Effects of pilot hole size on miniscrew insertion torque and synthetic bone transparency

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ผลกระทบของขนาดรูนำร่องต่อแรงบิดระหว่างการฝังวัสดุฝังเกลียวขนาดเล็กและความโปร่งใสของกระดูกสังเคราะห์

น.ส.ชุติมณฑน์ ฑีฆวาณิช

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรดุษฎีบัณฑิต
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ชุติมณฑน์ ฑีฆวาณิช : ผลกระทบของขนาดรูนำร่องต่อแรงบิดระหว่างการฝังวัสดุฝังเกลียวขนาดเล็กและความโปร่งใสของกระดูกสังเคราะห์. (Effects of pilot hole size on miniscrew insertion torque and synthetic bone transparency) อ.ที่ปรึกษาหลัก : รศ. ทพ. ดร.ไพบูลย์ เตชะเลิศไพศาล

ในปัจจุบันมีการใช้วัสดุฝังเกลียวขนาดเล็กหรือมินิสกรูในทางทันตกรรมจัดฟันอย่างแพร่หลายแต่ก็ยังมีข้อเสียที่พบอยู่ รวมถึงการหลุดของมินิสกรูซึ่งอาจเกิดได้จากการละลายของกระดูกโดยรอบจากการที่มีความเสียหายของกระดูกหรือไมโครดาเมจมากเกินไปประหว่างการปักมินิสกรู การกรอรูนำร่องให้ทะลุผ่านกระดูกทึบหรือกระดูกคอร์ติคัลมีผลช่วยลดไมโครดาเมจที่มากเกินไปได้ แต่ถ้าขนาดของรูนำร่องใหญ่เกินไปก็จะมีผลทำให้ความเสถียรปฐมภูมิแย่ลง ดังนั้น การวิจัยนี้จึงใช้วัสดุที่คล้ายคลึงกับกระดูกมนุษย์ในการประเมินไมโครดาเมจและความเสถียรปฐมภูมิเพื่อศึกษาหาขนาดรูนำร่องที่เหมาะสมที่จะช่วยลดความเสี่ยงที่จะทำให้มินิสกรูหลุดได้ โดยวัสดุที่ใช้ในการทดลองคือมินิสกรูที่ผลิตจากไทเทเนียมอัลลอย (Ti6Al4V) และกระดูกคอร์ติคัลสังเคราะห์ความหนา 1 มิลลิเมตร แรงอัดหลายขนาดได้ถูกนำมาใช้ในการทดสอบความแข็งเพื่อประเมินไมโครดาเมจที่เกิดขึ้นจากการวัดขนาดพื้นที่ของกระดูกที่มีการเปลี่ยนสีหลังจากที่ได้รับความเค้นจากแรงอัด ในอีกการทดลองมีการกรอขนาดรูนำร่องตั้งแต่ 0.7 ถึง 1.2 มิลลิเมตรแล้วปักมินิสกรูเข้าไปในรูนำร่อง จากนั้นวัดขนาดพื้นที่ของกระดูกที่มีการเปลี่ยนสีหลังจากที่ได้รับความเค้นจากแรงอัดและวัดแรงบิดสูงสุดขณะปักและขณะเอามินิสกรูออกเพื่อใช้ประเมินความเสถียรปฐมภูมิ ผลจากการทดลองพบว่าพื้นที่ของกระดูกที่มีการเปลี่ยนสีในกลุ่มขนาดรูนำร่อง 1.0 ถึง 1.2 มิลลิเมตรมีขนาดเล็กกว่ากลุ่มอื่นอย่างมีนัยสำคัญทางสถิติ ($p < 0.05$) ในขณะเดียวกันพบว่ากลุ่มขนาดรูนำร่อง 0.9 และ 1.0 มิลลิเมตรมีความเสถียรปฐมภูมิสูงกว่ากลุ่มอื่นๆ จากการศึกษานี้จึงสรุปได้ว่าสามารถนำกระดูกสังเคราะห์ที่มีคุณสมบัติเลียนแบบกระดูกมนุษย์มาใช้ในการประเมินไมโครดาเมจของกระดูกคอร์ติคัลและความเสถียรปฐมภูมิของมินิสกรูได้

สาขาวิชา	ทันตกรรมจัดฟัน	ลายมือชื่อนิสิต	....
ปีการศึกษา	2563	ลายมือชื่อ อ.ที่ปรึกษาหลัก	....

