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Mechanical stress development during dental implant surgery - a literature review

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Meiner geliebten Familie

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1 Abstract

1.1 Summary

Aim of the investigation: The application of dental implants, which are anchored in the alveolar process similar to a tooth root, has proven to be effective for the treatment of missing teeth. When placing the implant, high primary stability values were aimed for, which was particularly true in cases with immediate loading of the implant. Modern implant systems feature design and drilling protocols that are intended to prevent overloading of the alveolar bone during implant placement, since resorptive processes can impair esthetics and, in the long term, function. The aim of this literature study is to determine the current data situation regarding the effects of mechanical stress on the alveolar bone during implant placement and to present the new findings with regard to clinical relevance.

Material and method: The medical database PubMed was searched for the following terms and links: Dental implant insertion AND mechanical stress AND bone. The publications found were assigned to the groups I) in vitro studies and finite element studies, II) animal studies and III) clinical studies. The final search took place on September 30th 2019.

Results: Of the 163 publications covered, 57 papers were included in the analysis presented. Based on in vitro studies and finite element analyses, it was shown that cortical bone exhibits poorer stress reduction and a linear increase in insertion torque due to lower viscoelasticity compared to cancellous bone. When undersized osteotomy was used for implant placement, this was reflected in a clear tendency towards increased stress in the bone. The evaluation of the animal studies has shown that, depending on the extent of the undersized implant bed, the inner areas of the implant threads form healing chambers in which rapid bone regeneration occurs. The areas of direct contact between the implant body and alveolar bone, on the other hand, indicate resorption of the bone during the healing phase. The higher the insertion torque during implant placement, the greater the resorption seemed to be. This observation was made even though there was more implant-bone contact during the initial healing phase. The evaluated clinical studies show that the changes in marginal bone level appear to be more pronounced with implants inserted at high torque than with lower torque. Clinically mobile implants, however, show an a priori less favorable prognosis.

Discussion: When placing dental implants, a cautious and gentle approach is required. Negative effects on the alveolar process can be minimized by a controlled insertion torque that takes into account the biological characteristics of the implant healing process. Since the exact limit values for the mechanical load capacity of the alveolar bone are not known, the assessment of the bone quality that should precede implant placement is of paramount importance.

In this way, both the surgical protocol and the subsequent prosthetic loading protocol can be adapted to the patient situation found. Future implant systems should be provided with a refined macro design, which not only preserves implant stability from the compression of the cortical layer, but also includes the area of the trabecular bone.

Conclusion: Before dental implantation, the bony alveolar ridge must be analyzed with regard to the existing bone quality, since its condition is decisive for the incorporation of the implant. The obtained knowledge determines the selection of the appropriate drilling protocol and the implant design to be used, which is expected to lead to more sustainable results.

1.2 Zusammenfassung

Zur Spannungsentwicklung beim Setzen zahnärztlicher Implantate - eine Literaturstudie

Ziel der Untersuchung: Zur Versorgung fehlender Zähne hat sich die Verwendung zahnärztlicher Implantate bewährt, die - einer Zahnwurzel ähnlich - im Aveolarfortsatz verankert werden. Beim Setzen des Implantats hat man hohe Primärstabilitätswerte angestrebt. Dies traf besonders auf die Fälle mit Sofortbelastung des Implantats zu. Moderne Implantatsysteme sollen durch Design und Bohrprotokoll eine Überlastung des Alveolarknochens während der Insertion verhindern, weil davon ausgehende resorptive Prozesse die Ästhetik und längerfristig auch die Funktion beeinträchtigen können. Ziel dieser Literaturstudie ist es, die aktuelle Datenlage über die Auswirkungen mechanischer Beanspruchung des Alveolarknochens beim Setzen vom Implantaten zu eruieren und die neuen Erkenntnisse hinsichtlich klinischer Relevanz darzustellen.

Material und Methode: Die medizinische Datenbank PubMed wurde nach folgenden Begriffen und Verknüpfungen durchsucht: Dental implant insertion AND mechanical stress AND bone. Die gefundenen Publikationen ordnete man den Gruppen I) In-vitro-Studien und Finite-Element-Studien, II) Tierstudien und III) klinische Studien zu. Am 30. September 2019 fand die abschließende Recherche statt.

Ergebnisse: Von den 163 erfassten Publikationen gingen 57 Artikel in die vorgelegte Arbeit ein. Anhand von In-vitro-Studien und Finite-Element-Analysen konnte gezeigt werden, dass kortikaler Knochen im Vergleich zu spongiösem Knochen eine schlechtere Stressreduktion und aufgrund seiner geringeren Viskoelastizität einen linearen Anstieg des Einbringdrehmoments aufweist. Wenn bei Implantatinsertion mit unterdimensionierter Osteotomie gearbeitet wurde, machte sich dies in einer deutlichen Tendenz zu erhöhtem Stress im Knochen bemerkbar. Die Auswertung der Tierstudien hat ergeben, dass je nach Ausmaß der Unterdimensionierung des Implantatbetts die inneren Bereiche der Implantatgewinde Heilungskammern bilden, in denen es zu rascher Knochenneubildung kommt. Die Bereiche mit direktem Kontakt zwischen Implantatkörper und Alveolarknochen hingegen lassen eine Resorption des Knochens während der Heilungsphase erkennen. Die Resorption schien dabei umso größer zu sein, je höher das Eindrehmoment bei der Implantatinsertion war. Diese Beobachtung wurde gemacht, obwohl während der initialen Heilung ein höherer Implantat-Knochenkontakt vorlag. Die ausgewerteten klinischen Studien belegen, dass die Veränderungen am marginalen Knochenniveau bei den Implantaten, die mit hohem Drehmoment eingebracht wurden, offensichtlich größer sind, als wenn mit niedrigerem Drehmoment implantiert wurde. Darüberhinausgehend zeigen klinisch mobile Implantate jedoch a priori eine ungünstigere Einheil-Prognose.

Diskussion: Beim Setzen von zahnärztlichen Implantaten ist eine behutsame und schonende Vorgehensweise erforderlich. Durch ein kontrolliertes Einbringdrehmoment, welches die biologischen Besonderheiten des Implantat-Einheilungsprozesses berücksichtigt, können schädigende Auswirkungen auf den Alveolarfortsatz minimiert werden. Da die exakten Grenzwerte für die mechanische Belastbarkeit des Alveolarknochens nicht bekannt sind, ist die Beurteilung der Knochenqualität, die der Implantatinsertion vorausgehen soll, von großer Bedeutung. Dadurch können sowohl das chirurgische Protokoll als auch das folgende prothetische Belastungsprotokoll an die vorgefundene Patienten-Situation angepasst werden. Zukünftige Implantatsysteme sollten mit einem verfeinerten Makrodesign ausgestattet werden, welches die Implantatstabilität nicht nur aus der Kompression der kortikalen Schicht erhält, sondern auch den Bereich des trabekulären Knochens mit einbezieht.

Schlussfolgerung: Vor der zahnärztlichen Implantation gilt es, den knöchernen Alveolarfortsatz hinsichtlich der vorliegenden Knochenqualität zu analysieren, da sein Zustand für die Aufnahme des Implantates maßgeblich ist. Die erhaltene Kenntnis beeinflusst die Auswahl des entsprechenden Bohrprotokolls und des zu verwendenden Implantatdesigns, wodurch Ergebnisse größerer Nachhaltigkeit zu erwarten sind.

2 Introduction

Mechanical stability achieved during implant insertion is considered a prerequisite for successful osseointegration. Factors determining primary implant stability include the surgical protocol, implant macro- and microgeometry, bone quality and bone quantity (Baldi et al. 2018, Duyck et al. 2015, Jimbo et al. 2014, Coelho et al. 2013, Bartold et al. 2011). Secondary implant stability results from new bone formation and remodeling occurring at the bone implant interface (Eom et al. 2016, Coelho et al. 2013).

Several methods have been employed for determining bone quality and implant stability (Molly et al. 2006*), ranging from preoperative radiographic assessment and tactile sensation during implant site preparation (Falco et al. 2018*) to measurements of damping capacity (Monje et al. 2019*) and resonance frequency of already installed implants (Baldi et al. 2018, Eom et al. 2016). Modern surgical motors actively allow for determining maximum insertion torque (Lee et al. 2019, Eom et al. 2016, Duyck et al. 2015 and 2010, Coelho et al. 2013, Trisi et al. 2011) and insertion energy which has been described as the total energy needed to place an implant into its site (Di Stefano et al. 2019*). As an experimental method, removal torque measurements of implants have also been used (Coelho et al. 2013, Rabaudi et al. 2011). In this context, insertion torque represents a measure of the mechanical properties of the bone and frictional resistance encountered by the implant while moving forward apically through a rotatory movement on its axis (Baldi et al. 2018, Dorogoy et al. 2017). Despite numerous attempts, a mechanically and biologically optimal level of primary implant stability could not be defined yet and implant manufacturers try to reflect this by providing different drill protocols for different bone types (Taing-Watson et al. 2015).

Based on fundamental studies, the processes occurring at the implant bone interface may be described as follows. Bone which is in direct contact with an implant will render primary stability for a given period of time, but will suffer cell-mediated activity and remodeling because of compression (Coelho et al. 2013, Duyck et al. 2010). Void spaces left between implant and bone not contributing to primary stability will fill with a blood clot followed by rapid development of woven bone (Coelho et al. 2013, Duyck et al. 2010). High insertion torque is believed to result in excessive bone compression (Frisardi et al. 2012), compromised microcirculation (Duyck et al. 2015, Trisi et al. 2011), microdamage, broader zones of programmed cell death (Cha et al. 2015), a prolonged inflammatory phase, and delayed healing and marginal bone resorption (Monje et al. 2019*, Baldi et al. 2018, Yadav et al. 2012, Bartold et al. 2011) as a consequence of remodeling processes (Bartold et al. 2011). To some extent, still accepted success criteria for

*= article not included in literature review

dental implants constituting <1 mm of bone loss until one year after implantation and <0.2 mm bone loss per year thereafter seem to reflect this (Eom et al. 2016).

High and low insertion torque comparisons show significantly greater stress and strain levels in the surrounding bone in implants inserted with a high insertion torque (Cha et al. 2015). Different osteotomy site preparation results in different insertion torques. The mechanical stability achieved during implant insertion is considered to be a prerequisite for successful osseointegration. In a landmark study, three elementary requirements for osseointegration are described comprising (1) infliction of minimal trauma during surgery, (2) establishment of primary implant stability and (3) avoidance of infection and micromotion during healing (Berglundh et al. 2003).

