no need for a standardised tightening torque.

Salatti et al. also attempted to determine the optimal tightening torque for SmartPegs (97). One hundred IntraOss implants (Warie Industrial Ltd, Itaquaquecetuba, Brazil) were embedded in polyurethane and various standardised tightening torques were applied to SmartPegs ranging from 3 to 20 Ncm. Two operators also hand tightened SmartPegs. They recommended an optimal tightening torque value of 10-17 Ncm. Lower than 10 Ncm resulted in statistically significant lower ISQ values and higher than 17 Ncm resulted in fracture of the SmartPeg.

Pelegrine et al., part of Salatti et al.'s research group, re-published the Osstell data one year later when comparing Osstell to the Penguin device (98). Furthermore, they also recruited 100 volunteers to determine how much force they were generating when hand tightening transducers. They were instructed to generate a minimum, medium and maximum force while a digital torque gauge measured force. Males generated statistically more force than females. When groups were combined, at minimum force a mean of 2.2 Ncm was generated, at medium force 4.3 Ncm was generated and at maximum force 7.5 Ncm was generated.

1.5.8 Mucoperiosteal flap elevation

Katsoulis et al. assessed the influence of raising a mucoperiosteal flap versus flapless implant insertion in the maxilla on ISQ values (99). All 195 implants were clinically successful after 12 weeks however a statistically significantly higher mean ISQ was reported for the flapless implant group.

Jeong et al. reported that implants placed via a flapless protocol resulted in faster implant stabilisation (100). In 6 mongrel dogs, Straumann SLActive implants were placed in healed extraction sites and ISQ values monitored for 8 weeks. While the control group had a decrease in ISQ values, with ISQ values only returning to baseline at week 5, the flapless group had no decrease in ISQ values. The authors suggest that this may be due to the improved vascularity of the flapless group.

1.5.9 Bone vascularity

Vascularity of the peri-implant bone is an important consideration for osseointegration. Kokovic et al. assessed the influence of bone vascularity on ISQ values in the posterior mandible (101). Bone vascularity was measured using a laser doppler flowmetry (LDF) probe inserted into the osteotomy site. Of the 36 implants included in the study, 18 were immediately loaded and the remainder were subject to early loading. Statistical significance was only reached in the early loading group and demonstrated a correlation between LDF and ISQ at 5 weeks to the end of the study, at 26 weeks. No correlation was found in the immediate loading group.

1.5.10 Number of implants

The influence of the number of implants involved with a restoration on ISQ has only been scantly researched. In a randomised control trial, Al-Magaleh et al. investigated differences in ISQ between 2 and 4 implants when used to restore mandibular overdentures (102). A slight trend existed for increased ISQ values when 4 implants were used but the differences were non-significant.

1.5.11 Implant connection

No studies appear to exist that directly assess the influence of the implant connection on ISQ. In theory, the rigidity to which a SmartPeg is attached to the implant may differ depending on the intimacy of the connection between the two.

1.6 Reproducibility of ISQ values

Herrero-Climent et al., in a cross sectional study of 85 consecutively placed implants, assessed the reproducibility and repeatability of the Osstell ISQ system (103). Three consecutive measurements were taken from each implant twice, using two different SmartPegs. Intraclass correlation coefficients were 0.97 for both SmartPegs. Repeatability and reproducibility also reached 0.97. This demonstrates that the Osstell device is a reproducible tool. In agreement, Buyukguclu et al. reported, *in-vitro*, excellent reproducibility when implants were placed in rigid self-curing acrylic resin (104).

1.7 Other possible uses for RFA

The ability to record ISQ at various time points suggests a possible role in the empirical use of RFA for peri-implantitis diagnosis and management. Progressive loss of crestal bone would increase the height of the supracrestal component of the implant. This in turn would increase the possible bending force on the implant, decreasing its ISQ value. The loss of bone would also, in itself, decrease the stability of the implant causing a decrease in ISQ value. The clinician would then have some indication of the amount and rate of marginal bone loss (MBL). It is not ethical to prospectively assess untreated peri-implantitis in humans to assess changes in bone levels and ISQ. Therefore, the majority of studies in this area are animal studies with induced peri-implantitis.

Monje et al. assessed changes in ISQ values and marginal bone levels in dogs with ligature induced peri-implantitis (105). A decrease of one ISQ unit corresponded to marginal bone loss of 1.13mm. ISQ values were measured at three time points during ligature replacement and after a period of spontaneous disease progression. A trend for decreasing ISQ with increasing marginal bone loss was seen throughout the study but only reached statistical significance at the time of the 3rd and final ligature replacement, 6 weeks after insertion of the first ligatures. Furthermore, the decreasing ISQ did not correlate with any clinical parameter such as probing pocket depth, bleeding score, suppuration or recession. Accuracy of ISQ measurements deteriorated with progressive bone loss. Yao et al. also assessed the influence of peri-implant bone defects on ISQ values (106). Implants were placed in porcine ribs to create a 0.9mm circumferential marginal bone defect extending 2, 4 and 6mm apically from the bone crest. There was a strong correlation between ISQ value and depth of the defect however the most significant drop in ISQ was from 0 to 2mm in depth. This is likely explained by the removal of the majority of the cortical bone which was providing high stability. Turkyilmaz et al. in a cadaver study showed a linear decrease in ISQ values with bone defect depth (107). Mandibular teeth were extracted and implants placed in the sockets. Resulting vertical defects at each implant were measured and assigned to a group based on vertical defect depth. Each 1mm of increased defect depth corresponded to a decrease in ISQ of 2.7 units. One ISQ unit therefore corresponds to 0.37mm of vertical bone loss. This is less than half the value Monje et al. reported. Chan et al. assessed ISQ in surgically created narrow and wide dehiscence defects, as well as circumferential defects, in cadavers (108). Defects were increased in apical length by 1mm and circumferential defects were increased by 2mm between all measurements. ISQ values were significantly correlated with wide dehiscence defects but not narrow defects. There was also a statistically significant correlation between circumferential defects and ISQ. Although ISQ decreased with progressive bone loss, there was no definitive value for ISQ units corresponding to each millimetre of bone loss as the range was quite varied at different depths. In a retrospective cohort study, Chen et al. published data on 383 screw retained, non-grafted implants with a 10 year follow-up (109). Although an inverse relationship was observed, there was no statistically significant correlation between ISQ and MBL. Furthermore, while 21 implants were lost, and 20 of these were lost within the first year, no information is given regarding the health of the remaining implants. It is unclear how many had marginal bone loss.

1.8 Conclusion

A substantial number of *in-vivo* and *in-vitro* studies have used Osstell devices as a central part of their research. It is a valuable tool as a means to compare outcomes of different protocols. It is also a useful tool in monitoring implant healing and decision making to decide when implants should be loaded. As discussed, there are multiple factors which can influence ISQ values. The influence of bone density appears to be the most studied influence. Whereas, the influence of the implant connection to the SmartPeg has not been studied. The influence of tightening torque of the SmartPeg is only scantly reported with the studies showing a range of different result and being significantly limited in their range of implant types and bone densities. This poorly represents the clinical scenario faced in daily practice. Regardless of the optimal tightening force, it does appear too low or too high a torque will result in either an inaccurate ISQ reading or fracture of the components. Therefore, it does seem logical to attempt to standardise the force applied to the SmartPegs to ensure consistency.

2 Materials and methods

2.1 Aim

The primary aim of this study was:

- To evaluate the effect that different SmartPeg tightening methods might have on the ISQ values of implants placed in artificial bone blocks.

The secondary aim of the study was:

- To determine the reliability of ISQ measurements when different SmartPeg tightening methods are used in implants with different internal abutment connection geometry placed in artificial bone blocks of varying density.

2.2 Ethical approval

Ethical approval was not required as per the Dublin Dental University Hospital Research Ethics Committee guidelines on *in vitro* research on non-biological materials.

2.3 Study Design

This was an *in vitro* study involving several different implants placed in synthetic bone blocks of different densities.

The seven types of implants used in this study were:

1. Standard 4.1x10mm SLA (Institute Straumann AG, Basel, Switzerland)
2. Standard Plus 4.1x10mm SLA (Institute Straumann AG, Basel, Switzerland)
3. Tapered Effect 4.1x10mm SLA implant (Institute Straumann AG, Basel, Switzerland)
4. Standard 4.8x10mm SLA (Institute Straumann AG, Basel, Switzerland)
5. BNST 4.0x10mm internal hexagonal connection implant (Biomet 3i, Barcelona, Spain)
6. BOET 4.0x10mm external hexagonal connection (Biomet 3i, Barcelona , Spain)
7. Ankylos C/X 3.5x11mm (Dentsply Sirona, Hanau, Germany)

Eight resin polyurethane bone blocks (BoneModels, Castellón de la Plana, Spain) were used in this study. Each block was of uniform density and represented either D1, D2, D3 or D4. Two blocks of each density were used. One of each implant type was inserted into each block with uniform spacing as shown in figure 3. In total, 7 implants were placed per block resulting in a total of 56 implants. All implants were placed according to the implant manufactures' protocols. Implant osteotomies in D1 bone blocks were completed with a bone tap. Implant osteotomies in D4 bone blocks were undersized to achieve stability.