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Chutimont Teekavanich : Effects of pilot hole size on miniscrew insertion torque and synthetic bone transparency. Advisor: Assoc. Prof. PAIBOON TECHALERTPAISARN, Ph.D.

Orthodontic miniscrews have gained popularity; however, they have some drawbacks, including screw loosening due to bone resorption caused by excess microdamage during screw insertion. Pilot hole preparation through the cortical bone is considered beneficial to avoid such microdamage, while an overly large pilot hole impairs primary stability. Hence, we used a human bone analogue to evaluate the microdamage and primary stability to estimate the optimal pilot hole size that would minimize the screw loosening risk. Ti6Al4V miniscrews and 1.0-mm-thick synthetic cortical bone pieces were prepared. Various compressive loads were applied in indentation tests to bone surfaces, and the microdamaged areas were confirmed as stress-whitening zones. Screw insertion tests were performed in which a miniscrew was inserted into the test pieces' pilot hole with a diameter of 0.7–1.2 mm in 0.1-mm intervals, and the stress-whitening area was measured. The insertion and removal torque were also measured to evaluate primary stability. The stress-whitening areas of the 1.0–1.2 mm pilot hole size groups were significantly smaller than those of the other groups ($p < 0.05$), whereas the 0.9- and 1.0-mm pilot hole diameter groups showed higher primary stability than other groups. In conclusion, the bone analogue could be utilized to evaluate microdamage in cortical bones and the primary stability of miniscrews.

Field of Study:	Orthodontics	Student's Signature ....
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Chutimont Teekavanich

TABLE OF CONTENTS

LIST OF TABLES

Page

LIST OF FIGURES

Chapter 1

Introduction

1.1 Background and rationale

Miniscrew implants have been used increasingly as temporary anchorage devices (TADs)(1) due to their various advantages, such as ease of use, minimal surgical intervention, elimination of patient's compliance and low cost, which are beneficial for orthodontic treatment(2). A variety of complicated treatments can be successfully accomplished by using a miniscrew because it can provide absolute anchorage and thus avoid undesirable tooth movement. However, the success rate of treatment using orthodontic miniscrews has been reported to be over 70%(3), depending on screw types, placement methods and host characteristics, which is considerably lower than that of conventional dental implants used in prosthodontics, reported to be around 98% or 99%(4, 5).

Primary stability plays an important role in the success of orthodontic miniscrews. The most common and effective method to evaluate miniscrew primary stability is torque analysis by measuring the insertion torque value when tightening the miniscrew into the bone(6-8). With excessive insertion torque, a high level of stress can be generated, resulting in substantial microdamage to the bone and bone necrosis. On the other hand, if there is too low insertion torque, the screw can easily move during orthodontic loading. Thus, poor stability and failure of the miniscrew will be resulted(9).

Another issue that should be taken into consideration is a microdamage, which is a permanent deformation of the bone microstructure on loading(10). When evaluated histologically using an animal model, there are two types of the damage. The first, termed 'microcracks', consists of linear defects typically 100 μm in length. The second, termed 'diffuse damage', is a cluster of microcracks that are too small to be distinguished from one another(11). The accumulation of excess microdamage can produce local ischemia, bone necrosis, bone remodeling and premature loss of the miniscrew(12). If there is an appropriate amount of microdamage, it can prevent fatigue fracture of the miniscrew, and increase stability and longevity because of bone remodeling. In contrast, if there is an intensive and broad area of microdamage, it will weaken the bone and compromise the stability of the miniscrew(10).

Orthodontic miniscrews are more commonly inserted without pilot holes because the self-drilling procedure is simpler than self-tapping procedure(10), despite greater microdamage occurring with the former procedure(10, 12, 13). To avoid such microdamage, pilot hole preparation through the cortical bone is recommended as it reduces compressive load to the cortical bone during screw insertion. A pilot hole is always necessary for the insertion of self-tapping miniscrews, and predrilling into an area of thick cortical bone is also recommended, even when a self-drilling miniscrew is used, in order to remain in the ideal torque range(14). However, an overly large pilot hole impairs primary stability. Kim(1) has been summarized that one of the possible factors that can affect the stability of the miniscrew is the pilot hole size or pre-drilled hole diameter.