The question arises whether primary implant stability is resulting from anchorage in cortical bone or in trabecular bone. In the past, conical implants and implants with a taper in the cortical part were used for maximizing insertion torque. Current implant configurations which are characterized by a back-taper design in the shoulder area (NobelActive, Nobel Biocare AB, Gothenburg, Sweden) or which feature triangular cross sections (MIS V3, MIS Germany, Minden, Germany) are designed in that way to avoid stress on buccal bone during the insertion process. In addition, the idea behind such designs is to maximize the thickness of buccal bone and achieve a more favorable loading situation.

Furthermore, in implant dentistry a paradigm shift appears to be in progress with regard to the magnitude of the insertion torque applied. So far high implant insertion torque values were associated with high levels of primary implant stability and consequently low levels of micromotion which form a prerequisite for immediate loading protocols. More recently, lower insertion torque values have been advocated which are supposed to allow for better bone formation. The goal of this literature review is to summarize the existing data on the effects of mechanical stress on the alveolar bone as evolved from implant insertion.

3 Materials and methods

A literature search was conducted in PubMed using the user query “dental implant insertion AND mechanical stress AND bone”. Two persons screened titles and abstracts independently who then decided whether the full paper was to be assessed. The papers identified were grouped according to the research methodology applied into: I) in vitro studies and finite element analysis, II) animal studies, III) clinical trials. In addition, the bibliographies of the papers were checked and potentially relevant articles were identified.

Reviews and opinion articles were excluded from the analysis. Articles dealing exclusively with bone replacement materials such as polyurethane foam were also ignored. Furthermore, articles that reported on simulated masticatory loading or simulation of the loading condition after implant placement for design studies were not included, nor were articles that dealt with immediate implant placement in extraction sockets or with traumatology or orthopedics.

4 Results

A total of 163 articles were identified by a primary database search in PubMed. The last search took place on September 30^{th} 2019. The articles found are listed in the References paragraph in alphabetical order of the first authors.

Of the 163 publications found, 57 articles were included in the analysis. The most important results are summarized in tables 1-3.

The remaining 106 articles could not be considered. An overview of these articles and the reason for their exclusion is explained in the appendix in Table 4.

4.1 Finite element analyses and in vitro studies

Several finite element analyses and in vitro studies dealt with the problem of insertion-induced damage of alveolar bone (Tab. 1). The papers identified showed a clear tendency towards increased stress in bone resulting from the use of undersized osteotomies. This seems to be more critical in cortical bone as compared to trabecular bone, which rather behaves like a viscoelastic material. The drill protocol in combination with the implant design have proven to affect the amount of bone damage observed.

According to Sotto-Maior et al. (2010), the good long-term success of osseointegrated dental implants with over 90 % after 30 years is remarkable. But there is also a necessity for a better understanding of osseointegration process, as it requires ideal stress levels to guarantee efficient bone repair. Insertion torques over 50 Ncm can provoke a high compressive stress to peri-implant tissue, causing blood supply deficiency and bone necrosis. Different mechanical properties between cancellous and cortical bone reveal that cortical bone tissue has lower capacity to dissipate stress as well as a more uniform increase of the insertion torque, presenting higher principal maximum stress in comparison with cancellous bone.

Large amounts of stress induced by high insertion torques or highly dimensioned implants can cause excessive bone resorption and eventually complete implant failure (Udomsawat et al. 2018, Cha et al. 2015, Lee and Baek 2010). Continuous increase of implant thread geometry dimensions and bone-implant contact area also raises the stress level in the surrounding bone (Udomsawat et al. 2018). In accordance with Lee et al. (2010), an increase of implant diameter and the use of tapered implants yields in higher amounts of microdamage to the cortical bone and this could affect bone remodeling and implant stability. An animal study compared different implant designs resulting in high values of microdamage by the group of rough cylindrical implants, whereas rough tapered, smooth cylindrical and smooth tapered implants presented lower values of microdamage and microcracks (Bartold et al. 2011). The microdamage was caused by implant placement, not by osteotomy preparation, and microdamage was greater in direct surrounding of an implant than in periphery. Taing-Watson et al. (2015) also confirm through an in vitro study that more bone-microdamage is caused by cylindric implant designs than by tapered designs. They describe predrilling as a useful means to avoid excessive bone damage. Another in vitro study researched self-drilling implants in dogs without any pilot hole and resulted in greater microdamage in cortical bone, compared with the self-tapping technique and a previous pilot drill (Yadav et al. 2012).

The press-fit technique is aimed to guarantee satisfactory primary stability for implants and requires the diameter of osteotomy sites to be smaller than the implants´ major diameter (Natali et al. 2009 A). Undersized osteotomies and smaller drill diameters always lead to an increased maximum stress in cortical bone due a lack of viscoelasticity behavior in comparison to trabecular bone, whereas larger osteotomies result in a more uniform stress distribution (Frisardi et al. 2012). The correct measure of osteotomy site preparation seems to be an important factor if aiming for the correct dimension of pre-drilling. Stress level measurements for 0.25 mm undersized osteotomies were significantly lower than for 0.60 mm undersized osteotomies, which could cause bone resorption due to high stress levels and microdamages (Guan et al. 2011).

A listing of the included literature of finite element analyses and in vitro studies can be found in Tab. 1.

Tab. 1: Overview of finite element analyses (shaded in grey) and in vitro studies

Reference	Study Design	Findings
Cha et al. (2015) (please cf. Tab. 2 for corresponding animal experiments)	Simulation of implant placement with low and high insertion torques	▪ High insertion torques result in higher stress and strain levels in the surrounding of an implant
Dorogoy et al. (2017)	Advanced simulation of dental implant insertion (MIS Seven implant 3.75 mm x 13 mm) in a 2.80 mm osteotomy (0.95 mm undersizing)	▪ Torque alone is not sufficient for implant insertion ▪ An additional vertical force is required, which controls the amount of damage due to extrusion (greater force results in greater damage) ▪ Trabecular bone may contribute to implant stability
Frisardi et al. (2012)	Finite element analysis on stress development during insertion of a dental implant 4.0 mm in diameter into osteotomies with 2.8 mm, 3.3 mm and 3.8 mm in diameter	▪ Smaller drill diameters (undersized osteotomy) increase maximum stress particularly in cortical bone due to a less viscoelastic behavior as compared to trabecular bone ▪ Larger osteotomies result in a more uniform stress distribution
Guan et al. (2011)	Finite element analysis of implant insertion for 0.25 mm undersized osteotomies (thread forming), 0.60 mm undersized osteotomies (thread cutting) and tapered osteotomies with undersizing decreasing from bottom to top (thread forming and cutting)	▪ Stress levels in bone were less for 0.25 mm undersized osteotomies ▪ Stress levels in 0.60 mm undersized osteotomies may cause bone resorption due to high stress levels
Natali et al. (2009) A	Finite element analysis of implant placement (AstraTech 4.0 x 8)	▪ Simulating regular drill dimensions, the implant interacts fully in the area of microgrooves, interacts only with thread tips in the area of macrogrooves and partial/no interaction occurs apically ▪ Largest displacement of bone observed at the thread crests (increases during insertion)

Natali et al. (2009) B	Finite element analysis of implant placement (AstraTech 4.0 x 8) in osteotomies with 3.7 mm and 3.8 mm in diameter	▪ Less displacement of bone observed when a 3.7 mm osteotomy was considered ▪ Plastic flow of bone in the periimplant area leads to stress relaxation over time
Sotto-Maior et al. (2010)	Finite element analysis of implant placement at different torque levels	▪ An increase in insertion torque led to an increase in stress and strain observed in bone. ▪ Stress was lower in trabecular bone, but strains were higher
Udomsawat et al. (2019)	Finite element analysis of implant placement for different macrodesigns	▪ Stress increased with implant insertion ▪ Highest stress values and concentrations observed in cortical bone ▪ Implant designs affected stress distribution patterns
Bartold et al. (2011)	Placed implants in animal cadaver bone (sheep mandible) and assessed microdamage histomorphometrically (microcracks, cross-hatch damage, diffuse damage)	▪ Microdamage was greater in the direct surrounding of an implant than in greater distance ▪ Rough cylindrical implants caused maximum microcracks ▪ Microdamage was introduced by implant placement not by osteotomy creation
Lee and Baek (2010)	Placed tapered and cylindrical orthodontic mini implants (1.5 mm and 2.0 mm in diameter) in rabbit tibia and analyzed resulting microdamage	▪ Increasing implant diameter and the use of tapered implants resulted in greater insertion torque, but also in greater bone damage

Tabassum et al. (2010)	Placed implants in animal cadaver bone (iliac wings of goats) following a press fit or undersized surgical technique	▪ Higher insertion torque, more translocated bone particles and better bone to implant contact observed with under-sized drilling ▪ Implants inserted in undersized osteotomies showed more bone like tissue and calcium content after cultiva-tion (1 and 6 days) than implants placed with press fit
Taing-Watson et al. (2015)	Placed orthodontic mini implants (1.6 mm / 2.0 mm, cylindrical / tapered) in an-imal cadaver bone (dog mandible and maxilla) following pilot drilling (1.0 mm) and analyzed resulting microdamage	▪ Tapered and cylindrical implants led to different levels of microdamage. ▪ Predrilling can help reducing microdamage
Wawrzinek et al. (2008)	Placed orthodontic microscrews 1.5 mm in diameter in animal cadaver bone (por-cine pelvis) following predrilling (1.0 mm in diameter) and applied regular or exag-gerated tightening	▪ Overtightened implants showed greater bone damage (number of cracks, accumulated length of all cracks, maximum radius of crack alteration, longest crack)
Yadav et al. (2012)	Placed self-drilling and self-tapping (pilot drill 1.0 mm) orthodontic implants (1.6 mm) in animal cadaver bone (dog man-dible and maxilla) and analyzed resulting microdamage	▪ Self-drilling implants (without pilot hole) resulted in greater microdamage (total crack lengths; crack surface density) of cortical bone

4.2 Animal studies

Despite substantially differing in study design, the various animal trials considered (Tab. 2) allow for following statements. The inner parts of implant threads create healing chambers where bone formation seems to progress very well. The size of these chambers is dependent on the amount of undersizing chosen with a specific drill protocol. Areas of direct contact between implant body and alveolar bone experience resorption during healing and more resorption seems to occur when implants have been placed with higher insertion torque. However, implants placed with high insertion torque have been shown to maintain greater total bone to implant contact during initial healing. This could be due to the two counteracting processes of resorption of damaged native bone on the one hand and formation of new bone on the other, which occur at different rates. Several reports identified bone chips in the apical region of implant osteotomies, which had obviously been translocated by implant design features such as cutting flutes. These bone chips seem to have osteogenic potential.

While not directly comparable to trauma caused by undersizing of an osteotomy, the use of osteotomes may also be considered as being more traumatic than using drills. The papers evaluated here seem to be inconclusive with partially contradicting results with respect to both mechanical and biologic consequences. One clinical study (Donati et al. 2008), however, indicates a potentially higher risk for implants placed using the osteotome method.