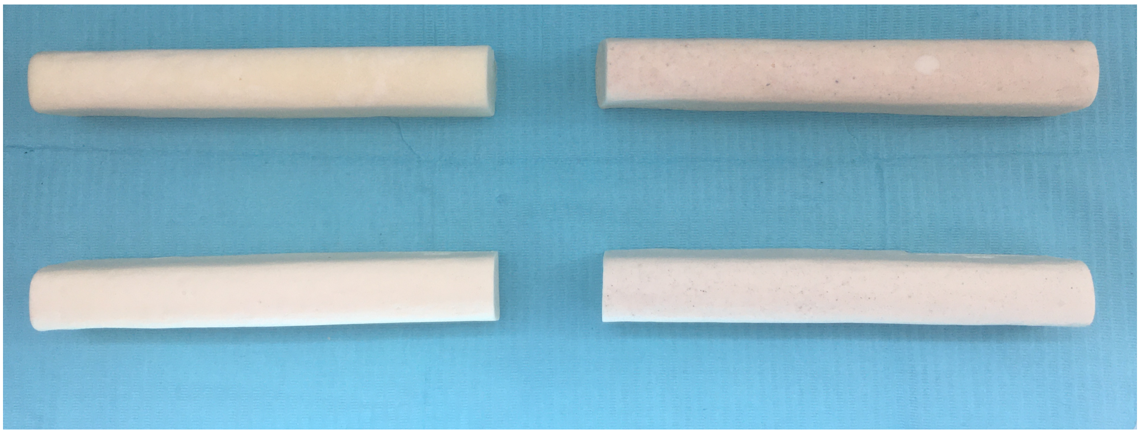

Figure 2 Photograph of four bone blocks, each of different density (BoneModels, Castellón de la Plana, Spain)

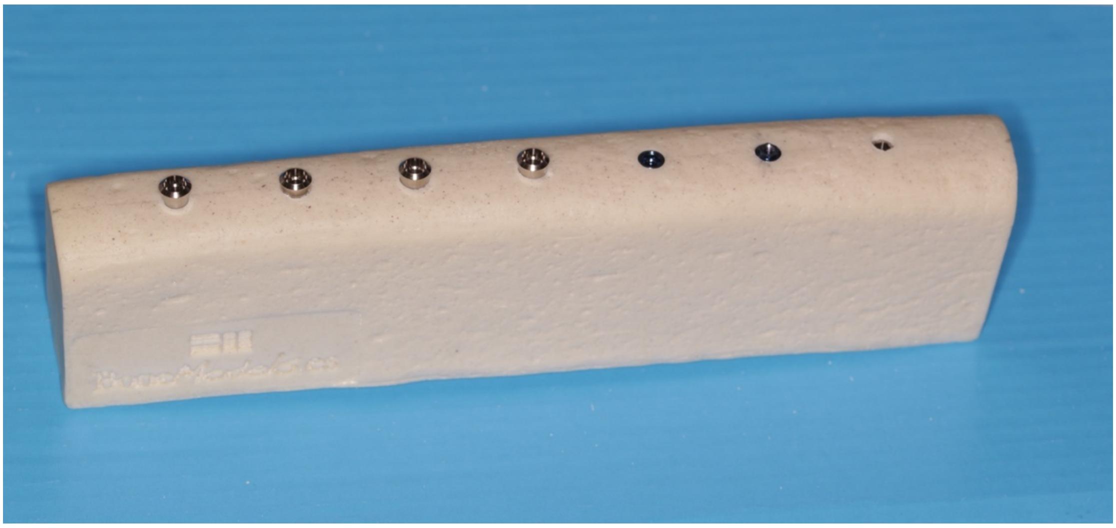

Figure 3 Photograph of a bone block with each of the seven implants

Osstell SmartPegs were paired to implants as per Osstell's recommendation for each implant as follows:

- Straumann Standard, Standard Plus, Tapered Effect and Standard wide – SmartPeg type 4
- Biomet 3i internal hexagonal connection – SmartPeg type 15
- Biomet 3i external hexagonal connection – SmartPeg type 1
- Ankylos C/X – SmartPeg type 16

SmartPegs were attached to each implant four different ways:

- Group 1: Hand tightened with gauze
- Group 2: Hand tightened with the plastic torque wrench supplied with SmartPegs
- Group 3: Hand tightened with the novel SmartPeg SafeMount
- Group 4: 6 Ncm of standardised force with an independently calibrated torque wrench (Tohnichi, Tokyo, Japan) (figure 4) (Appendix 1)

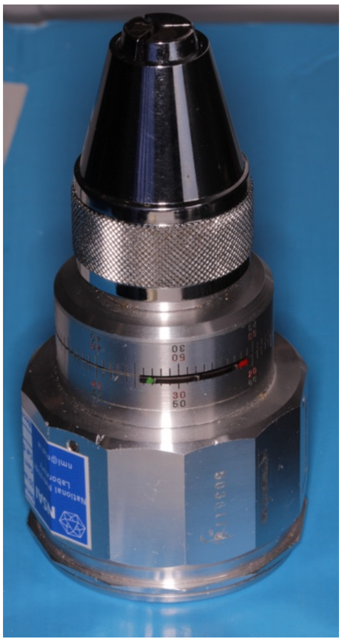

Figure 4 Photograph of the calibrated torque wrench (Tohnichi, Tokyo, Japan)