Increases in pilot hole size have been reported with decreases in miniscrew insertion torque value because less bone needs to be displaced(8, 15, 16). However, some studies reported different results. Battula et al(17) showed the outcome using bone screws for rigid fixation that the highest insertion torque value was not from the smallest pilot hole size. Another study reported that the insertion torque of a 2.0-mm diameter orthodontic miniscrew was higher when inserted into a larger pilot hole(8). Therefore, in order to improve the success rate of orthodontic miniscrews, it is important to find the optimum pilot hole diameter that reduces microdamage while providing primary stability.

There are several articles focusing on the optimum pilot hole diameter for the miniscrew(8, 18). However, in these papers, the diameter was determined with characteristics such as the Periotest value or the insertion torque, which are related to the screw's stability and not related to the minimization of risk factors related to screw loosening (e.g., magnitude of microdamage). Moreover, reproducibility in the experiments and extrapolation to clinics might be questionable because rodent or swine models were utilized(8, 18, 19). On the other hand, the human bone analogue enabled us to prepare uniform test pieces and was considered ideal for the quantitative evaluation of bone damage(20, 21). Thus, the objective of this study was to utilize a human bone analogue to evaluate cortical bone microdamage around the miniscrew and to evaluate the primary stability of the miniscrew to estimate an optimal pilot hole size that could minimize the risk of screw loosening.

1.2 Research questions

1.2.1 Which pilot hole size provided greatest primary stability by using 1.3-mm diameter miniscrews in synthetic cortical bone?

1.2.2 Which pilot hole size caused appropriate amount of microdamage of the cortical bone by using 1.3-mm diameter miniscrews in synthetic cortical bone?

1.2.3 Was it able to use synthetic cortical bone as human bone analogue to evaluate cortical bone microdamage around the miniscrew?

1.3 Research objectives

1.3.1 To evaluate cortical bone microdamage around the miniscrew using a human bone analogue.

1.3.2 To evaluate the primary stability of the miniscrew to estimate an optimum pilot hole size that could minimize the risk of miniscrew loosening.

1.4 Research hypothesis

Null hypothesis: There were no differences regarding primary stability and microdamage area among six difference sizes of pilot hole.

Alternative hypothesis: There were differences regarding primary stability and microdamage area among six difference sizes of pilot hole.

1.5 Benefits of this study

This study provided information focusing on miniscrew primary stability and area of stress-whitening, indicating microdamage of the cortical bone, in relation to varying six pilot hole sizes. It has been known that rat, larger animals or human has different cortical bone structure and properties(22). The use of synthetic bone is recommended for biomechanical testing studies to represent human bone. Therefore, synthetic cortical bone was used in this study to examine primary stability of the miniscrews. Furthermore, stress-whitened area of the bone, caused by miniscrew insertion torque, was evaluated using synthetic bone for the first time due to the reason that it might refer to the microdamage of the cortical bone, which has been investigated using only the animal bones(10, 11, 13, 23, 24).

1.6 Keywords

- Orthodontic miniscrew
- Microdamage
- Primary stability
- Pilot hole
- Synthetic cortical bone