A comparison between conventional and commercially available implant types (Astra Tech implants, Osseospeed 3.5S, Astra Tech, Mölndal, Sweden) and an experimental implant type, demonstrated greater bone loss, larger marginal bone defects and a lower overall peri-implant bone fraction in the experimental implant design group (Duyck et al. 2010). The experimental implant type, which consisted of pure titanium and underwent a surface treatment of sandblastings and acid etching, is intended to achieve higher insertion torque values and inferentially more primary stability.

Regarding insertion torque, Duyck et al. (2015) described only a small amount of new bone formation for implant placement with high insertion torque, whereas placements with low insertion torque, however, showed a substantial amount of new bone formation. However, overall more bone was to be observed around high insertion torque implants such that there was no direct negative effect of high insertion torque implants on the cortical bone. In the group with low insertion torque, the increased bone formation indicated that osseointegration coincides with bone formation. The increased amount of total bone around implants with high insertion torque could, however, be due to the undersized osteotomy and thus to a reduced bone removal due to less preparation of the osteotomy site during the surgical procedure.

Marin et al. (2016) compared implant insertion (3.75 mm diameter implants) in three different osteotomies (3.0 mm, 3.25 mm and 3.5 mm). As expected, insertion torque increased with smaller osteotomy size. The created healing chambers were important for further osseointegration and secondary stabilization. The widest osteotomies (3.5 mm) showed highest amounts of healing chambers, where healing chambers occupied almost the entire thread extension. The amount of woven bone also increased with higher drill diameter.

The influence of lateral pressure due to undersized osteotomies was tested in an experimental study with dogs (Pantini et al. 2010) and compared to a standard procedure with a healing time of 4 months. The results revealed that lateral pressure to the implant bed as resulting from undersized osteotomies did neither affect osseointegration, bone resorption, the degree of mineralization nor the value of bone-to-implant contact. In both groups crestal bone resorption behaved similarly at about 1 mm.

Regarding crestal bone loss, Novaes et al. (2005) compared implant placement under conventional preparation technique with placement using an additional crestal drill. The authors concluded that crestal bone loss was significantly lower when an additional crestal drill was used. Other studies also investigated the effect of different preparation techniques. Büchter et al. (2005 B) compared implant insertion in mini-pigs under the usage of drills or osteotomes. When drills were used, greater implant stability and a higher bone to implant contact after 28 days were reported. Implant insertion with usage of osteotomes revealed a higher density of peri-implant bone, but also a slightly lower bone-to-implant contact and fractured trabeculae as compared to the procedure using drilling. The authors concluded that decreased implant stability based on microfractures in peri-implant bone resulted from using the osteotome technique.

Drill and osteotome technique were also compared in a similar study by Nkenke et al. (2002), where bone to implant contact after 2 weeks, 4 weeks and 8 weeks was better in sites prepared using osteotomes. The difference, however, was not statistically significant. The paper concluded that a localized trauma caused using osteotomes induced faster osseointegration.

Coelho et al. (2013) investigated the effect of an implant insertion with 4.0 mm diameter in different osteotomy sizes of 3.2 mm, 3.5 mm and 3.8 mm. As expected, an inversely proportional behavior of insertion torque and removal torque levels to the drilling dimension was found. Furthermore, higher levels of necrotic bone and greater loss in insertion to removal torque occurred in 3.2 mm and 3.5 mm osteotomies after 1 and 3 weeks observation time. On the other side, 3.8 mm osteotomy healing chambers were observed which were filled with newly formed bone, and minor loss in insertion torque compared to removal torque was recorded.

Also, Campos et al. (2012) showed similar outcomes as appositional bone healing was found in areas of direct bone to implant contact. In undersized osteotomies, extensive necrotic bone areas were found, whereas implants placed in standard sized osteotomies resulted in less bone-to-implant contact i.e. in intramembranous bone healing and healing chambers with osteogenic tissue. No signs of extensive necrotic bone areas were observed.

Orthodontic mini implants were placed in hard mandibular bone of sheep, and undersized osteotomies were compared with standard osteotomies by Rebaudi et al. (2011). Removal torque measurement immediately after insertion and after 8 weeks of healing revealed a higher loss of removal torque in narrower osteotomies. Cavities in cortical bone (resorption) and microcalli in soft bone were found in microcomputed tomographic morphometric and morphologic analyses. This paper revealed that a narrow drill for an osteotomy site preparation increased insertion torque, damaged the periimplant bone and decreased removal torque after 8 weeks of healing time.

Implant insertion in 0.15 mm and 0.05 mm undersized osteotomies was carried out by Halldin et al. (2011 & 2014). Higher insertion torques were induced in undersized osteotomies and constantly higher removal torques were observed for implants placed in undersized osteotomies. However, increased removal torque was described for implants placed without undersized osteotomy, and furthermore significantly more new bone formation was described in this group. Both publications conclude that increased static bone strains resulting from undersized osteotomies do not affect extensive bone resorption. However, higher insertion and removal torques have a tendency towards greater bone-to-implant contact and higher primary stability which is maintained over time. Implant stability generated by moderate strain decreases over time, in this case over a period of 13 days.

The coherence between different osteotomy sizes and removal torques is described by Okazaki et al. (2008). Removal torque values for implants in undersized osteotomies were concluded to decrease within the first 6 weeks and do remain static afterwards. Normal sized osteotomies initially showed lower removal torque values. In the observation period from 3 weeks to 6 weeks they increased reaching similar values as implants placed in undersized osteotomies.

Bone-to-implant contact remains stable in undersized osteotomies after 8 weeks, but increases in non-undersized osteotomies, and the gap between implant and osteotomy is filled by newly formed bone (Jung et al. 2012).

Eom et al. (2016) state that an undersized osteotomy does not only result in higher values of primary implant stability and bone-to-implant contact throughout the healing period, but also produces a higher number of microcracks. Furthermore, enlarged osteotomies resulted in faster bone growth in cortical bone areas, whereas undersized osteotomies lead to faster marginal bone loss.

Trisi et al. (2011) examined tapered implants of 3.7 mm in diameter, which were inserted in different osteotomies of sheep mandibles. A parallel-walled implant-design of 2.7 mm diameter and coronal enlargement represented the high torque group. In the low torque group, the implants had diameters ranging from 3.2 to 3.9 mm from apical to coronal and tapered osteotomies were used. The high torque group (110 Ncm) resulted in cracks, microfractures, plastic bone deformation and necrotic material after 1 week, while the low torque group (10 Ncm) manifested a gap between implant and bone, filled with debris, blood cells and granulation tissue. Initial woven bone was present and no cracks in bone were observed. After an observation period of 2 weeks in the high torque group, microfractures and large cracks were undergoing resorption and replacement by woven bone. Meanwhile, osteoid formation occurred in the gap between implant and bone and only minor resorption of cortical bone appeared in the low torque group. Results 3 weeks after implant insertion showed pores in cortical bone and repair process going on in the high torque group whereas low torque implants filled the gap between implant and bone partially with woven bone. After 4 weeks the originally cut bone was largely substituted in the high torque group and in the low torque group, on the other hand, the gap between implant and bone was mostly filled by composite bone. At 6 weeks the high torque group showed not completely restored cortical porosity. Old crestal bone had been almost completely replaced by new woven bone and infra-bony pockets could be found around the implant neck. After 6 weeks, the low insertion group showed no extensively bone remodulation at peri-implant bone. So, a tendency of cortical bone fracture at high insertion torque implants can be concluded. In the low torque group, the removal torque increased dramatically between 3^{rd} and 4^{th} week, while in the high torque group it dropped to 50% in the first week.

Another paper compared site preparation in different undersized dimensions of 5 %, 15 % and 25 % and resulted that the 25 % group led to less new bone formation and less bone-to-implant contact. At the same time microfractures and functional repair, including osteoclast activity and remodeling lacunae intensified. On the other hand, new bone formation was more representative in the 5 % and 15 % group, and even bone-to-implant contact was significantly higher in these groups than in 25 % undersized osteotomies. The authors concluded that a discrepancy between implant and final drill diameter of more than 15 % represents a risk for inferior tissue response (Tabassum et al. 2011).

In a similar study by Tabassum et al. (2014), no differences in removal torques of 5 %, 15 % and 25 % undersized osteotomies were found. However, less abundant bone ingrowth into screw threads occurred in the 25 % undersized osteotomies. The authors concluded that there is no mechanical beneficial effect of the 25 % undersized surgical technique in comparison to the 5 % or 15 % undersized surgical technique to improve primary or secondary implant stability.

Uemura et al. (2012) investigated the effect of different implant designs. They tested a conical implant design with a dimeter of 1.2 mm at the apex and 1.4 mm at the implant shoulder which was inserted in osteotomies of 0.8, 0.9, 1.0 and 1.1 mm. Results revealed greater bone to implant contact in 0.9 mm and 1.0 mm sites after 3 weeks of healing. Moreover, in the 0.9 mm and 1.0 mm osteotomies higher implant stability was measured

Coelho et al. (2010) dealt with the importance of implant threads and their effect on osseointegration. Different implants with different thread pitches and depths were inserted in tibiae of dogs and resulted in either appositional bone healing in areas where direct contact between implant and bone existed (no healing chamber) or rather intramembranous bone healing in areas where no primary contact to bone existed (healing chamber).

A study evaluated the effects of self-cutting and non-self-cutting thread designed implant (V-shape self-cutting versus power thread design, non-self-cutting) in rabbit femur with different thread depths of 0.4 and 0.6 mm on variable insertion torques. Results revealed a tendency towards better performance of low torque implants with respect to bone to implant contact after 4 weeks of healing, as well as volume of new bone and total bone volume. Bone to implant contact in power thread design implants with a thread depth of 0.4 mm was improved when high torque had been applied (Muktadar et al. 2018).

Based on implant geometry, Yin et al. (2019) investigated a new model of tri-oval implant design, aiming to create a combination of high strain and low strain peri-implant environment that would ensure both primary implant stability and rapid but gentle osseointegration. Results showed that at the minima regions of tri-oval implants low compressive strain and significantly less osteocyte apoptosis and bone resorption occurred as compared to round implants. Beyond this, the rate of new bone accrual was also faster around the tri-oval implants. At the maxima regions, on the other hand, a similar distribution of dead and dying cells as in round implants was observed together with superior primary stability without increasing insertion torque. Different implant designs (low, moderate and high compression group) were dealt by another paper, regarding their affection of bone compression on bone-to-implant contact. It was concluded that high compression implants did not achieve greater implant stability. Low compression implants, however, showed an increase in bone-to-implant contact in the early healing phase. Implants with medium compression had higher initial values, and high compression implants caught up by day 28 (Nevins et al. 2012). A listing of included literature of animal studies can be found in Tab. 2.