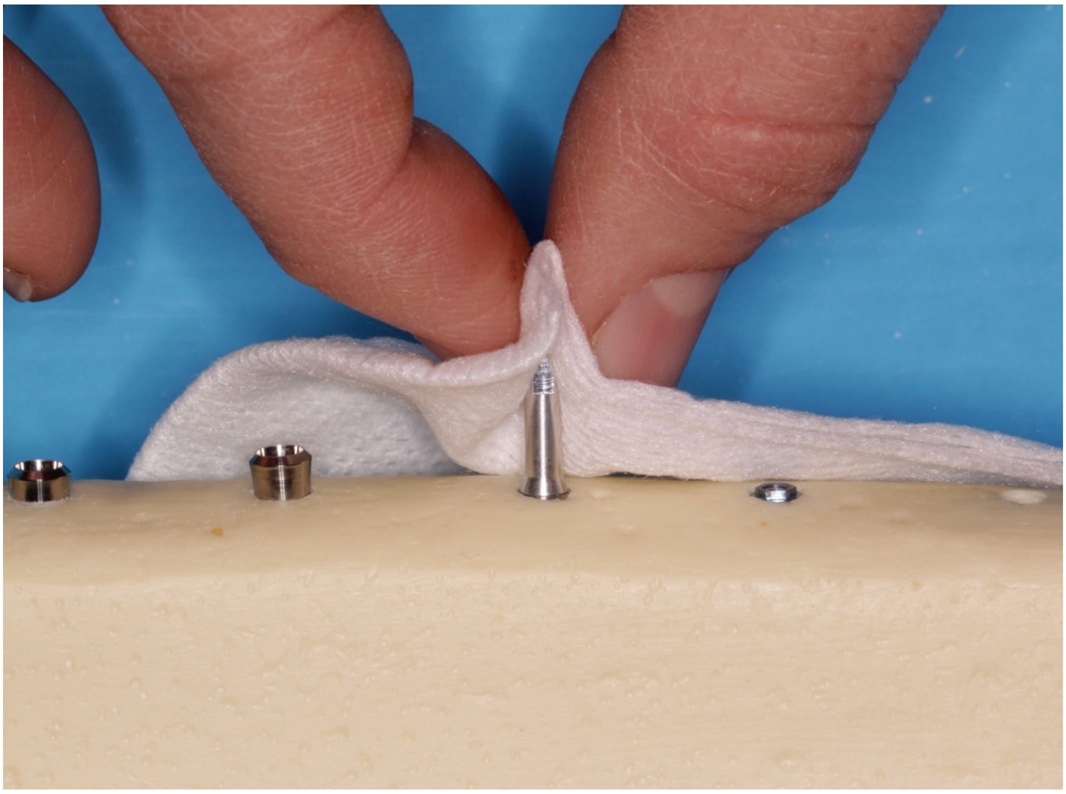

Figure 5 Photograph of SmartPeg tightening by hand with gauze

Figure 6 Photograph of SmartPeg tightening by plastic torque wrench

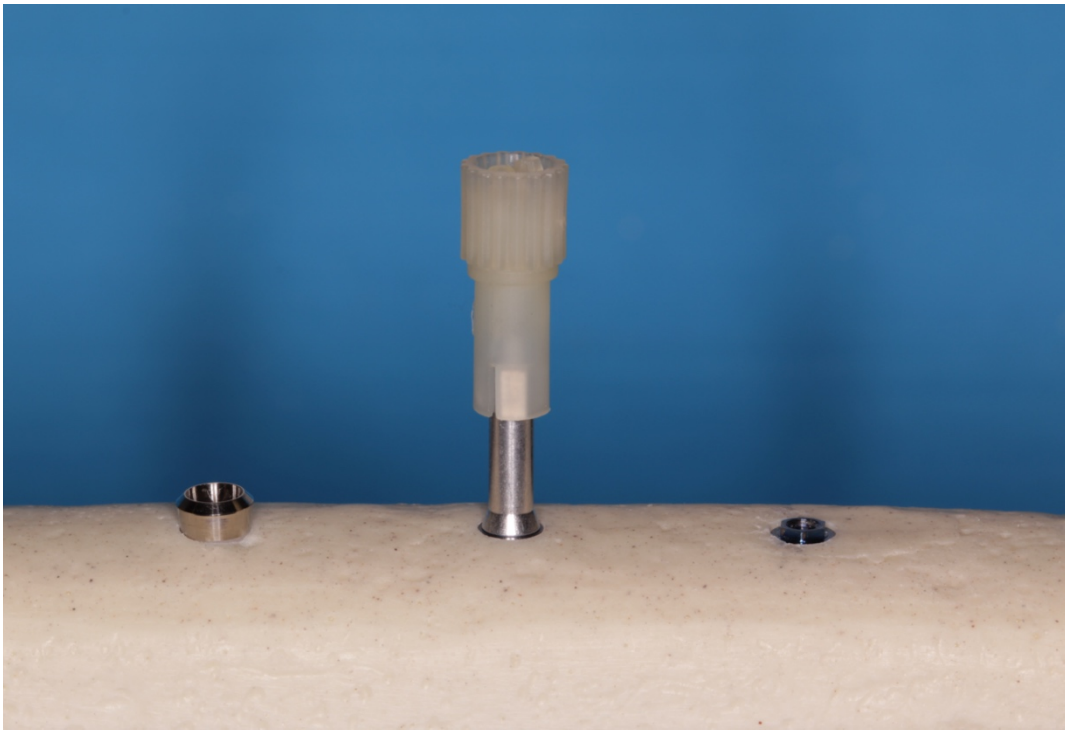

Figure 7 Photograph of SmartPeg tightening by the novel SafeMount

Figure 8 Photograph of SmartPeg tightening to 6 Ncm by a calibrated torque wrench

Bone blocks were secured to a bench top with a vice. A SmartPeg was attached to each implant in a randomised order by means of an online randomiser (https://www.calculator.net/random-number-generator.html), in each of the four ways. Two Osstell devices were used throughout to record ISQ values (Osstell IDx and Osstell ISQ). All initial measurements were repeated by the second Osstell device. All measurements were taken with the probe tip approximately 2mm and 90° to the SmartPeg in a buccal and mesial direction. ISQ values were recorded onto an Excel (Microsoft Excel v16.55) spreadsheet. Measurements were then repeated by a second investigator.

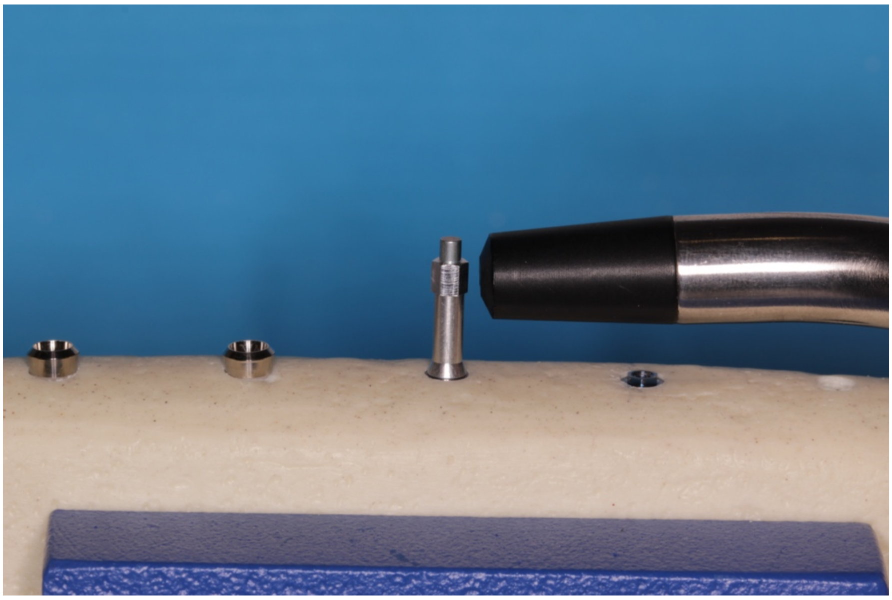

Figure 9 Photograph of a bone block, secured in a vice, with an Osstell probe measuring ISQ

2.4 Null Hypothesis

There is no difference between ISQ values of the four SmartPeg torqueing methods for different types of implants in different bone densities.

2.5 Statistical Analysis

Descriptive statistics were used to express ISQ values for different bone densities. Distribution of these values was visually represented using boxplots. Means of ISQ values by implant type were compared using a Kruskal-Wallis test when all bone densities were included and using an ANOVA when D4 was omitted from analysis. An intra-class correlation coefficient (ICC) was calculated to determine the relationship between the accuracy of the two Osstell devices and to compare investigator one and two, buccal and mesial directions and torquing method. These statistical analyses were performed with IBM SPSS software v27.

Linear mixed effects regression was used to determine the effect explanatory variables had on ISQ reading. Previous literature suggests that variables be included as random effects if they have at minimum five levels, otherwise it is suggested to include these variables as fixed effects in the model (110). Recent literature which examined variables with less than five levels, suggested to change to a fixed-effect model if a singular fit occurs, thus avoiding overconfidence in the results (111).

Specifically, for this research, operator and implant nested within bone density per bone block were considered random effects. Torquing device and bone density were fixed effects. Interactions were also examined. Model complexity was determined by examining change in deviance and information criterion – Akaike's Information Criterion and Bayesian information criterion. The final model selected followed the principle of parsimony.

Models were developed using Statistical Software: R (version 4.1.2) (112) and R Studio (113). Models were further developed using packages lme4 (114) and lmerTest (115). P-values displayed for the model are based Satterthwaite's method of approximation. Model diagnostics were checked using a simulation-based approach on scaled residuals from the R package DHARMa (116). Package emmeans was used for posthoc comparisons (117).

2.6 Power calculation

No previous study exists which used a mixed effect model as in this study. Therefore, a meaningful power calculation was not possible.

2.7 Funding

Funding for all materials was through the postgraduate research budget of the Dublin Dental University Hospital.

3 Results

3.1 Descriptive statistics

A total of 56 implants were used and the SmartPegs were tightened in each one of them with four different tightening methods. ISQ values were measured from the buccal and mesial of each attached SmartPeg, for each Osstell device and repeated by a second examiner. This resulted in 1792 ISQ measurements. The overall mean ISQ value was 65.58 ± 13.70. The highest mean value was observed in the 6 Ncm of torque group and the lowest in the hand tightening with gauze group.

SmartPeg tightening method	Mean ISQ, SD
Hand tightening with gauze	64.17 ± 12.99
Plastic SmartPeg mount	65.89 ± 13.57
SafeMount	66.04 ± 14.33
Calibrated torque wrench (6 Ncm)	66.22 ± 14.12

Table 1: Table of mean ISQ values by SmartPeg tightening group

When comparing data based on SmartPeg tightening method, a similar range and interquartile range of ISQ values were observed in all groups, as per figure 10.

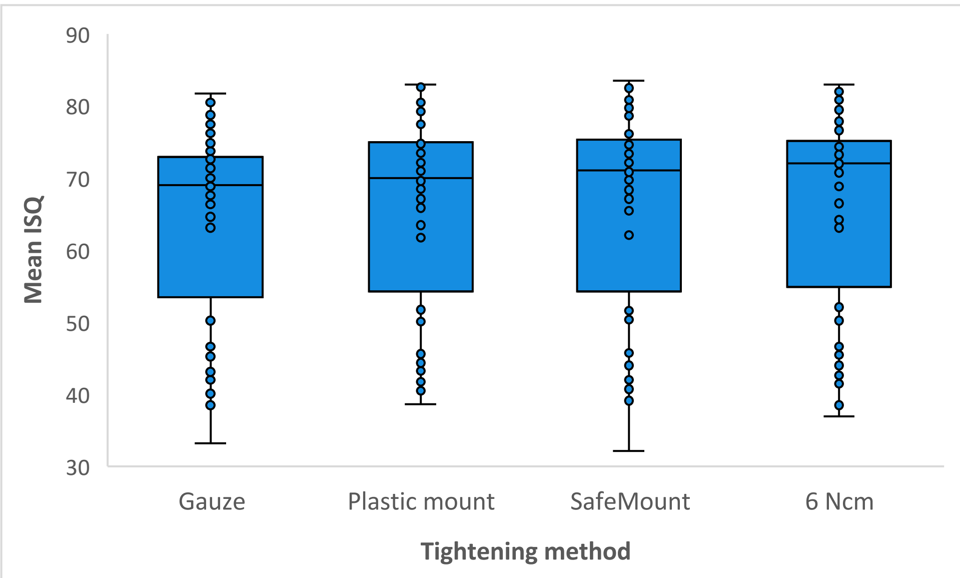

Figure 10 Boxplots of ISQ values by SmartPeg tightening method

All torquing methods showed similar data distribution of the recorded ISQ values (figure 11).