1.7 Conceptual framework

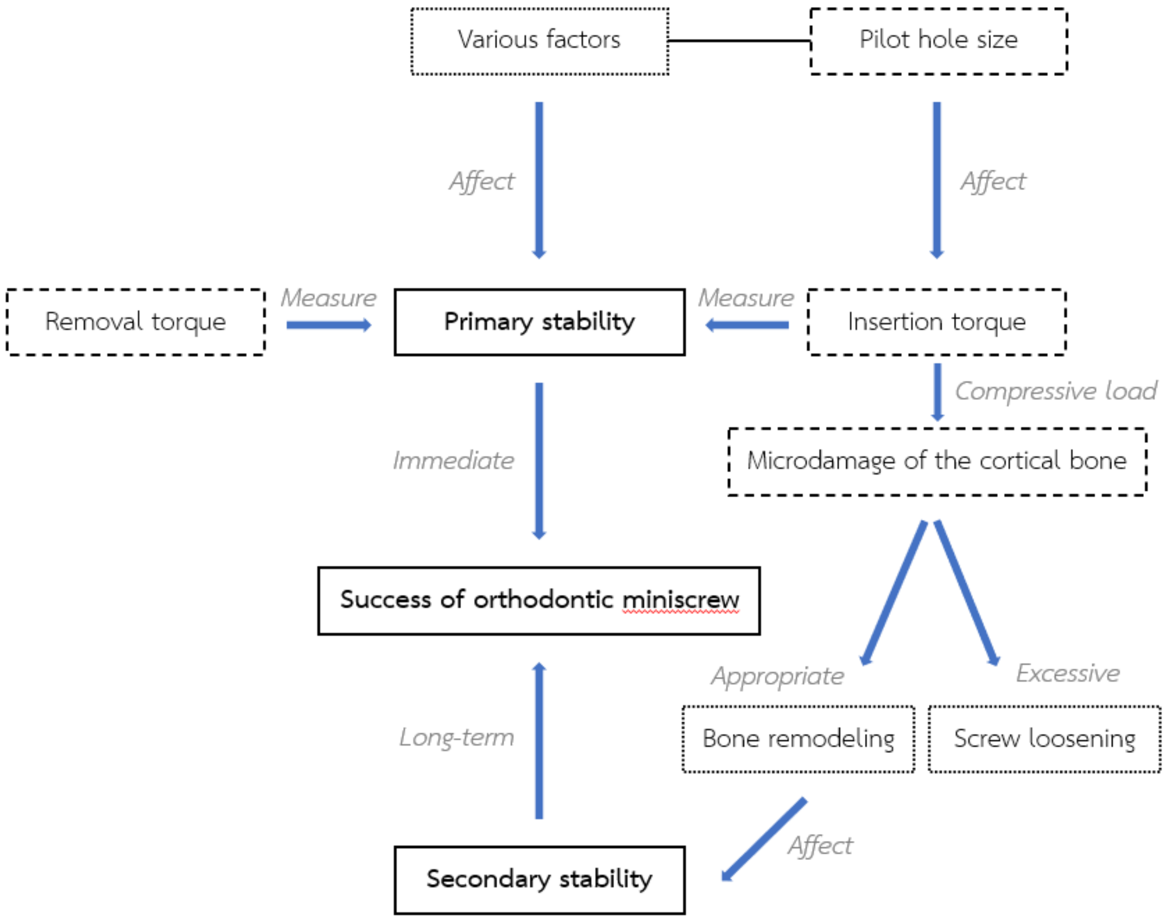


Figure 1 *Conceptual framework of this study.*

Chapter 2

Review of literatures

2.1 Temporary anchorage devices (TADs)

Orthodontic anchorage is defined as “resistance to unwanted tooth movement”(25, 26), or the amount that allowed reactive unit movement(27). According to Gianelly and Goldman’s suggestion(28), the terms of maximum, moderate, and minimum are used to determine the amount of teeth, both active and reactive units, that can be moved when there is an applied force. Teeth, intraoral appliances and extraoral appliances are used traditionally to control anchorage. However, there are many limitations to completely control all aspects of tooth movement. This led to the development of new devices to overcome this obstacle.

Temporary anchorage devices (TADs) are fixed to bone impermanently to enhance orthodontic anchorage. They can provide absolute anchorage, which is difficult to achieve by conventional anchorage systems. Cope(27) classified TADs as biocompatible and biological types, with each sub-classifications (Figure 2). Cornelis et al(29) simply categorized TADs as miniplates and miniscrews. Miniplates have been used in orthognathic surgery for rigid fixation firstly and then have been modified to use as a temporary skeletal anchorage for tooth movement(30), with the survival rate of over 90%(31). Miniscrews are much smaller, which can be placed in several locations for anchorage control. Furthermore, miniscrews can provide the anchorage without the need of patient co-operation, leading to simplification of the orthodontic treatment(32-34).