Tab. 2: Overview of animal studies (studies using osteotomes for implant site preparation are shaded in grey)		
Reference	**Study Design**	**Findings**
Berglundh et al. (2003)	Placed implants with a healing chamber in dog mandibles and evaluated bone healing between 2 hours and 12 weeks	▪ Healing chambers were occupied with coagulum and granulation tissue which were replaced by provisional matrix ▪ Bone formation started during the first week of healing ▪ Bone in contact with implant threads was resorbed and replaced with newly formed bone
Campos et al. (2012)	Placed implants (4.0mm in diameter) into osteotomies with different diameters (3.2mm, 3.5 mm, 3.8 mm) in the radius of dogs	▪ Increasing insertion torque observed with decreasing osteotomy diameters ▪ Appositional bone healing in areas of direct bone to implant contact ▪ Intramembranous bone healing in areas where no primary contact to bone existed (healing chamber) ▪ Extensive necrotic bone areas in sites drilled to 3.2 mm and 3.5 mm in diameter at 1 week evolving to remodeling sites at 3 weeks ▪ Implants placed in 3.8 mm sites showed osteogenic tissue in healing chambers, but no extensive necrotic bone areas at 1 week and extensive woven bone formation at 3 weeks
Cha et al. (2015)	Placed implants in murine femurs following the creation of osteotomies differing in diameter	▪ Osteotomy preparation alone created a zone of dead and dying osteocytes ▪ High insertion torque doubled the size of this zone ▪ The lower the insertion torque, the more the peri-implant environment favored cell proliferation and osteogenic differentiation
Coelho et al. (2010)	Placed implants with different thread pitch and thread depth in the tibia of dogs	▪ Appositional bone healing in areas where direct contact between implant and bone existed ▪ Intramembranous bone healing in areas where no primary contact to bone existed (healing chamber)

Coelho et al. (2013)	Placed implants (4.0 mm in diameter) in osteotomies with diameters of 3.2, 3.5 and 3.8 mm diameter created in the radius of dogs	▪ Necrotic bone / remodeling sites and greater loss in insertion / removal torque in 3.2 and 3.5 mm osteotomies after 1 and 3 weeks observation time ▪ Healing chambers filling with newly formed bone and less loss in insertion / removal torque observed in 3.8 mm osteotomies
Coyac et al. (2019)	Placed implants in maxillary osteotomies in rats with 6 % vs. 15 % undersizing	▪ Periimplant bone showed micro-fractures after implant insertion ▪ Maximum compressive stress of 200 - 400 MPa ▪ Bone volume / total volume significantly lower at thread tips as compared to intact bone ▪ Stiffness of periimplant bone reduced ▪ High misfit implants had higher failure rate (crestal radiolucencies), granulation tissue at the bone implant interface, decline in bone to implant contact in the crestal area; bone to implant contact in apical region did not change significantly and new bone formed at sites of low interfacial pressures ▪ High strain implants caused a zone of dying osteocytes and cell death ▪ Bone resorption exceeded new bone formation based on enzymatic activity
de Oliveira et al. (2007)	Placed implants in dog mandibles in osteotomies prepared with or without using a crestal drill	▪ Greater bone to implant contact after 12 weeks of healing when the crestal drill had been used ▪ Greater bone density in the vicinity of implants after 12 weeks of healing when the crestal drill had been used
Duyck et al. (2010)	Compared bone behavior of a commercially available implant type and an experimental implant type modified for achieving high insertion torque using an intraoral minipig model	▪ High torque implants showed greater bone loss, larger marginal bone defects and a lower overall peri-implant bone fraction ▪ Peri-implant strains measured were higher in high torque implants

Duyck et al. (2015)	Placed implants (3.9 mm in diameter) in 3.8 mm or 3.2 mm osteotomies in the tibia of rabbits	▪ Little new bone formation observed in implants placed with high insertion torque, but substantial new bone formation found in implants placed with low insertion torque ▪ More total bone around implants placed with high insertion torque
Eom et al. (2016)	Placed implants (3.5 mm in diameter) in osteotomies with 3.0 mm, 3.3 mm and 3.5 mm in diameter using an intraoral minipig model	▪ Small diameter osteotomy resulted in microcracks, but higher levels of stability and bone to implant contact throughout the healing period ▪ Marginal bone loss was faster in small osteotomy sites ▪ Enlarged osteotomies resulted in faster bone growth in the cortical area ▪ No difference in new bone formation in the area of trabecular bone
Halldin et al. (2011)	Inserted implants in osteotomies undersized by 0.15 mm and 0.05 mm vs. no undersizing in the tibia and femur of rabitts	▪ Significantly greater insertion torque observed in implants placed in undersized osteotomies ▪ Greater removal torque observed in implants placed in undersized osteotomies (not significant in one instance) ▪ Significantly more native bone around implants with 0.15 mm of undersizing as compared to implants without undersizing, but significantly more new bone formation around implants without undersizining which were placed in tibiae
Halldin et al. (2014)	Inserted implants in osteotomies undersized by 0.15 mm and 0.05 mm vs. no undersizing in the tibia of rabbits	▪ Greater insertion torque and removal torque observed in implants placed in undersized osteotomies ▪ Increase in removal torque over time for implants placed without undersizing ▪ Decrease in removal torque over time for implants placed with 0.05 mm of undersizing and no change in removal torque over time for implants placed with 0.15 mm of undersizing ▪ Tendency towards greater bone to implant contact in implants placed in undersized osteotomies

Ivanoff et al. (1996)	Placed 3.75 mm implants in the tibia and femur of rabbits in (a) 3 mm osteotomies following countersinking, (b) caused rotational instability of implants by clockwise rotation, (c) placed implants in 4 mm osteotomies	▪ All implants stable after healing with extensive bone formation around some implants placed in 4 mm osteotomies ▪ Less bone to implant contact and less bone within threads in implants placed in 4 mm osteotomies as compared to implants placed in 3 mm osteotomies with countersinking (tibia) ▪ Rotation mobile implants showed more bone to implant contact and more bone within threads as compared to implants placed in 3 mm osteotomies with countersinking (tibia) ▪ Implants placed in 4 mm osteotomies showed more bone to implant contact and more bone within threads as compared to implants placed in 3 mm osteotomies with countersinking (femur)
Jimbo et al. (2014)	Placed two different types of implants (Blossom / DT, Intra-Lock, Boca Raton, FL) in sheep mandibles	▪ Blossom implants (with cutting flute): required less insertion torque; bone chips found in healing chambers between threads with cutting flutes; less resorption around thread tips ▪ DT implants (self tapping): healing chambers between threads filled with new bone; resorption around threads
Jung et al. (2012)	Placed 3.4 mm implants in 3.4 mm or 2.85 mm osteotomies in dog mandibles	4 weeks of healing ▪ Gap between implant and osteotomy filled with newly formed bone ▪ Voids at thread tips of implants placed in 2.85 mm osteotomies 8 weeks of healing ▪ No general difference between both groups ▪ Bone to implant contact remained stable in implants placed in 2.85 mm osteotomies but increased in implants placed in 3.4 mm osteotomies

Marin et al. (2016)	Placed implants (3.75 mm in diameter) in radii of dogs using osteotomies with 3.0 mm, 3.25 mm and 3.5 mm in diameter	▪ Insertion torque decreased with increasing osteotomy size ▪ Intramembranous or appositional bone healing ▪ Amount of woven bone increased with drill diameter ▪ No significant differences in bone to implant contact and bone area fraction occupancy between different drill sizes
Muktadar et al. (2018)	Placed implants with different thread forms (V-shape self cutting; power thread design nonself-cutting) and thread depths (0.4 and 0.6mm) in rabbit femur	▪ After 4 weeks of healing a tendency towards better performance of low torque implants with respect to bone to implant contact, volume of new bone and total bone volume was found (within thread type groups) ▪ Only bone to implant contact in power thread design implants with 0.4 mm thread depth was better when high torque had been applied
Nevins et al. (2012)	Placed implants in dog mandibles using low compression (osteotomies tapped), moderate compression (sites prepared to minor diameter of the implant), high compression (sites prepared to minor diameter of the implant; cutting features removed from implant)	▪ Modest decrease in implant stability at postoperative day 7 ▪ High compression implants did not achieve greater implant stability ▪ Only minimal differences in crestal bone loss among groups ▪ Bone chips observed in apical region when cutting feature was present in implant design ▪ Bone to implant contact improved for all groups during healing with final (56 days of healing) values around 70 % ▪ Low compression implants showed an increase in bone to implant contact in the early healing phase; medium compression showed higher initial values; high compression caught up by day 28

Novaes et al. (2005)	Placed implants in dog mandibles using conventional drilling protocols or an additional crestal drill	▪ Crestal bone loss significantly lower when the crestal drill was used
Okazaki et al. (2008)	Placed orthodontic mini implants 1.2 mm in diameter into 1.0 mm and 1.2 mm osteotomies in dog femurs and measured implant removal torque	▪ Removal torque values for implants in 1.0 mm sites decreased over the first 6 weeks and then remained static ▪ Removal torque values for implants in 1.2 mm sites were initially 11-fold lower and then increased from 3 weeks to 6 weeks reaching similar values as implants placed in 1.0mm sites
Pantani et al. (2010)	Placed implants (3.75 mm in diameter) in osteotomies (dog mandible) with a diameter of 2.8 or 3.0 mm and allowed to heal for 4 months	▪ Lateral pressure to the implant bed did neither affect osseointegration nor bone resorption nor the degree of mineralization (4 months of healing)
Rebaudi et al. (2011)	Placed orthodontic mini implants (1.6mm in diameter) in sheep mandibles into osteotomies with 1.0 and 1.2 mm in diameter	▪ Implants placed in narrower osteotomies showed greater decrease in removal torque after 8 weeks of healing ▪ Described cavities in cortical bone (resorption) and microcalli in soft bone (stimulation of bone formation)
Tabassum et al. (2011)	Placed implants 4.2 mm in diameter in the iliac crest of goats following site preparation with 5 % undersizing, 15 % undersizing and 25 % undersizing	▪ Less new bone formation and less bone to implant contact in implants placed with 25 % undersizing ▪ Microfractures and functional repair including osteoclasts and remodeling lacunae observed around implants placed with 25 % undersizing
Tabassum et al. (2014)	Placed implants 4.2 mm in diameter in the iliac crest of goats following site preparation with 5 % undersizing, 15 % undersizing and 25 % undersizing	▪ No significant differences in removal torque values (5 % undersizing: 44.39 Ncm, 15 % undersizing: 39.4 Ncm and 25 % undersizing: 35.03 Ncm) and percentage peri-implant bone volume ▪ Percentage peri-implant bone volume directly adjacent to the implants was improved due to bone condensation and translocation of host bone particles ▪ Less abundant bone ingrowth into screw threads in 25 % undersizing