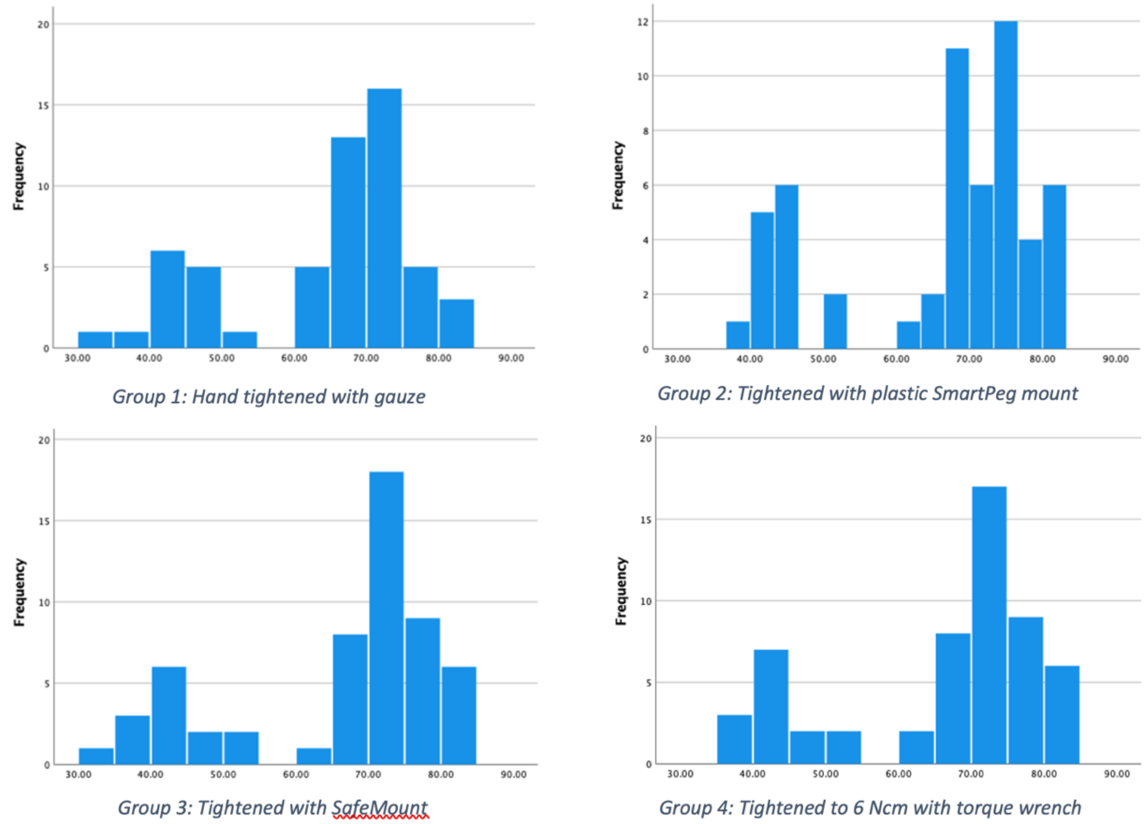

Figure 11 Distribution of ISQ values by SmartPeg tightening method

D1 and D2 bone densities demonstrated similar ISQ values with D4 bone demonstrating the lowest ISQ values as per figure 12.

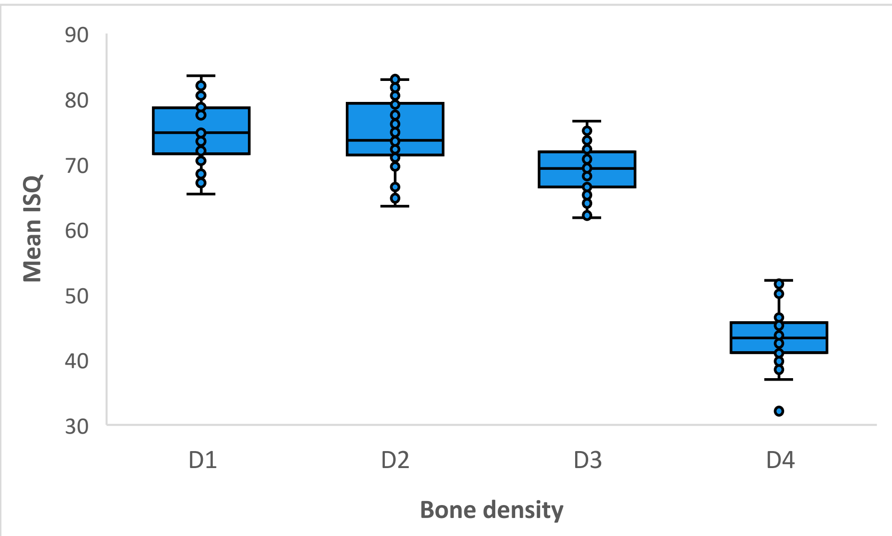

Figure 12 Boxplot of ISQ values by bone density

A Kolmogorov-Smirnov test showed a significance value of <0.001 indicating that the overall data was not normally distributed. This is also visually demonstrated by the quantile-quantile (Q-Q) plot in figure 13.

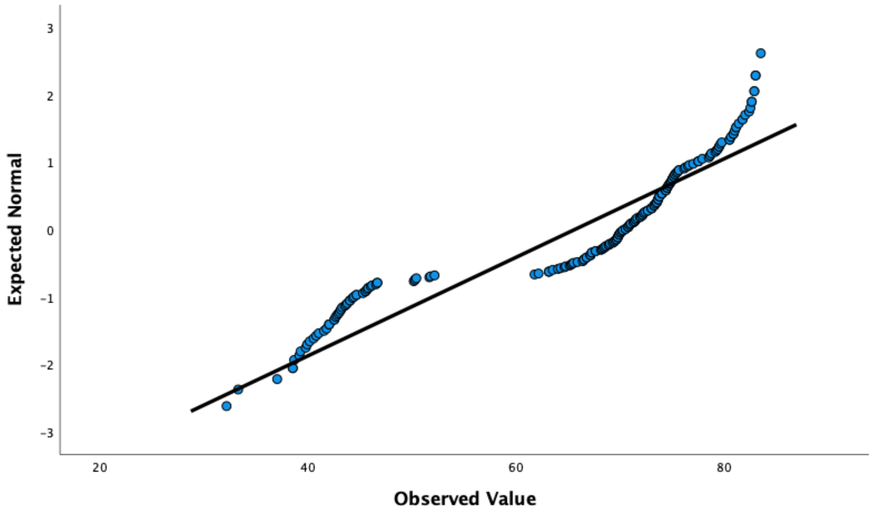

Figure 13 Q-Q plot showing non-normally distributed data

All 7 types of implants showed a similar range of ISQ values when all bone densities and torquing methods were combined as per figure 14.

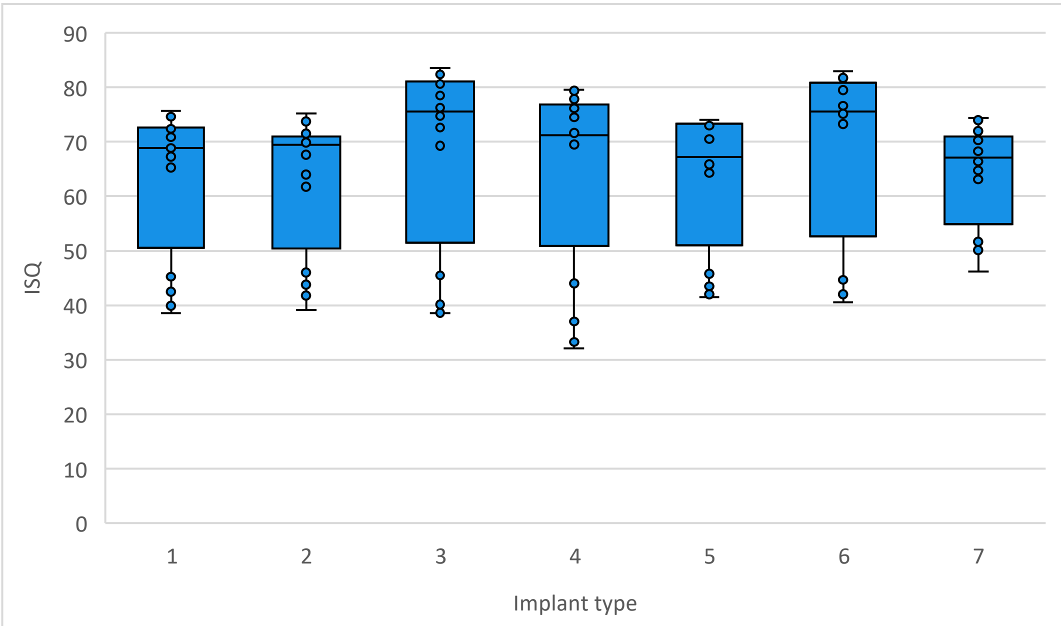

Figure 14 Boxplot of ISQ values by implant type across all bone densities and tightening methods.Type 1= Straumann Standard, 2= Straumann Aesthetic Plus, 3= Straumann Tapered Effect, 4= Straumann wide body, 5= Biomet 3i internal connection, 6= Biomet 3i external connection, 7= Ankylos

To assess the specific influence of the implant on ISQ values and spread, ISQ values were arranged to compare the seven implant types when SmartPegs were tightened with 6

Ncm of force. Data to compare the 7 different types of implants was not normally distributed when all four bone densities were included but was normally distributed when only D1, D2 and D3 was included. A Kruskal-Wallis test demonstrated no statistically significant difference between the implants when all four densities were included (p 0.361). When D4 bone was removed however, a one-way ANOVA demonstrated statistically significant differences between the implants (p <0.001). The spread of ISQ values for each implant type can be seen below for the 6 Ncm of torque group with D4 included (figure 15) and omitted (figure 16).