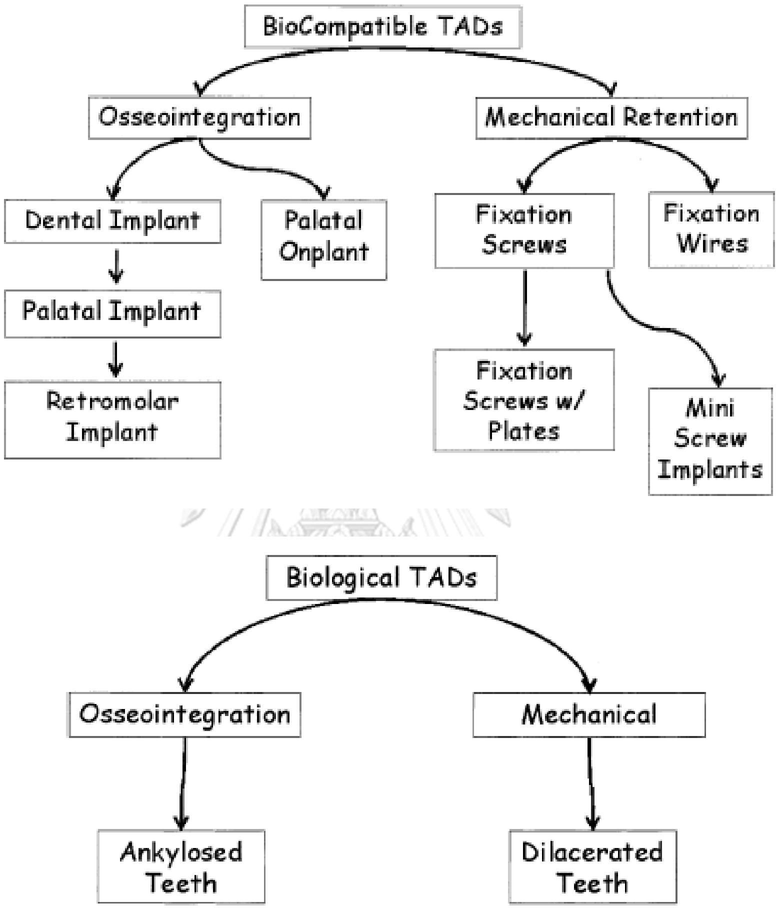


Figure 2 *Biocompatible and biological temporary anchorage devices (TADs) classification (27).*

2.2 Orthodontic miniscrews

The screws were first used by Gainsforth and Higley in 1945(35) by fixing them in ascending ramus to retract canines in dogs. About 40 years later, the first clinical report was published showing the use of screws in human(36). However, it was not certainly accepted at that point of time. With the development of the screws during recent decades, the use of orthodontic miniscrews has become more popular because of their ability to control anchorage, ease of use and inexpensive cost(2). Clinical indications and contraindications are reviewed and presented in Table 1(37).

Indications	**Contraindications**
- Insufficient anchorage due to lack of dental elements - Asymmetric tooth movement - Intrusion of anterior teeth with insufficient anchorage - Space closure - Protraction or distalization of molars - Correction of anterior openbite - Extrusion or intrusion of individual teeth or groups of teeth without antagonists	- Patients with metabolic bone diseases - Patients with allergic reactions to specific materials - Patients on chronic therapy with steroids or bisphosphonates - Patients with severe neurological or psychological problems - Patients with poor quality or quantity of bone tissue - Patients with latent infections or circulatory problems - Patients with insulin-dependent diabetes - Patients with hypersensitivity to the miniscrew materials - Patients on immunosuppressive therapy - Patients with poor oral higene - Receiving radiotherapy in the head and neck region

Table 1 *Clinical indications and contraindications for miniscrew placement (37).*

The typical miniscrew composes of 4 parts: head, collar, core, and thread, presented in Figure 3(2, 37). Firstly, the head of the miniscrew is the part for applying torque during implantation and acting as a point for force application. Mah and Bergstrand(38) suggested that an excellent head design should be match with contemporary edgewise technique. Thus, there are several designs fabricated for orthodontic treatment, such as bracket-like, hook, button, and hole. Among them, the most popular one is the bracket-like design because square and rectangular wires and other auxiliaries can be used with it, providing numerous types of tooth movement. Secondly, the collar or the neck of the miniscrew is the part between the head and the core that providing a stop when the screw reaches the bone. The surface of this area is usually smooth, which will be surrounded by gingival soft tissue, preventing plaque accumulation and gingival irritation(37). Thirdly, the core or the body is a part that is fixed within the bone, producing retention. The last component is the thread, which can be served as self-tapping or self-drilling miniscrew.

Two designs of the miniscrews are available in common: tapered and cylindrical. Tapered miniscrews can provide higher insertion torque compared with the cylindrical design, leading to achieving more primary stability because of tighter contact between the miniscrew and bone tissue(7, 8, 39, 40). However, excessive insertion torque could also produce higher stress, resulting in microfracture of the surrounding bone and implant failure(40). On the other hand, cylindrical miniscrew requires less insertion torque and has more stable torque during implantation, decreasing the risk of bone injury. Cylindrical miniscrews also provide better biomechanical properties and higher pull-out strength than tapered ones(39, 41).