Trisi et al. (2011)	Placed tapered implants 3.7 mm in diameter in sheep mandible in tapered (3.2 - 3.9 mm in diameter) and parallel walled (2.7 mm) osteotomies with coronal enlargement	Histologic findings – High torque ▪ 1 week: Cracks, microfractures, plastic bone deformation, necrotic material ▪ 2 weeks: Microfractures, large cracks undergoing resorption and replacement by woven bone ▪ 3 weeks: Pores in cortical bone, repair process going on ▪ 4 weeks: Originally cut bone largely substituted ▪ 6 weeks: Cortical porosity not completely restored, old bone at crest almost completely replaced by new woven bone, infrabony pockets around the implant neck Histologic findings – Low torque ▪ 1 week: Gap between implant and bone filled with debris, blood cells and granulation tissue, initial woven bone present, no cracks ▪ 2 weeks: Osteoid formation in the gap between implant and bone, only minor resorption of cortical bone ▪ 3 weeks: Gap between implant and bone partially filled with woven bone ▪ 4 weeks: Gap between implant and bone mostly filled by composite bone ▪ 6 weeks: Old peri-implant bone had not extensively remodeled ▪ Cortical bone fracture tendency when high insertion torque had to be applied ▪ Removal torque in Low torque group increased dramatically between 3^{rd} and 4^{th} week while in High torque group dropped to 50 % in the first week ▪ Authors concluded that high insertion torque did not induce necrosis or implant failure, but led to greater bone apposition and removal torque values

Uemura et al. (2012)	Placed conical implants (1.2 mm at apex; 1.4 mm at shoulder) in osteotomies with diameters of 0.8, 0.9, 1.0, 1.1 mm in rat tibiae [Note: Only control group considered here i.e. no orthodontic loading]	▪ After 3 weeks of healing, greater bone to implant contact observed in 0.9 and 1.0mm sites ▪ Greater implant stability measured in 0.9 and 1.0 mm sites after healing
Warreth et al. (2009)	In dog mandibles (a) osteotomies were prepared, (b) osteotomies were prepared and tapped, (c) osteotomies were prepared and received implants, (d) osteotomies were prepared, tapped and received implants	▪ More microcracks observed in all experimental sites as compared to unaltered bone ▪ No difference in microcrack length between treatment modalities
Yin et al. (2019)	Placed round and trioval implants in an intraoral mouse model	▪ Maxima regions of trioval implants showed similar distribution of dead and dying cells as in round implants ▪ Minima regions of trioval implants resulted in lower compressive strain, less osteocyte apoptosis and bone resorption as compared to round implants ▪ New bone formation was faster around trioval implants

Büchter (2005) A	Placed implants in minipig tibiae using drills vs. osteotomes	▪ Greater implant stability when drills were used ▪ Fractured trabeculae when osteotomes were used
Büchter (2005) B	Placed implants in minipig tibiae using drills vs. osteotomes	▪ Higher density of peri implant bone when osteotomes were used ▪ Initial bone to implant contact slightly lower for implants placed with osteotomes ▪ Greater bone to implant contact after 28 days for implants placed with drills
Nkenke et al. (2002)	Placed implants in rabbit femur using drills vs. osteotomes	▪ Bone to implant contact after 2 and 4 weeks significantly better in sites prepared using osteotomes ▪ Bone to implant contact after 8 weeks still better in sites prepared using osteotomes, but the difference was no longer statistically significant ▪ Localized trauma caused using osteotomes induced faster osseointegration
Shalabi et al. (2007) A	Placed implants 4.6 mm in diameter and with different surfaces in goat femurs following site preparation with no undersizing (4.6 mm), undersizing (4.0 mm), osteotomes (4.6 mm)	▪ No significant differences in bone to implant contact and amount of bone among groups ▪ Blasted and etched implants placed in undersized osteotomies appeared to support an enhanced bone to implant contact
Shalabi et al. (2007) B	Placed implants 4.6 mm in diameter and with different surfaces in goat femurs following site preparation with no undersizing (4.6 mm), undersizing (4.0 mm), osteotomes (4.6 mm)	▪ Only one significant difference in removal torque observed: Machined implants in osteotome sites showed lower removal torque as compared to blasted and etched implants in undersized sites ▪ All implants showed new bone formation and interfacial bone contact

4.3 Clinical studies and reports

The clinical reports evaluated (Tab. 3) show that on the one hand implants being mobile upon insertion seem to have a compromised prognosis while on the other hand high insertion torques seem not to guarantee successful osseointegration. Marginal bone level changes obviously have a tendency of being greater in implants which were inserted with high levels of torque.

This is affirmed by various papers where tapered and straight-walled implants were compared. Tapered implants recorded higher insertion torques with a failure rate of 14 % after 90 days of submerged healing (Menicucci et al. 2012). Therefore, the primary stability of tapered implants was higher than of straight-walled implants, but with 100 %, straight-walled implants had a higher success rate. An increased insertion torque can lead to destruction of peri-implant bone and compromise osseointegration, especially if only a thin cortical layer contributes towards primary stability as it is, for example, in low-density bone.

Barone and coworkers also evaluated the effect of implants placed with regular insertion torques (<50 Ncm) in comparison to implants placed with high insertion torques (50-100 Ncm) in healed patient ridges. After 12 months of healing, 2 out of 58 implants in the high insertion torque group and 1 out of 58 implants in the low insertion torque group failed. Additionally, another 4 implants in the high insertion torque group and 1 implant in the low insertion torque group showed marginal bone loss higher than 1.5 mm. The authors observed greater marginal bone loss in the high insertion torque group as well as more soft tissue recessions in the high insertion torque group. It was also shown that sites with buccal wall thickness higher or equal to 1 mm were less prone to buccal soft tissue recession (Barone et al. 2016).

In a similar study, the difference between regular torque implants (30 - 50 Ncm, 9 implants) and high torque implants (70 - 176 Ncm, 42 implants) was investigated. No implant was lost and no significant differences between both groups in bone stability were found. Mean marginal bone level change for low torque implants was 1.03 mm at the time of loading and 1.09 mm after 1 year, whereas for the high torque implants 0.72 mm at time of loading and 1.24 mm after 1 year were observed. This led to the conclusion that the use of high insertion torque up to 176 Ncm did not prevented osseointegration (Khayat et al. 2013).

Other results in relation to high insertion torques were presented by Motoyoshi et al. (2006). Orthodontic mini implants were placed in patients' mandibula and loaded immediately. All failing implants were in the high insertion torque group.

In their study Baldi et al. (2018) found that insertion torques above 50 Ncm did not result in higher values of resonance frequency analysis. Moreover, higher insertion torques led to unnecessary biological and mechanical stress, such as bone compression, without advantages in terms of implant stability. Two implants which were placed with high insertion torque had not osseointegrated even after a healing period of 3 months.

In a case study by Bashutski et al. (2009), possible reasons for implant failure on 4 mandibular implants were revealed such as infection, overheating and overcompression.

Donati et al. (2008) compared two different implant installation procedures (site preparation with drills versus osteotomes) and differences in immediate and delayed loading. 5 % of implants placed using osteome preparation failed after immediate loading, whereas after implant insertions with the drill technique, 2 % of implants failed after immediate loading. 0 % failure occurred in the drill group with delayed loading. Furthermore, there were no significant differences in terms of marginal bone loss between the groups. The authors concluded that immediate functional loading of implants that are placed with a conventional installation technique and with sufficient primary stability may be considered as a valid treatment alternative in a single-tooth replacement.

Other studies dealt with the issue of mobile implants, i.e. implants which could be rotated or depressed with gentle force. It resulted that 93.8 % of mobile implants and 97.5 % of immobile implants osseointegrated. 79.8 % of initially mobile implants and 93.4 % of initially immobile implants were still under function after 36 months. Bone quality was not a significant predictor of survival for implants mobile at placement (Orenstein 1998 & 2000).

Results of implants with rotation at insertion are reported in a prospective case study by Rodrigo et al. (2010). The implants were subdivided in different grades of stability levels at implantation moment (no rotation, light rotation, rotation, rotation and lateral oscillation). Results showed 99.1 % survival rate for implants presenting no rotation and 97.2 % survival rate for implants manifesting a rotation at implant insertion moment, after 6 - 42 months.

A listing of included literature of clinical studies and reports can be found in Tab. 3.

Tab. 3: Overview of clinical studies and reports (studies using osteotomes for implant site preparation are shaded in grey)

Reference	Study Design	Most Relevant Finding
Baldi et al. (2018)	Insertion of one specific implant type (Anyridge, Megagen, Gyeongsan, South Korea); Measuring implant stability using insertion torque and resonance frequency analysis	▪ Insertion torque exceeding 50 Ncm did not result in higher values for resonance frequency analysis ▪ 2 implants with high insertion torque did not osseointegrate after three months of healing
Barone et al. (2016)	Placed 116 implants with low (<50Ncm) or high (>/=50Ncm) insertion torque	▪ 2 implants in the high insertion torque group and 1 implant in the low insertion torque group failed at 12 months follow up ▪ 4 implants in the high insertion torque group and 1 implant in the low insertion torque group showed marginal bone loss >1.5mm ▪ Greater marginal bone loss in high insertion torque group observed ▪ Greater soft tissue recession in high insertion torque group observed ▪ Sites with buccal wall thickness >/= 1 mm were less prone to buccal soft tissue recession
Bashutski et al. (2009)	Case report of four failing mandibular implants placed in healed sites	▪ 1 implant exfoliated after three weeks ▪ 3 implants showed bone loss between 50 % and 90 % ▪ Blood tests revealed no abnormalities ▪ After two months 1 implant was removed due to bone loss ▪ After three months the remaining 2 implants were removed due to bone loss and mobility ▪ Histology showed bony sequestra ▪ Overheating, overcompression, infection and undiagnosed systemic disease discussed as potential causes

Khayat et al. (2013)	Placed implants 4.5 mm in diameter with maximum insertion torque of 50 Ncm (n = 9) or a minimum insertion torque of 70 Ncm (n = 42)	▪ No implant was lost ▪ Mean marginal bone level change in low torque implants was 1.03 mm at time of loading and 1.09 mm after 1 year ▪ Mean marginal bone level change in high torque implants was 0.72 mm at time of loading and 1.24 mm after 1 year
Lee et al. (2019)	Retrospective analysis of 169 implants (different manufacturers) placed with low primary stability i.e. manual rotation and follow up time between 34 days and 9.28 years	▪ Seven implants failed (cumulative survival rate > 94 %) ▪ Failures occurred only when advanced surgical interventions such as guided bone regeneration were needed ▪ Minimal changes in crestal bone levels ▪ Undisturbed healing is necessary
Menicucci et al. (2012)	Placed 36 straight-walled and 21 tapered dental implants in 20 patients	▪ Higher insertion torques required in tapered implants. ▪ 86 % success for tapered and 100 % success for straight-walled implants after 90 days of submerged healing
Motoyoshi et al. (2006)	Placed orthodontic mini implants in patients and loaded them immediately (2 N)	▪ Failing implants in the mandible had been inserted with significantly higher insertion torque as compared to successful implants
Orenstein et al. (1998)	Analysed the database of the Dental Implant Clinical Research Group consisting of 2641 implants	▪ 89 implants were mobile (“could be rotated or depressed with gentle force”) at placement ▪ The use of a bone tap was associated with an increased likelihood of implant mobility ▪ 93.8 % of mobile implants osseointegrated while 97.5 % of immobile implants osseointegrated