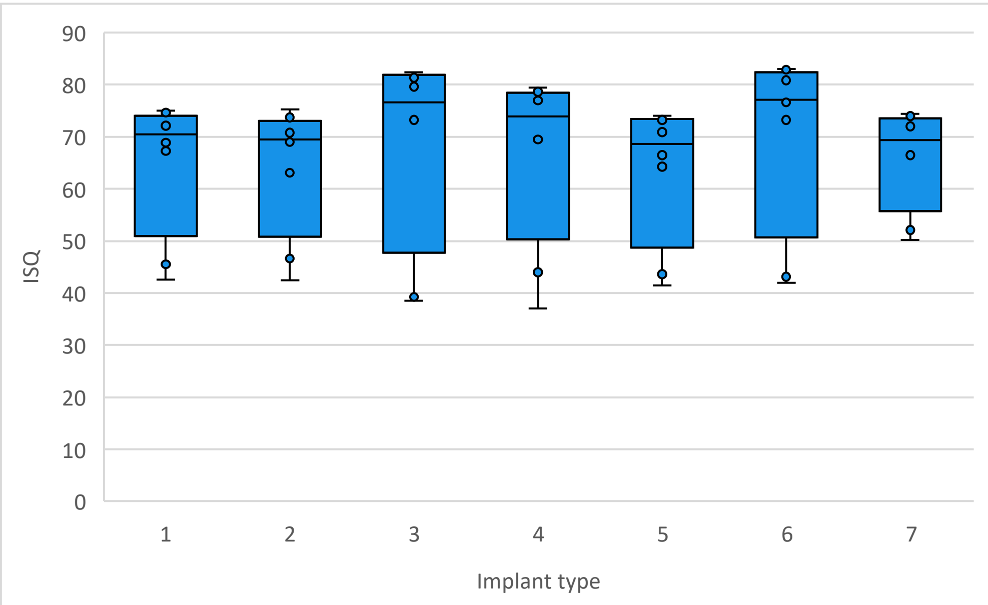

Figure 15 Boxplot of ISQ values by implant type in all bone densities with SmartPegs torqued to 6 Ncm. Type 1= Straumann Standard, 2= Straumann Aesthetic Plus, 3= Straumann Tapered Effect, 4= Straumann wide body, 5= Biomet 3i internal connection, 6= Biomet 3i external connection, 7= Ankylos

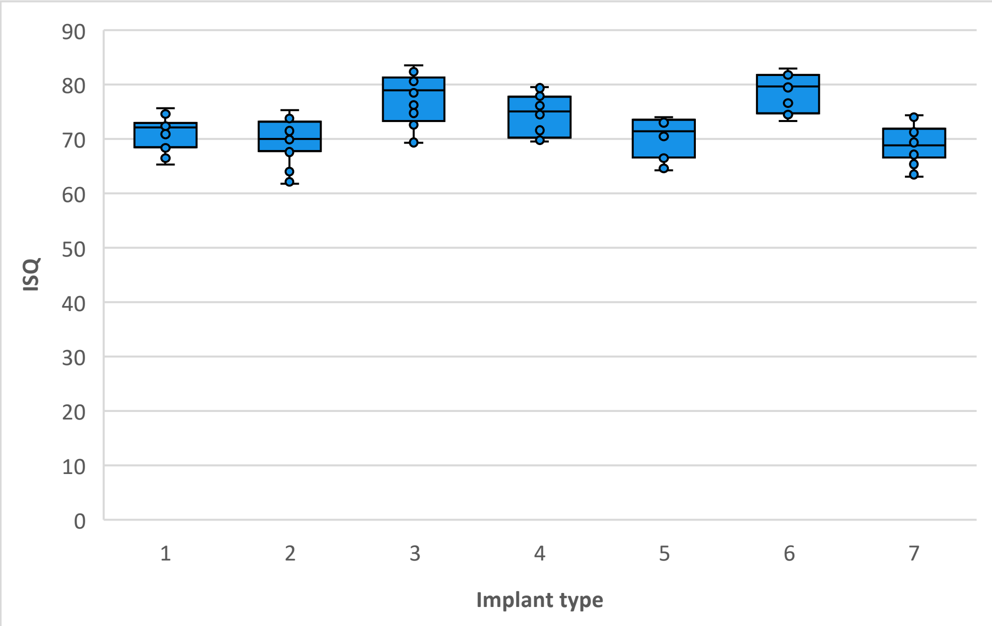

Figure 16 Boxplot of ISQ values by implant type in D1, D2 and D3 with SmartPegs torqued to 6 Ncm. Type 1= Straumann Standard, 2= Straumann Aesthetic Plus, 3= Straumann Tapered Effect, 4= Straumann wide body, 5= Biomet 3i internal connection, 6= Biomet 3i external connection, 7= Ankylos

3.2 Intraclass Correlation Coefficient (ICC)

3.2.1 Between operators

Operator 1 and operator 2 demonstrated excellent reliability between their measurements (ICC 0.995). The ICC varied slightly between operators depending on the method of SmartPeg tightening. The hand tightening with gauze group showed the lowest, but still excellent, intraclass correlation coefficient (0.993). The plastic SmartPeg mount and calibrated torque wrench had an ICC of 0.996, and the novel SafeMount had an ICC of 0.997 when comparing operators.

3.2.2 Buccal and mesial directions

Both operator one and operator two also showed excellent correlation between buccal and mesial measurements. Operator one had an ICC of 0.983 and operator two had an ICC of 0.947 between their respective buccal and mesial directions. Combining operator ISQ values for each direction, there was an ICC of 0.977 between buccal and mesial directions.

3.2.3 Between Osstell devices

For both operators, the two Osstell devices demonstrated a very strong correlation to each other with an ICC of 0.986.

Due to the excellent reliability of measurements between operators, between buccal and mesial directions and between the two Osstell devices, these ISQ values were then averaged for all further statistical analysis unless otherwise indicated.

3.2.4 By torquing method

Using the 6 Ncm of torque group as the control, all methods showed high ICC values as reported in the below table. The SafeMount resulted in the highest ICC value.

SmartPeg tightening method	ICC value (with 6 Ncm of torque as reference)
Hand tightening with gauze	0.978
Plastic SmartPeg mount	0.990
SafeMount	0.994

Table 2: Table of ICC values between SmartPeg torquing method and the standardised 6 Ncm of torque

Figures 17-19 show Bland Altman plots comparing ISQ values of each tightening method to the calibrated torque wrench. In agreement with the ICC values, these visually demonstrates a very high level of agreement between each group and the calibrated torque wrench.

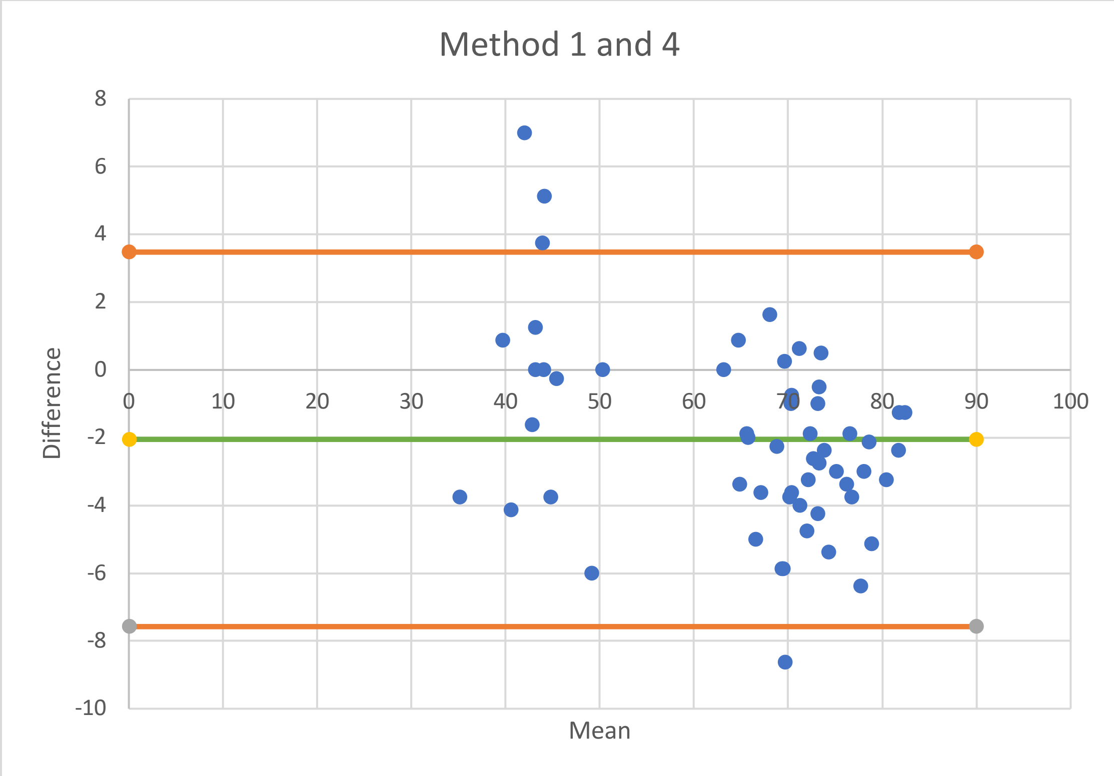

Figure 17 Bland Altman plot comparing the hand tightening with gauze group and the 6 Ncm of torque group