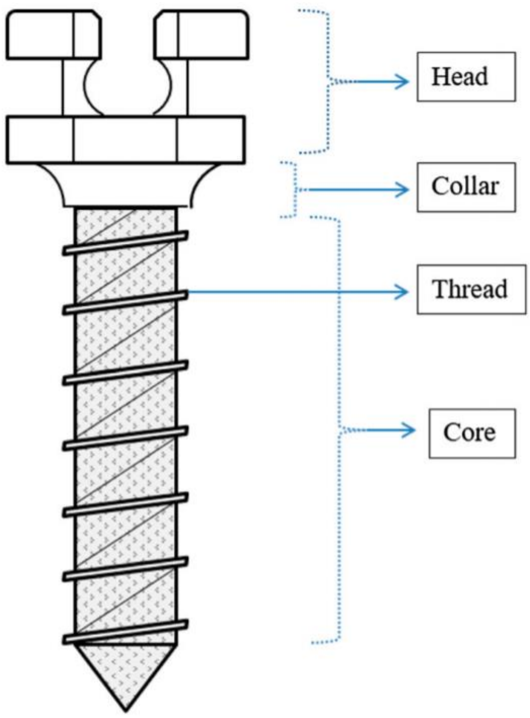


Figure 3 *Miniscrew components (37).*

Miniscrews can be fabricated from stainless steel, pure titanium, or titanium alloys; titanium-6 aluminum-4 vanadium (Ti6Al4V). When comparing between pure titanium and titanium alloys, the latter is more superior due to their higher strength, better corrosion resistance and favorable mechanical properties(42). Using stainless steel is reduced the risk of screw breakage because of higher Young's modulus of elasticity, but regarding other material properties, titanium alloys are more superior than stainless steel, including allowing bone contact or osseointegration(41). However, Brown et al(43) found that there were no significant differences between stainless steel and titanium alloys in the miniscrew stability, insertion torque, removal torque, microdamage of surrounding bone and osseointegration. They also suggested that both materials were appropriate for immediate loading.

According to the mode of insertion, miniscrews can be categorized into self-tapping and self-drilling. Self-tapping miniscrew has a blunt tip and requires a pilot drill before insertion. In contrast, self-drilling miniscrew refers to an insertion technique in which it can be inserted into the bone without predrilling due to its fine tip. There are several advantages of self-drilling miniscrew over self-tapping one, including less time-consuming, less thermal damage to bone tissue and more patient satisfaction(44). Many studies compared between these two types and found that self-drilling miniscrews provide higher insertion torque(45, 46), which has both pros and cons because it might achieve more initial stability owning to more bone-implant contact, but at the same time, it can generate more stress and more damage to the surrounding bone(12, 45). However, both types can be used as effective orthodontic anchorages due to their comparable resistance to lateral loading, success rate and stability(46, 47). Regarding the predrilling procedure, it might be beneficial, including the use of self-drilling miniscrews, in thick cortical bone, such as mandible or palate(8), to decrease bone resistance, which in turn, reducing the insertion torque. Baumgaertel(14) summarized the predrilling guidelines associated with cortical bone thickness as presented in the Table 2.

Cortical bone thickness	Recommended procedure
< 0.5 mm	Placement not recommended
0.5 – 1.5 mm	No predrilling required
1.5 – 2.5 mm	Perforate cortical bone only with 1-mm-diameter round bur
> 2.5 mm	Predrill with drill bur 1.1 mm in diameter, 4 mm length

Table 2 *Predrilling recommendations in relation to cortical bone thickness (14).*

2.3 Success rate of orthodontic miniscrews

Lower success rate of the orthodontic miniscrews was reported when comparing with the conventional dental implants used in prosthodontics(3-5, 48-50), with the overall success rate of over than 80%(51). Chen et al(3) reported in their systematic review according to the success of orthodontic miniscrews that the success rates of self-tapping miniscrews, using a 1.5-mm diameter pilot hole for 2.0-mm diameter miniscrews, ranged from 85% to 100%, and over 90% when using a 0.9-mm diameter drill for 1.2-mm miniscrews. Furthermore, when focusing on the loading protocol, the success rates of immediate loading miniscrews were 75% to 100%, while the rates of early loading one ranged from 70% to 100%.