Orenstein et al. (2000)	Update to Orenstein 1998	▪ 79.8 % of initially mobile implants were still under function after 36 months ▪ 93.4 % of immobile implants were still under function after 36 months ▪ Bone quality was not a significant predictor of survival for implants mobile at placement ▪ Marginal bone level change between surgery and uncovering: 0.82 mm for mobile implants and 0.98mm for immobile implants
Rodrigo et al. (2010)	Prospectively evaluated (6 - 42 months post restoration) the performance of 4114 implants according to their stability level upon placement (no rotation, light rotation, rotation, rotation and lateral oscillation)	▪ Implants with no rotation showed 99.1 % survival and unstable implants showed 97.2 % survival
Donati et al. (2008)	Placed single implants following site preparation with drills or osteotomes and loaded implants immediately or delayed	▪ Failing implants: 5.5 % osteotome group & immediate loading; 2 % drill group & immediate loading; 0 % drill group & delayed loading ▪ No significant differences in terms of marginal bone loss between groups

5 Discussion

5.1 Insertion torque

Over a long period of time and partly until today, implantologists have striven to insert implants with a high insertion torque. The value of the measured implant primary stability depends, among other things, on the insertion torque used to place an implant. Higher insertion torques result in higher values of primary stability. The resulting high primary stability was seen as the main advantage when compared to low insertion torques, and the resulting high bone-to-implant contact seemed to confirm this. Especially when it comes to immediate loading of implants, clinicians often decide for a high insertion torque, which, due to the higher primary stability values, suggests that the implant is supposedly more secure and more likely to osseointegrate. High insertion torques or the resulting high primary stability, should therefore allow immediate loading of the implants, which is due to the implant being firmly anchored in the bone.

Various studies, however, showed the advantages of lower insertion torques. For example, Sotto-Maior et al. (2010) declared insertion torques over 50 Ncm as high, which can provoke a high compressive stress to peri-implant tissue, thus causing blood supply deficiency and bone necrosis. On the other hand, the authors also stated that mobile implants can negatively affect osseointegration through micromotion. On the basis of their findings they postulated the importance not to overstress the bone by limiting the insertion torque. At the same time, insertion torques should be high enough to prevent mobility of the inserted implant.

Other studies reported high insertion torques due to undersized osteotomies which resulted in higher stress levels in surrounding bone (Udomsawat et al. 2018, Dorogoy et al. 2017, Frisardi et al. 2012). An interesting finding was that cortical bone recorded higher values of stress than trabecular bone, whereas trabecular bone showed higher strains. The results should be further examined to allow stress reduction in cortical areas, even if trabecular areas are stretched. Strains in trabecular bone are less dangerous than high stress in cortical areas, especially considering esthetic and functional aspects. Frisardi et al. (2012) showed that larger osteotomies result in a more uniform stress distribution, which also represents an advantage for the protection of implant surrounding bone structures.

Clinical studies about insertion torque reveal that high torque values do not guarantee a successful implant osseointegration. Baldi et al. (2018) showed that insertion torques over 50 Ncm did not result in higher values of resonance frequency analysis and that even some implants, inserted with high insertion torques, failed to osseointegrate after three months of healing time. Barone et al. (2016) and Motoyoshi et al. (2006) also described more implant failures for the high insertion group than for the low insertion group. In addition, major marginal bone and soft tissue losses were observed in the group of implants with high insertion torques. Coyac et al. (2019) described that high misfit implants had a higher failure rate and showed crestal radio-lucencies, granulation tissue at the bone implant interface, decline in bone to implant contact in the crestal area. Above this, the high strain implants caused a zone of dying osteocytes with cell death and bone resorption exceeded new bone formation. In a retrospective analysis, Lee et al. (2019), described the outcome of implants with low primary stability at the time of insertion. They revealed a survival rate of 94 % and only minimal changes in crestal bone level. On the one hand, we see a certain risk of excessive insertion torques, which can adversely affect the surrounding bones and the osseointegration process, on the other hand, lower torques - despite lower primary stability - can achieve very good results and carry a far lower risk for the long-term success of implants.

With mobile implants, one would expect an unfavourable prognosis from the outset. But the loss rates of mobile implants were limited, as some studies suggest. Orenstein (2000) presented survival rates of 79.8 % for initially mobile implants after three years. A retrospective analysis by Lee et al. (2019) examined the follow-up of 169 implants with low primary stability and concluded that survival rates of 94 % were achieved. Rodrigo et al. (2010) compared the survival rates of implants that did not describe rotation after implantation with unstable implants and came to similar results for both groups (99.1 % no rotation vs. 97.2 % mobile implants). The results demonstrate that the implants, even if they are initially mobile after insertion, have an enormous osseointegration potential and that high primary stability is not a prerequisite for further successful osseointegration and long-term survival.

Other investigations reported the creation of healing chambers in the inner parts of implant threads which was the topic of various studies, such as Berglundh et al. (2003), Campos et al. (2012) and Coelho et al. (2010 & 2013). These healing chambers seem to progress new bone formation very well as they were occupied with coagulum and granulation tissue which later were replaced by provisional matrix and finally followed by new bone formation. The osseointegration process is caused by a callus-like healing pathway which enables a fast implant stabilization. Implants placed with low insertion torques showed a higher tendency in creating healing chambers than implants inserted with high insertion torque.

In contrast, implants with high torque generally had more bone-to-implant contact. However, the higher bone-to-implant contact was significant only during the initial healing phase, as shown by Duyck et al. (2015). The implant threads were almost completely in contact with the bone, which is explained by the undersized osteotomies. The studies showed that the bone in contact with the implant threads first undergoes an inflammatory reaction, then resorption and finally the formation of new bone according to the rules of appositional bone healing.

Direct osseointegration - without prior bone resorption - appears to be more favorable and is possible through intramembranous bone healing initiated by healing chambers. It has been demonstrated that implants inserted with lower insertion torque form more healing chambers due to the lower bone-to-implant contact. Therefore, it has been recommended that undersizing be kept to a minimum to ensure the conditions for creating healing chambers and to reduce the load on the peri-implant bone.

5.2 Bone quality assessment

An important factor for successful osseointegration is the individually available volume and the quality of this bone. A high level of primary stability is sought by clinicians, which often results in increased insertion torques. The primary stability depends, among other things, on bone quality, bone density and the surgical procedure used. Inadequate bone volume often requires prior bone augmentation. However, augmented bone carries the risk of later bone resorption and thus implant failure or loss of aesthetics in cases of soft tissue recession. A retrospective study which dealt with low insertion torque implants described loss rates of 6 % which occurred in implants for which the bone had to be subjected to an augmentative measure beforehand (Lee et al. 2019). Low density bone also poses a difficulty in achieving adequate implant anchorage in the bone. Adequate bone density and sufficient bone quantity are therefore a prerequisite for successful implantation with the aim of subsequent osseointegration of the implant.

The studies of de Oliveira et al. (2007) and Novaes et al. (2005) point to positive effects when additional crestal drills were used during the surgical process. Their results report lower levels of crestal bone loss, greater bone-to-implant contact and higher bone density near the implants. In addition, a buccal wall thickness of more than 1 mm was less prone to buccal soft tissue recession (Barone et al. 2016). Clinicians should therefore consider the use of crestal drills, especially in poor quality bone. To prevent bone resorption with subsequent esthetic soft tissue recession, they should try to maintain sufficient buccal wall thickness.

With the goal of achieving high values of primary stability, clinicians are ready to risk high insertion torques, and the survival rates do not contradict this thanks to the enormous bone regeneration potential. Cha et al. (2015) emphasized that peri-implant cell vitality is of high importance for a successful osseointegration, especially in cases of poor bone quality or a slowed bone formation rate as the result of a systemic or metabolic disease. The authors described a difference between “high” torque and “dangerously high” torque with negative effects on the bone when this threshold was exceeded - without giving further details. Long term success of implants placed with high insertion torque is explained by the time of loading. Bone resorption because of bone compression due to high insertion torque would also lead to new bone formation if implants were not loaded immediately. A danger was described for implants placed with high insertion torque which then were immediately loaded. These implants have a high risk of micromotion after initial bone resorption which could lead to even more bone resorption and implant loosening in the end (Cha et al. 2015). It seems important to evaluate individual patient factors as well, such as patient´s bone quality and bone regeneration ability, and also a possible existence of underlying diseases. In a case report of failed mandibular implants, Bashutski et al. (2009) described overheating, overcompression, infection and undiagnosed systemic disease as possible reasons for implant failure. The prior assessment of bone quality and diagnosis of possible underlying diseases is therefore an important preliminary examination before implantation.

5.3 Refined implant design

Various included studies dealt with an innovative implant design which could have a positive effect on osseointegration. They compared conventional implant designs with different experimental implant designs and revealed some interesting results that need further research. They clearly showed positive effects on osseointegration and the prevention or reduction of bone resorption. The new implant designs try to achieve a sufficient primary stability while reducing the insertion torque, which should later lead to successful osseointegration and reduced bone resorption.

Taing-Watson et al. (2015), Menicucci et al. (2012) and Lee et al. (2010) compared cylindrical vrsus tapered implant designs and their effects on insertion torque and peri-implant bone. The studies concluded that tapered implants resulted in greater insertion torque, but also in higher levels of bone damage. Menicucci et al. (2012) even reported of lower success rates for tapered implants. A specially modified experimental implant, which was designed to create high values of insertion torque, revealed greater bone loss, larger marginal bone defects, a lower overall peri-implant bone fraction and higher peri-implant strain values (Duyck et al. 2010). Even if pre-drilling can help to lower the level of microdamage, implantologists should be aware of the risks of tapered implants and, if the individual situation allows, switch to cylindrical implants.