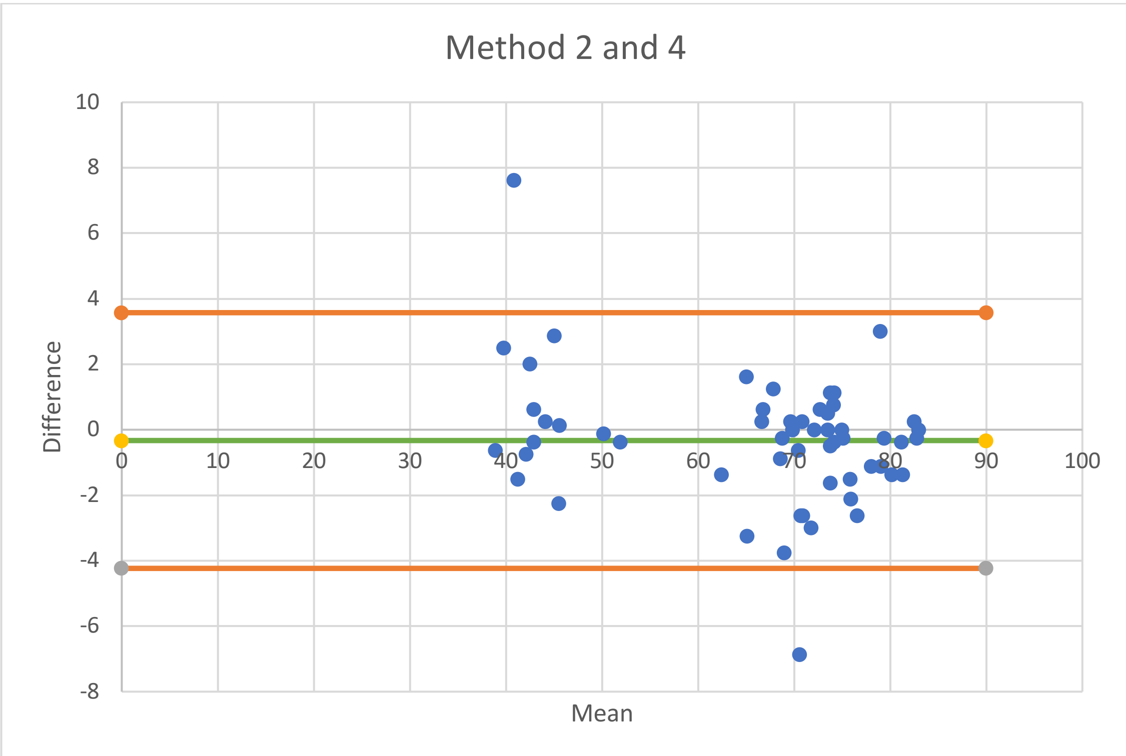

Figure 18 Bland Altman plot comparing the plastic SmartPeg mount group and the 6 Ncm of torque group

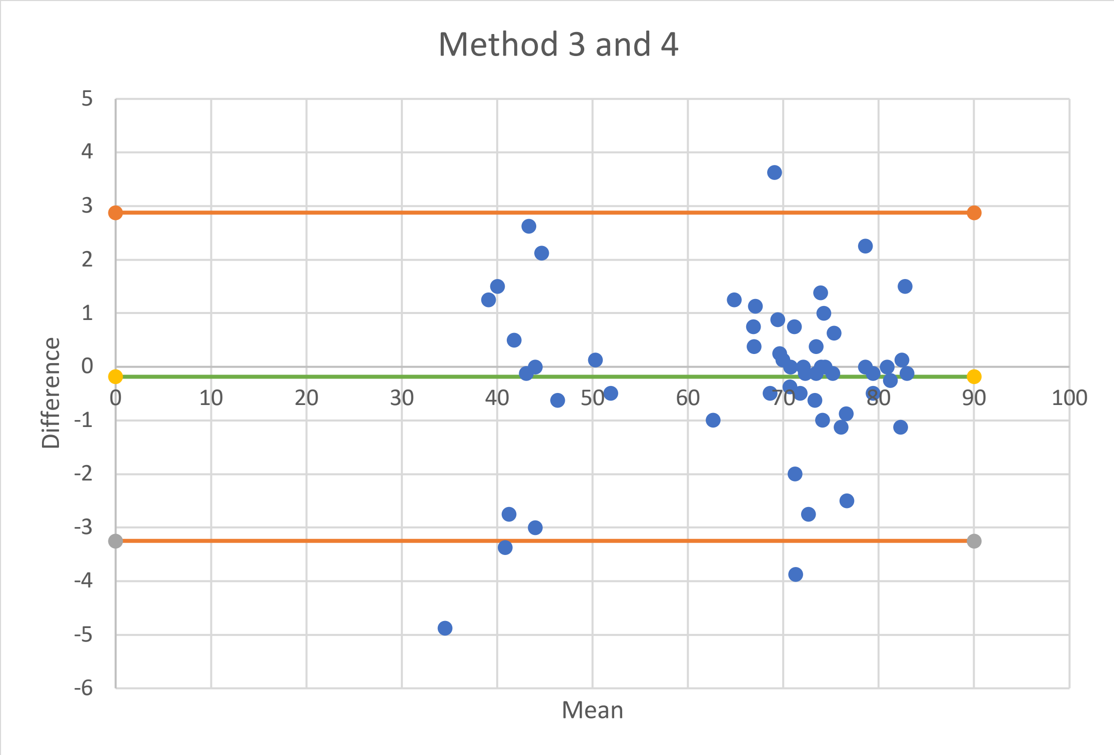

Figure 19 Bland Altman plot comparing the SafeMount group and the 6 Ncm of torque group

Intraclass correlation coefficient values were also calculated between operators for each SmartPeg tightening method in each type of bone density. As per the table below, D1 and D2 had excellent agreement between examiners, D3 also had strong agreement but this became very poor for D4 bone.

Bone Density	Hand torque with gauze	Plastic torque mount	SafeMount	6 Ncm of torque
D1	0.830	0.811	0.977	0.944
D2	0.934	0.972	0.972	0.983
D3	0.791	0.767	0.762	0.803
D4	0.112	0.192	0.238	0.039

Table 3: Table of ICC values between operator 1 and 2 for each type of bone density by SmartPeg torquing method

3.3 Linear mixed effects model

Interactions were not found to be statistically significant and examination of deviance and information criterion indicated that these terms did not need to be included in the final model.

Model diagnostics were performed on simulated residuals. Results from the outlier test and the Kolmogorov-Smirnov test were non-significant (p-value >0.5). A Q-Q plot of the standardised residuals illustrated a linear pattern thus indicating that residuals assumptions are satisfied.

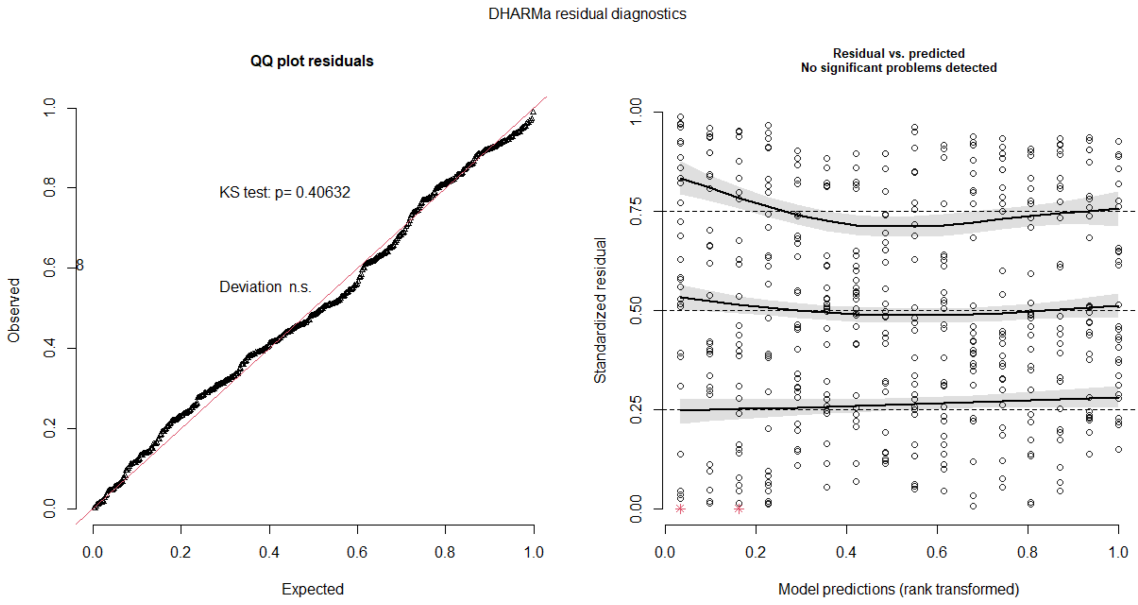

Figure 20 Q-Q plot of the standardised residuals (left) and residual vs predicted plot (right)

Examination of random effects indicated that approximately 10.36% of the total variation of random effects was due to the nested effect of the implants within bone density per bone block. Approximately 36.34% of the total random variation was due to implants within bone density. The effect for the implants alone accounted for approximately 11.23% of the total variation of random effects and the effect of operator alone accounted for 6.06%.

Random effects	Variance	% of total
Bone block:Density:Implant	3.00	10.36
Density:Implant	10.52	36.34
Implant	3.25	11.23
Operator	1.76	6.08
Residual variance	10.42	35.99

Table 4: Table demonstrating the percentage variance due to random effects

3.3.1 Torquing method

Adjusting for model factors, SmartPeg torquing method was found to have a statistically significant effect on ISQ reading. The estimated mean ISQ for hand torquing with gauze group was lower than the 6 Ncm torque group (-2.05, 95%CI (-2.89, -1.21)). The plastic wrench group and the SafeMount group were not found to be statistically significant.