Based on implant geometry, Yin et al. (2019) investigated a new model of tri-oval implant design, aiming to create a combination of high strain and low strain peri-implant environment that would ensure both primary implant stability and rapid as well as gentle osseointegration. Results showed at the minima lower compressive strain, less osteocyte apoptosis and bone resorption than compared to round implants. Beyond this, the rate of new bone accrual was also faster around the tri-oval implants. At the maxima, on the other hand, a similar distribution of dead and dying cells as in round implants occurred. This innovative implant design seems to combine adequate primary stability values with a gentle osseointegration process. It was without resorption and without high stress on the bone as we know it from conventional implants with high insertion torques, so that further studies on this innovative design should be undertaken.

Different authors described - depending on implant design and preparation technique - the occurrence of bone debris particles (bone chips) in implant osteotomies, especially in the apical region (Jimbo et al. 2014, Nevins et al. 2012). Jimbo et al. (2014) compared an implant with cutting flutes on every thread to a conventional implant system showing that the experimental implant design did neither induce multinucleated giant cells nor bone resorption in peri-implant bone. The insertion torques were also less, compared to the conventional implant group. The cutting flutes on every thread enabled a gentler implantation accompanied with less stress to peri-implant bone. The authors also described bone chips in healing chambers between threads with cutting flutes. These bone chips seem to have osteogenic potential. Both implant designs and surgical techniques that favor the formation of bone chips should therefore be investigated further so that they can be used in practice.

Yadav et al. (2012) researched in an animal study the different effects of self-drilling and self-tapping implants on bone. The study only evaluated microdamage at the time of implant placement and in dead bone. The authors noted that it is not clear if dead bone and live bone react identical. Nevertheless, results revealed greater microdamage of cortical bone by self-drilling implants without a pilot hole. This yields that previous osteotomy preparation is less stressful than self-drilling implant systems or undersized osteotomies. Similar results are presented in studies by Udomsawat et al. (2018) and Bartold et al. (2011). They showed that stress results from implant insertion, not from osteotomy creation. Clinicians should not shrink back from an adequate osteotomy preparation, even under the risk of reducing insertion torque values. The advantages in terms of bone survival rate outweigh here and speak for a reduction of insertion torque to ensure long-term success.

5.4 Limitations

The publications that have been included in this work are characterized by a large number of topics examined and study designs used which makes it difficult to compare the individual contributions in detail. Furthermore, the clinical studies included in this work do not have a high level of evidence. For example, only three randomised clinical trials on the topic at hand were found, of which only two could be accepted in this thesis.

5.5 Conclusion

While the implantologist can hardly influence the individual factors of the patient, negative effects on the alveolar process can be minimized by a controlled insertion torque that takes into account the biological pecularities of the implant healing process. Since the precise threshold values for the mechanical load capacity of the alveolar bone are not exactly known, the assessment of bone quality prior to implant placement is of great importance. This allows both the surgical protocol and the prosthetic loading protocol to be adapted to the patient situation. Future implant systems should feature a refined macrodesign that derives implant stability also from trabecular bone instead of merely compressing the cortical layer.

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7 Publications

The results of this review were accepted as poster presentation at the 33th Annual Conference of the German Association of Oral Implantology (DGI): Marin Ikar, Tanja Grobecker-Karl, Matthias Karl, Constanze Steiner (2019) Effekt der Knochenkompression während der Implantatinsertion auf die bukkale Lamelle – eine Literaturübersicht.

Parts of the thesis are published in Quintessence International: Ikar M, Grobecker-Karl T, Karl M, Steiner C (2020) Mechanical Stress During Implant Surgery and Its Effects on Marginal Bone: A Literature Review. Quintessence Int 51:142-150.

8 Appendix

The following represents a tabular overview of all articles excluded from this review (table 4).

Tab. 4: Overview of excluded papers

Reference	Title	Reason for exclusion
Albogha et al. 2015	Letter to the Editor, "Multiscale Analyses of the Bone-implant Interface".	No findings - Commentary
Allahbakhshi et al. 2017	Immediate vs. delayed endosseous integration of maxi implants: a torque removal animal study.	No relevant data (Immediate loading; Reverse torque testing; Insertion not considered)
Agustín-Panadero et al. 2019 A	Influence of Implant-Prosthetic Connection on Peri-Implant Bone Loss	Bone levels evaluated 24 months after implant placement / prosthetic reconstruction
Agustín-Panadero et al. 2019 B	A Prospective Clinical Trial with 2-Year Follow-up	Bone hight change measerud 2 years later
Bardyn et al. 2010	Prediction of dental implant torque with a fast and automatic finite element analysis: a pilot study.	Development of a FE based method for predicting insertion torque; not focused on bone damage
Bentolila et al. 1998	Intracortical remodeling in adult rat long bones after fatigue loading.	Orthopedics (fatigue loading of ulnae)
Bickley et al. 1998	Self-tapping versus standard tapped titanium screw fixation in the upper extremity.	Orthopedics
Bolm et al. 2007	Self-drilling and self-tapping miniscrews for osteosynthesis fixture after LeFort I osteotomy: An ex vivo trial for primary stability and a randomized clinical study	Inconsistent reporting on bone damage in Abstract vs. Discussion
Bonfante et al. 2011	Early bone healing and biomechanical fixation of dual acid-etched and as-machined implants with healing chambers: an experimental study in dogs.	Focus on implant surfaces not on bone stress

Calandriello et al. 2003	Immediate functional loading of Brånemark System implants with enhanced initial stability: a prospective 1- to 2-year clinical and radiographic study.	Immediate loading; MBL after 12 months and thereafter; cannot be related to stress during implant insertion
Cha et al. 2015	Strain of bone-implant interface and insertion torque regarding different miniscrew thread designs using an artificial bone model.	No relevant data (Sawbones strain measurements after orthodontic implants)
Chang et al. 2012	Effects of thread depth, taper shape, and taper length on the mechanical properties of mini-implants.	FEA and in vitro study on design parameters of orthodontic mini implants; focus on stress in implants
Chang et al. 2017	Effect of microthreads on coronal bone healing of narrow-diameter implants with reverse-tapered design in beagle dogs.	Evaluated the effect of microthreads; not focused on bone damage
Checa et al. 2010	Effect of cell seeding and mechanical loading on vascularization and tissue formation inside a scaffold: a mechano-biological model using a lattice approach to simulate cell activity.	FEA of bone scaffolds; no screws simulated
Chen et al. 2019	A Novel Osteotomy Preparation Technique to Preserve Implant Site Viability and Enhance Osteogenesis	No implants placed; focus on osteotomy preparation
Cho et al. 2012	Effects of predrilling depth and implant shape on the mechanical properties of orthodontic mini-implants during the insertion procedure.	In vitro study on orthodontic mini implants – Sawbones
Chowdhary et al. 2013	Biomechanical evaluation of macro and micro designed screw-type implants: an insertion torque and removal torque study in rabbits. Clin Oral Implants Res 24:342-346.	Different implant designs; bone stress not evaluated
Chou et al. 2010	Combined effects of implant insertion depth and alveolar bone quality on periimplant bone strain induced by a wide-diameter, short implant and a narrow-diameter, long implant.	FEA under loading

Chowdhary et al. 2015	Influence of Micro Threads Alteration on Osseointegration and Primary Stability of Implants: An FEA and In Vivo Analysis in Rabbits.	FEA under loading; animal results only speculation about differences in bone morphology; could not properly develop high and low insertion torque groups; focus on the effect of microthreads
Cobo-Vázquez et al. 2018	Effect of the lack of primary stability in the survival of dental implants.	Not focused on marginal bone; only reporting implant survival
Coelho et al. 2015	Osseointegration of Plateau Root Form Implants: Unique Healing Pathway Leading to Haversian-Like Long-Term Morphology.	Book chapter; no real study
Cory et al. 2010	Compressive axial mechanical properties of rat bone as functions of bone volume fraction, apparent density and micro-ct based mineral density.	Not related to oral implants
Degidi et al. 2009	Is insertion torque correlated to bone-implant contact percentage in the early healing period? A histological and histomorphometrical evaluation of 17 human-retrieved dental implants.	Heterogeneous group of retrieved implants; only overall description of histologic images
Degidi et al. 2013	Development of a new implant primary stability parameter: insertion torque revisited.	Focus on insertion energy but not on potential bone damage
Degidi et al. 2015	Influence of underpreparation on primary stability of implants inserted in poor quality bone sites: an in vitro study.	Focus on insertion energy but not on potential bone damage
Degidi et al. 2017	Influence of Stepped Osteotomy on Primary Stability of Implants Inserted in Low-Density Bone Sites: An In Vitro Study.	Focus on insertion energy but not on potential bone damage
Dhore et al. 2008	In vitro osteogenic potential of bone debris resulting from placement of titanium screw-type implants.	no focus on stress in marginal bone; show that bone debris has osteogenic potential
Di Stefano et al. 2018	The insertion torque-depth curve integral as a measure of implant primary stability: An in vitro study on polyurethane foam blocks.	Implant insertion only not on effect of stress and strains; focus on novel bone evaluation technique
Di Stefano et al. 2019	Correlation between Implant Geometry, Bone Density, and the Insertion Torque/Depth Integral: A Study on Bovine Ribs.	Implant insertion only not on effect of stress and strains; focus on novel bone evaluation technique

Dos Santos et al. 2011	The effects of superficial roughness and design on the primary stability of dental implants.	implant design study in polyethylene; not focused on bone reaction
Eckert et al. 2019	Immediately Loaded Fixed Full-Arch Implant-Retained Prosthesis: Clinical Analysis When Using a Moderate Insertion Torque.	Full arch restorations; effect of torque on implant performance cannot be inferred; immediate loading
Elias et al. 2012	Influence of implant shape, surface morphology, surgical technique and bone quality on the primary stability of dental implants.	Not focused on potential bone damage
Falco et al. 2018	Correlation Between Implant Geometry, Implant Surface, Insertion Torque, and Primary Stability: In Vitro Biomechanical Analysis.	No evaluation of potential bone damage
Freitas et al. 2012	The effect of implant design on insertion torque and immediate micromotion.	Sawbones; comparison of different implant designs
Garetto et al. 1995	Remodeling dynamics of bone supporting rigidly fixed titanium implants: a histomorphometric comparison in four species including humans.	Analysis of osseointegrated implants; no information about bone damaged during insertion
González-Martín et al. 2012	CBCT fractal dimension changes at the apex of immediate implants placed using undersized drilling.	Immediate implant placement in extraction sockets; marginal bone not evaluated
Hasan et al. 2017	Experimental investigation of commercial small diameter dental implants in porcine mandibular segments.	Loading considered
Hasan et al. 2014	Biomechanical finite element analysis of self-tapping implants with different dimensions inserted in two bone qualities.	Osseointegrated implants considered
Helms et al. 2015	Response to Letter to the Editor, "Multiscale Analyses of the Bone-implant Interface".	Commentary
Hermann et al. 2007	Factors influencing the preservation of the periimplant marginal bone.	Not a scientific study; opinion article and clinical examples
Hoshaw et al. 1994	Mechanical Loading of Brånemark Implants Affects Interfacial Bone Modeling and Remodeling.	Not focused on strains generated by implant placement; loading experiment