SmartPeg tightening method	Coef	95%CI	p-value
6 Ncm torque	Ref		
Hand tightening with gauze	-2.05	(-2.89, -1.21)	<0.001
Plastic SmartPeg mount	-0.33	(-1.17, 0.51)	0.444
SafeMount	-0.19	(-1.03, 0.66)	0.668

Table 5: Table demonstrating the influence of SmartPeg tightening method on mean ISQ values

3.3.2 Bone density

Bone density was found to have a statistically significant effect on ISQ reading. The estimated mean ISQ for D3 (-5.90, 95%CI (-9.52, -2.28)) and D4 bone density (-31.50, 95%CI (-35.11, -27.89)) were lower than the estimated mean ISQ for D1 bone density. The difference between D1 and D2 bone densities was not statistically significant.

Bone density	Coef	95%CI	p-value
D1	Ref		
D2	-0.27	(-3.88, 3.35)	0.889
D3	-5.90	(-9.52, -2.28)	0.006
D4	-31.50	(-35.11, -27.89)	<0.001

Table 6: Table demonstrating the influence of bone density on ISQ values

4 Discussion

This study aimed to evaluate the effect that different transducer tightening methods might have on the reliability of ISQ measurements of different types of implants placed in artificial bone blocks. A further aim of this study was to assess the reliability of these ISQ measurements across a range of different bone densities.

The two operators involved showed excellent agreement in their ISQ measurements (ICC 0.995). Buccal and mesial measurements also showed excellent agreement for each individual Osstell device (ICC >0.95). Furthermore, both Osstell devices showed excellent agreement with each other (ICC 0.986). Herrero-Climent et al. used the Osstell ISQ device on 85 implants placed in healed extraction sites in 23 consecutive patients (103). Two different SmartPegs were used on each implant and measurements were taken from a buccal direction in triplicate by one clinician. These reported an excellent ICC value of 0.97 for repeatability of ISQ values. A more recent study by Norton compared the same two Osstell devices used in the study herein, the Osstell ISQ and Osstell IDx (118). He evaluated ISQ values in 210 implant at placement and 3 months after insertion. In the mesiodistal direction, he reported an ICC value of 0.97 between ISQ values from each device. Of note, there was a lower agreement for bucco-palatal measurements, with an ICC value of 0.71 . Norton noted that the Osstell IDx appeared to give several “false” readings of 35 ISQ units on several occasions. The same trend was not seen in this present study. Although Norton’s study shows the Osstell devices and RFA to be generally reliable, there are other Osstell devices, such as the Osstell Beacon, and other RFA devices from different manufacturers like the Penguin from which these results may differ. In his study, Norton also evaluated the Penguin device for reliability, comparing it to the two Osstell devices. The results indicated that the two Osstell devices were more reliable (118). Diker et al. recently reported excellent intra- and interobserver agreements when using the Osstell IDx, Osstell Beacon and the Penguin (119) while Buyukguclu et al. reported the Osstell ISQ device to be more reliable than the Penguin (104). Osstell ISQ had an ICC value of 0.9 between repeated measurements compared to 0.6 for the Penguin for implants embedded in stiff acrylic resin. Herrero-Climent et al., in a different study to that previously mentioned, reported both the Osstell ISQ and

Penguin devices to be very reliable with an ICC of >0.9 (120). Overall, it is well documented that the Osstell ISQ, Osstell IDx and Osstell Beacon are reliable devices.

The recommended Osstell protocol is to take a buccal and a mesial or distal measurement from each SmartPeg, as in the clinical situation there may be a discrepancy between these values. For example, if there is a significant loss of buccal bone, this may reduce the buccal ISQ measurement but may not affect the mesio-distal measurement. Usually, the mean ISQ value is then used as the recorded ISQ value. In the study herein, excellent correlation was seen between the two measurements. This is to be expected in a polyurethane bone block where no bony defects are present and the density is uniform throughout.

D4 bone appeared to have the most significant impact on ISQ values. ISQ values were similar in D1 and D2 bone, displayed a slight drop in D3 bone and had a significant fall in D4 bone. This is in agreement with the current literature where the influence of bone density on ISQ values has been demonstrated. In a systematic review, Marquezan et al. reported moderate to strong correlations between bone density, measured by HU, and ISQ values (52). Similarly, Ivanova et al. recently showed a significant positive linear correlation between ISQ values and bone density as measured by bone biopsies from a trephine bur prior to the implant osteotomy (25).

In this study, the ISQ values for D1, D2 and D3 overlapped with each other but no value for D4 overlapped with the higher density bone values. D1 ISQ values ranged from 65 to 84, D2 ranged from 64 to 83, D3 from 62 to 77 and D4 from 32 to 52. Interestingly, there is a drop of 10 ISQ units between the lowest ISQ value in D3 bone and the highest value in D4 bone. Both D1 and D2 had a spread of 19 ISQ units, D3 had a spread of 15 ISQ units and D4 had a spread of 20 ISQ units. D4 bone has the largest spread but is very similar to D1 and D2. D3 however, has the narrowest spread of values. This is a somewhat unexpected result given that there is a slightly wider ISQ spread in densities higher and lower than D3.

When testing for reliability of measurements depending on the way SmartPegs were tightened, the highest agreement with the control group was obtained using the

SafeMount (ICC 0.994) and the lowest using the hand torquing with gauze method (ICC 0.978). These findings agree with the findings of earlier studies where hand torquing results in lower ISQ values than from a torque wrench (95, 97). Linear mixed effects regression analysis demonstrated a statistically significant difference between ISQ values obtained from hand tightening SmartPegs with gauze compared to the control group which applied 6 Ncm of torque ($p<0.001$). No statistically significant difference was seen for the group using the plastic SmartPeg mount or the novel SafeMount compared to the 6 Ncm of torque group.

There are only a handful of studies assessing the influence of the tightening torque of SmartPegs on ISQ. One study concluded that all their investigated torque values of 2-11 Ncm were appropriate (96). Whereas, the other two study groups recommended specific values of 5-8 Ncm (95) and 10-17 Ncm (97).

Geckili et al. were the first to publish on the influence of SmartPeg tightening torque (95). They assessed values of 1, 3, 4, 8, 9, 10 and 11 Ncm of torque. While they concluded that 5 to 8 Ncm of torque should be the standardised range they did not actually test 5, 6 or 7 Ncm of torque. Their conclusion is based on 8-11 Ncm showing reliable ISQ values, whereas 1-4 Ncm had lower ISQ values. No negative consequences of tightening above 8 Ncm were reported.

Kastël et al. undertook a study of similar design to Geckili et al. (96). They reported that all investigated torque values of 2-11 Ncm were appropriate for clinical use. They used a calibrated torque device to tighten SmartPegs to 2-6 Ncm and also had four different examiners hand tighten SmartPegs. Hand tightening torque values were reported as 2-11 Ncm. This measurement was based on the torque value required to remove the SmartPeg. However, this assumption may be incorrect. SmartPegs which where torqued to a known force with the calibrated torque wrench consistently required less torque to remove them. The removal torque amounted to 79-93% of the initial insertion torque. Therefore, their actual hand tightening torque values were likely higher than reported.

Salatti et al. assessed a wider range of torque values from 3-20 Ncm and also had two examiners hand tighten SmartPegs (97). They reported an optimal torque range of 10-17 Ncm. They assessed 3, 4, 5, 6, 10, 13, 17 and 20 Ncm of torque. Values of 3-5 Ncm had clinically significantly lower ISQ values than ≥6 Ncm however the 6 Ncm group had a wider standard deviation than the other groups with higher torque value. At 20 Ncm, the

SmartPeg connection to the implant was stripped in all cases. However, of interest, the obtained ISQ values were clinically similar to the 6-17 Ncm groups even with the damaged connection.

While Kastël et al. reported hand tightening was sufficient and no standardisation of torque values was required, the other two studies published specific torque ranges. They reported that too low a torque value reduced the ISQ value. Neither of these studies agree or overlap on their suggested torque value ranges however. Osstell recommend SmartPegs to be tightened to 4-5 Ncm which they report to be "finger tight". This present study used 6 Ncm as the control value. This value allowed for agreement with both the Kastël et al. and Geckili et al. studies. The 6 Ncm group in the Salatti et al. study also had very close mean ISQ value to the higher torque value groups. Furthermore, 6 Ncm was also very close to Osstell's recommended 4-5 Ncm torquing value. Of note, the calibrated torque device used in this study could only record 6 Ncm of force or over. Overall, it is not possible to pick a torque value to agree with all previous studies. However, 6 Ncm appeared to us to be the most suitable.

Implant stability is arguably where the use of RFA is of greatest importance in terms of guiding a clinician as to when an implant is ready to be restored. This current study is the first to assess SmartPeg tightening protocols in different bone densities. Indeed, linear mixed effects regression analysis demonstrated bone density to have a statistically significant effect on ISQ readings. The difference between D1 and D2 was minimal, accounting for less than 1 difference in ISQ values. The difference however was clinically and statistically significant between D1 and D3, accounting for a reduction in ISQ of 5.9 units, and between D1 and D4, accounting for a reduction in ISQ of 31.5 units. Overall, approximately 36% of the difference in ISQ values recorded in this study was found to be due to differences in bone density.