Huang et al. 2011	Initial stability and bone strain evaluation of the immediately loaded dental implant: an in vitro model study.	Sawbones measurements under loading
Huang et al. 2018	Application of Plasma Sprayed Zirconia Coating in Dental Implant: Study in Implant.	Effect of bone stress not studied
Isidor 2006	Influence of forces on peri-implant bone.	Review
Joos et al. 2005	Strain driven fast osseointegration of implants.	Not focussed on bone stress from insertion but immediate loading
Kadkhodazadeh et al. 2013	Radiographic evaluation of marginal bone levels around dental implants with different designs after 1 year.	no information on insertion torque given; only different implant macrogeometries; MBL data only at 12 months follow-up
Khouja et al. 2019	A Critique of Resonance Frequency Analysis and a Novel Method for Quantifying Dental Implant Stability in Vitro.	Development of novel implant stability measurement technique
Kim et al. 2008	Comparison of stability between cylindrical and conical type mini-implants. Mechanical and histological properties.	Bone evaluated after orthodontic loading
Kim et al. 2014	Reosseointegration of mechanically disintegrated implants in dogs: mechanical and histometric analyses.	Temporary removal of implants during healing; no focus on marginal bone or stress
Kim et al. 2011	Primary stability and self-tapping blades: biomechanical assessment of dental implants in medium-density bone.	Design study, Sawbones, no focus on bone damage
Kitamura et al. 2004	Biomechanical aspects of marginal bone resorption around osseointegrated implants: considerations based on a three-dimensional finite element analysis.	FEA under implant loading
Leonard et al. 2009	A study of the bone healing kinetics of plateau versus screw root design titanium dental implants.	Compared screw form (minimal undersizing) and platform implants (no undersizing) finding no difference; use of different implant design squestionable
Li et al. 2017	Relationships among Bone Quality, Implant Osseointegration, and Wnt Signaling.	Implants placed in oversized osteotomies in Types I and III bone

Liu et al. 2018	Effects of mechanical loading on cortical defect repair using a novel mechanobiological model of bone healing.	Orthopedics (tibia defects; loading)
Luzi et al. 2009	Immediate loading of orthodontic mini-implants: a histomorphometric evaluation of tissue reaction.	Compared immediately loaded and unloaded orthodontic implants in monkeys
Makaray et al. 2011	Peak insertion torque correlated to histologically and clinically evaluated bone density.	Bone quality assessment only but no information on stress / strain
Makaray et al. 2017	Standard Drilling Versus Ultrasonic Implant Site Preparation: A Clinical Study at 4 Weeks After Insertion of Conical Implants.	Do not evaluate different stress levels
Marão et al. 2017	Cortical and Trabecular Bone Healing Patterns and Quantification for Three Different Dental Implant Systems.	Compared bone healing of three different implant systems; undersizing and insertion torques not given hence the amount of stress cannot be inferred
Marin et al. 2010	Histomorphologic and histomorphometric evaluation of various endosseous implant healing chamber configurations at early implantation times: a study in dogs.	Compared different healing chamber configurations but not different levels of bone stress
Molly 2006	Bone density and primary stability in implant therapy.	Review
Monje et al. 2019	Relationship Between Primary/Mechanical and Secondary/Biological Implant Stability.	Review
Mumcu et al. 2011	Marginal bone loss around implants supporting fixed restorations.	Retrospective analysis of MBL after loading; implant insertion not considered
Norton 2011	The influence of insertion torque on the survival of immediately placed and restored single-tooth implants.	Immediate implant placement in extraction sockets
Norton 2017	The Influence of Low Insertion Torque on Primary Stability, Implant Survival, and Maintenance of Marginal Bone Levels: A Closed-Cohort Prospective Study.	Also considered immediate implant placement in extraction sockets
Novsak et al. 2015	Machine-driven versus manual insertion mode: influence on primary stability of orthodontic mini-implants.	Only static evaluation; no information about potential bone damage

Oh et al. 2002	The causes of early implant bone loss: myth or science?	Review
O'Sullivan et al. 2000	Measurements comparing the initial stability of five designs of dental implants: a human cadaver study.	Only focused on primary stability; not focused on potential bone damage
O'Sullivan et al. 2004	Influence of implant taper on the primary and secondary stability of osseointegrated titanium implants.	Bone reaction not considered, EXP2 not fully inserted, groups pooled
Ottoni et al. 2005	Correlation between placement torque and survival of single-tooth implants.	No focus on stress / strain; correlate survival with insertion torque in immediate loading
Pei et al. 2017	Contribution of the PDL to Osteotomy Repair and Implant Osseointegration.	Role of PDL remnants in extraction socket healing
Pozzi et al. 2015	Immediate loading with a novel implant featured by variable-threaded geometry, internal conical connection and platform shifting: three-year results from a prospective cohort study.	No differentiation with respect to insertion torque; MBL after 3 years but not postsurgical
Pozzi et al. 2016	Immediate Loading of Conical Connection Implants: Up-to-2-Year Retrospective Clinical and Radiologic Study.	No focus on bone strain; included immediate implant placement
Rittel et al. 2017	Modelling dental implant extraction by pullout and torque procedures.	Evaluates removal torque tests; does not focus on potential damage of bone during implant insertion
Romeed et al. 2013	Marginal bone loss influence on the biomechanics of single implant crowns.	FEA of implant loading
Rundle et al. 2006	Microarray analysis of gene expression during the inflammation and endochondral bone formation stages of rat femur fracture repair.	Orthopedics (femur fracture)
Sasaki et al. 2008	Bone metabolic activity around dental implants under loading observed using bone scintigraphy.	Implants loaded
Sennerby & Gottlow 2008	Clinical outcomes of immediate/early loading of dental implants. A literature review of recent controlled prospective clinical studies.	Review

Sennerby et al. 2015	Two different implant designs and impact of related drilling protocols on primary stability in different bone densities: an in vitro comparison study.	Comparison of different implant designs; not focused on potential bone damage
Sierra-Rebolledo et al. 2016	Primary Apical Stability of Tapered Implants Through Reduction of Final Drilling Dimensions in Different Bone Density Models: A Biomechanical Study.	Implant stability assessed in simulated extraction sockets realized in Sawbones
Slaets et al. 2006	Early cellular responses in cortical bone healing around unloaded titanium implants: an animal study.	Describe cellular response around implants following insertion; not focused on bone stress
Slaets et al. 2007	Early trabecular bone healing around titanium implants: a histologic study in rabbits.	Describe cellular response around implants following insertion; not focused on bone stress
Stanford & Brand (1999)	Toward an understanding of implant occlusion and strain adaptive bone modeling and remodeling.	Review
Stocchero et al. 2016	Biomechanical, Biologic, and Clinical Outcomes of Undersized Implant Surgical Preparation: A Systematic Review.	Review
Strbac et al. 2014	Thermal effects of a combined irrigation method during implant site drilling. A standardized in vitro study using a bovine rib model.	Temperature measurements during drilling only; no implants placed
Sugiura et al. 2000	Evaluation of threshold stress for bone resorption around screws based on in vivo strain measurement of miniplate.	Fracture plate fixation
Tabassum et al. 2012	Translocation of autogenous bone particles to improve peri-implant osteogenesis.	Not focused on bone stress; evaluated biologic potential of bone covered implants
Takashi et al. 2011	Regulatory mechanism of osteoclastogenesis by RANKL and Wnt signals.	Review

Taylor et al. 2007	Living with cracks: damage and repair in human bone.	Review
Trisi et al. 2013	Primary stability, insertion torque, and bone density of conical implants with internal hexagon: is there a relationship?	In vitro measurements of micromotion
Turkyilmaz et al. 2009	Biomechanical aspects of primary implant stability: a human cadaver study.	No focus on bone damage
Ueno et al. 2018	A stepwise under-prepared osteotomy technique improves primary stability in shallow-placed implants: a preliminary study for simultaneous vertical ridge augmentation.	Study in Sawbones; no evaluation of potential bone damage
Urdaneta et al. 2012	The effect of implant size 5 × 8 mm on crestal bone levels around single-tooth implants.	Not related to implant insertion
van Staden et al. 2008	Step-wise analysis of the dental implant insertion process using the finite element technique.	Simulated only regular implant insertion process
Verborgt et al. 2000	Loss of osteocyte integrity in association with microdamage and bone remodeling after fatigue in vivo.	Orthopedics (fatigue loading of ulnae)
Wang et al. 2014	Repair of microdamage in osteonal cortical bone adjacent to bone screw.	Orthopedics, Traumatology
Wang et al. 2016	Relative Contribution of Trabecular and Cortical Bone to Primary Implant Stability: An In Vitro Model Study.	Insertion tests in sawbones; focus on insertion torque not on strains / stresses in bone
Wang et al. 2015	The effect of implant design and bone quality on insertion torque, resonance frequency analysis, and insertion energy during implant placement in low or low- to medium-density bone.	Torque and ISQ in Sawbones
Wang et al. 2017 A	Biophysical regulation of osteotomy healing: An animal study.	No implants placed; only osteotomy healing evaluated
Wang et al. 2017 B	Effects of Condensation on Peri-implant Bone Density and Remodeling.	Bone condensation

Wilmes et al. 2011	Impact of bone quality, implant type, and implantation site preparation on insertion torques of mini-implants used for orthodontic anchorage.	Not focused on bone damage
Wilson et al. 2016	Tapered Implants in Dentistry: Revitalizing Concepts with Technology: A Review.	Review
Yalçın et al. 2019	Three-Dimensional Finite Element Analysis of the Effect of Endosteal Implants with Different Macro Designs on Stress Distribution in Different Bone Qualities.	Simulation of masticatory loading
Yang et al. 2008	Relationship between implant stability measured by resonance frequency analysis (RFA) and bone loss during early healing period. Oral Surg Oral Med Oral Pathol Oral Radiol Endod 105:e12-19.	Did not compare different groups; only describe bone loss and no change in ISQ during healing
Yoo et al. 2014	A comparison of tapered and cylindrical miniscrew stability.	Clinical comparison of cylindrical and tapered orthodontic implants; effects of stress on bone cannot be inferred
Zanardi et al. 2015	Stress Distribution Around Dental Implants Placed at Different Depths.	Loading simulated
Zheng et al. 2014	Three dimensional finite element analysis of a novel osteointegrated dental implant designed to reduce stress peak of cortical bone.	FEA of new implant type after osseointegration

9 Curriculum Vitae

Aus datenschutzrechtlichen Gründen wird der Lebenslauf in der elektronischen Fassung der Dissertation nicht veröffentlicht.

10 Gratitude

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