Both Geckili et al. and Kastël et al. used bovine bone ribs. Only the latter commented on bone density, reporting it to be D1. Salatti et al. used polyurethane blocks of a uniform bone density corresponding to low D2, reported as 0.32 – 0.35 g/cm^3. Their study also had lower mean ISQ values compared to the two previous studies. In contrast, the two studies on bovine bone had very high ISQ values. For example applying 3 Ncm of tightening force to the SmartPeg resulted in a mean ISQ of 29 in Salatti et al.'s study, 79 in Kastël et al.'s study and 82 in Geckili et al.'s study. This may, in part, be due to the differences in bone density. While the density of the bone used in Geckili et al.'s study is unknown it is likely to be similar to that of Kastël et al.'s as they both used bovine ribs. Therefore, no study to date has assessed soft bone.

The effect of the implant design on ISQ is well studied and can affect ISQ values. All the above studies assessing SmartPeg torque values used only one implant system each. Little information was provided on the specific implants. Only Kästel et al. reported on the actual implants used. The other studies only reported the manufacturer, the implant diameter and implant length. Thus, it is not clear exactly what macrogeometry these implant had. This current study aimed to address this by using a variety of different implants. Of the seven types of implant used, four were Straumann which had identical connections but different body designs. Two types of Biomet 3i implant were used of similar dimensions to the Straumann implants but with one external and one internal hexagonal connection. An Ankylos implant was also included in the analysis as they have a combination of a Morse taper and internal hexagonal design in their implant connection. This is of interest as the influence of any connection has not been studied to date on SmartPeg tightening torque values. In theory, the intimacy of the fit of the connection of the SmartPeg would affect the ISQ value. When data was assessed from the control group, 6 Ncm of torque, no statistically significant difference was seen between the ISQ values of the various implant types but that difference did reach statistical significance when all the values generated from implants placed in D4 bone were removed. The Ankylos implant system had the narrowest range of ISQ values across all bone densities. This may be, in part, due to the intimate fit of the Morse taper connection.

All of the studies assessing SmartPeg torque values included groups who hand tightened the SmartPegs as well as using a standardised torque gauge to apply a known force. Pelegrine et al. recruited 100 volunteers to assess variations in tightening torque (98). Volunteers were asked to generate a minimum, medium and maximum amount of force to tighten a transducer with the force measured on a digital torque gauge. Of note, the lowest applied force in the maximum force group was the same as the highest force in

the minimum force group. In several cases, the maximum amount of force a participant could generate was ≤4 Ncm. In general, males demonstrated higher torque values than females. This study demonstrates the wide range of individual variation in torque values from different operators.
Salatti et al. included two groups where examiners, one male and one female, hand tightened SmartPegs. Their individual mean ISQ values were <20 and at least 10 ISQ values less than the 3 Ncm group, implying that these two examiners were likely only applying 1-2 Ncm of force. This corresponds to the group in Pelegrine et al.'s study applying only the minimum amount of force possible. These two studies were conducted on the exact same implants and bone block as part of the same research group. This is likely not representative of the tightening force most clinicians would apply to SmartPegs intra-orally where the risk exists of a loose SmartPeg either dislodging or giving an inaccurate ISQ reading.

At present SmartPegs are hand tightened to implants with either finger pressure only, the adjunctive use of gauze or with a plastic mount supplied with the SmartPeg. Variable amounts of force can be generated with these methods. The only study to report any damage to the implant or SmartPeg occurred at 20 Ncm. It is unlikely this amount of force would be applied by a clinician by hand. Indeed, the maximum amount of torque generated by any participant in Pelegrine et al.'s study was 16 Ncm. Therefore, the more practical concern is under tightening SmartPegs. The Osstell SafeMount attempts to overcome this issue by having an audible and tactile click when a certain amount of force is achieved. Osstell report this to be 4-4.5 Ncm. Like the SmartPeg, the SafeMount is designed to be single use. The results of this study show it to have no statistically significant difference in ISQ values to our control group of 6 Ncm of force. However, the plastic mount group also had no statistically significant difference with the 6 Ncm of torque group. All three methods showed good reliability compared to the 6 Ncm of torque control. Overall ICC values were excellent for each torquing method.

From the above results it was clear that torquing method had some degree of an influence on the reliability of measurements but bone density accounted for the largest influence. Therefore ICC values were calculated between operator 1 and 2 for each torquing method and bone density. Agreement between the two operators was very strong except for in D4 bone which showed very poor agreement. The low reliability of Osstell devices in very soft bone does not appear to be well documented in the current scientific literature. In the clinical scenario, an implant placed in D4 bone with a low ISQ value will usually not be loaded. It will generally be allowed to osteointegrate undisturbed, over which time the ISQ value will rise. With the increase in stability of the implant, the reliability of the ISQ measurement will also improve. Therefore, this poor reliability in D4 bone would likely not change any loading protocols as Osstell recommend all ISQ values <60 to be allowed heal undisturbed.

Given that bone density seemed to have an effect on the reliability of measurements a linear mixed effects model was performed to compare the effect of bone density to other factors such as the operator and the implant. The implant within each bone density accounted for the largest amount of variance in measurements at approximately 36%. The implant itself accounted for 11% and the operator for 6%. The nested effect of the implant within bone density per bone block accounted for 10% of the variation. This shows bone density to have the largest influence the ISQ measurements.

Although the ICC was slightly higher for the SafeMount group compared to the plastic torque wrench group this difference was clinically insignificant. The greatest advantage of the SafeMount is possibly for standardisation of the use of Osstell SmartPegs for research purposes and for long term monitoring of changes in ISQ such as after peri-implantitis treatment. There may also be a roll for their use with users who are inexperienced with Osstell SmartPegs to ensure they have applied a sufficient amount of force when tightening the SmartPeg. In clinical practice, there may be a change in operators between the implant surgery and the final restoration unless one operator is placing and restoring their own implant. Likewise, if peri-implant bone levels are being monitored with the aid of ISQ values over a period of time, there may be several different operators involved. The results of this study showed 6% of the variation in ISQ values to be due to the operator. Applying this to an implant which has been treated for peri-implantitis, a change in operator may result in a misleading ISQ value. This study also demonstrates that if implants with low ISQ values are being treated for peri-implantitis, a small change in ISQ values at subsequent visits may be due to poor reliability of Osstell in low ISQ values rather than any crestal bone level changes.

A limitation of this study is that the statistical power did not allow for comparison between the different individual designs of implants. For example, comparing the Biomet 3i internal and external hexagonal connection implants would have allowed for the comparison of two identical implants other than for their connection type. There were no similar previous studies to base a priori power calculation on and post-hoc power calculations are often reported to be conceptually flawed with misleading results (121, 122).

A further limitation is that only two operators were involved in hand tightening the SmartPegs. As demonstrated by Pelegrine et al., there can be significant differences between different operators however, both operators in this study, overall, had excellent agreement with each other. Furthermore, the two operators were male. A broader range of operators, including female operators, would allow for a greater generalisability of these results.

5 Conclusion

This study sought to determine the influence of different Osstell SmartPeg tightening methods on ISQ values. A further aim was to assess the reliability of these tightening methods across a range of implants and bone densities.

SmartPeg tightening method had a statistically significant influence on ISQ values. The hand tightening with gauze group had a statistically significantly lower ISQ value than the control group of 6 Ncm of force. Clinically, this amounted to approximately 2 ISQ values lower than the control group. The plastic SmartPeg wrench currently supplied with SmartPegs and the novel SmartPeg SafeMount both had similar results to the control. All methods had excellent reliability between operators in D1 and D2 bone. There was a slight drop in reliability in D3 bone and very poor reliability in D4 bone.

Linear mixed effects regression showed the nested effect of implants within bone density to account for the largest variance in ISQ values at approximately 36%. The implant itself accounted for 11% and the operator for 6%.

Previous research in this field has mostly shown the need for a standardisation of the tightening torque of Osstell SmartPegs. While there is disagreement as to the optimal torque value, hand tightening has been reported to result in variable ISQ values and a range of actual applied torquing forces. The novel SafeMount overcomes this limitation by having an audible and tactile click when the intended torque is reached, thereby allowing for application of a standardised amount of torque to SmartPegs during each use.

This is the first study to assess the influence of SmartPeg tightening methods on ISQ values across a range of implants and to include soft bone. Furthermore, the poor reliability of Osstell devices in very soft bone is not well documented in the scientific literature to date.

Future research should further investigate the influence of implants' abutment connection geometry on the accuracy of ISQ measurements. In theory, this could affect the intimacy of the fit between the SmartPeg and the implant thereby affecting the ISQ value.

6 References

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7 Appendices

Appendix I: Torque wrench certificate of calibration

NSAI

National Metrology Laboratory

Certificate of Calibration

Issued to	Dublin Dental University Hospital Lincoln Place Dublin 2
Attention of	David Naughton

Certificate Number	204637
Item Calibrated	Torque Meter
Serial Number	503817J
Client ID Number	N/A
Manufacturer	Tohnichi
Model	6BTGN
Range	0-60 cNm
Resolution	1 cNm
Units	cNm
Order Number	David Naughton
Date Received	7 Dec 2020
NML Procedure Number	D4P-NM-04
Calibration Standards	Transducer & Display, ID No.: 0708, Due Date: 18 Sep 2021

Calibrated by	Graham Thomas	**Approved by**	Paul Hetherington
Date of Calibration	12 Dec 2020	**Date of Issue**	14 Dec 2020

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