Several factors can be affected the success or failure of the orthodontic miniscrews, which can be divided into 3 main factors: patient-related, implant-related, and management-related factors(51), described below:

- patient-related factors
    - age
    - sex
    - type of malocclusion
    - thickness and kind of mucosa
    - features of the bone
    - thickness of the cortical bone
    - location in the bone
    - side of the placement
    - location in relation to roots
    - soft tissue inflammation
    - hygienic care
    - smoking habit
- implant-related factors
    - type
    - length
    - diameter
- management-related factors
    - time of loading
    - type of movement

- clinician.

Recently, another factor that should be taken into consideration is the excess microdamage of the cortical bone, which has been reported to cause miniscrew failure(24, 52).

2.4 Microdamage of the cortical bone

Miniscrew insertion is a mechanical process that can immediately produce a large amount of microdamage, which can be defined as a permanent deformation of the bone microstructure on loading. Stress can be generated by miniscrew insertion torque and it causes overcompression of the cortical bone, resulting in microdamage(10). Nguyen et al(24) reported the effect of insertion torque on microdamage of the cortical bone that an increase in insertion torque produced larger amounts of microdamage. When evaluating histologically using an animal model, there are mainly two types of the damage following an insertion of miniscrews(10, 11). The first one is called microcracks, which are small linear defects typically 100 μm in length. The second, called diffuse damage, can be defined as an intensely stained mineralized matrix, which is a cluster of microcracks that are too small to be distinguished from one another. The schematic and the fluorescence images of cortical bone microdamage following miniscrew insertion were presented in Figure 4 and Figure 5, respectively.

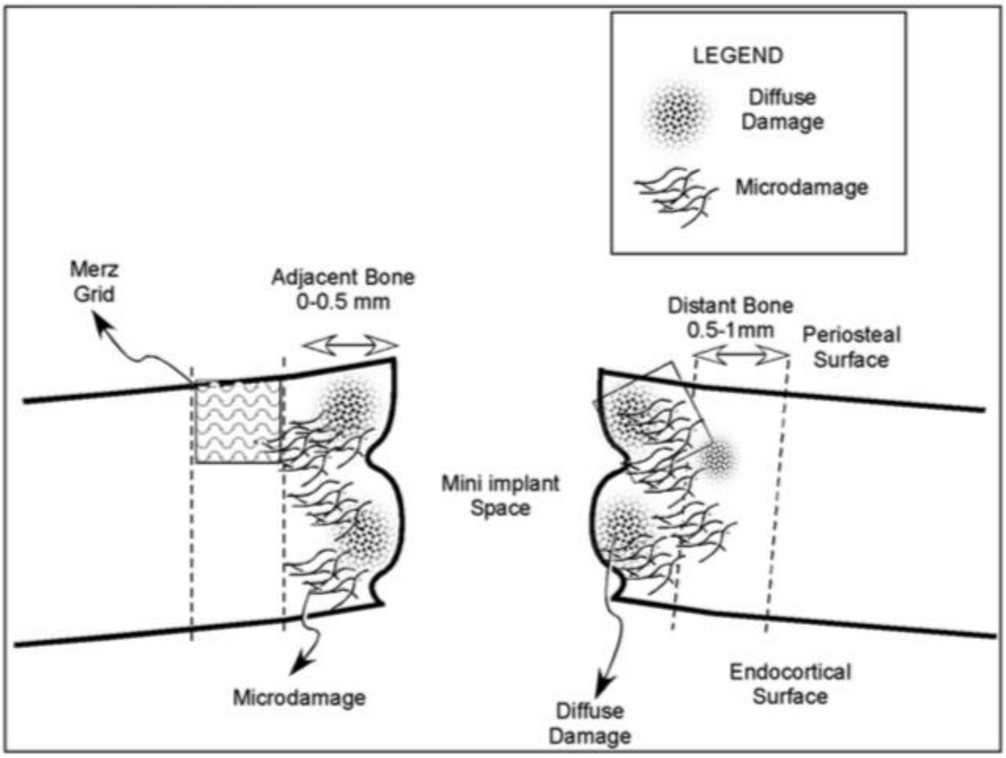


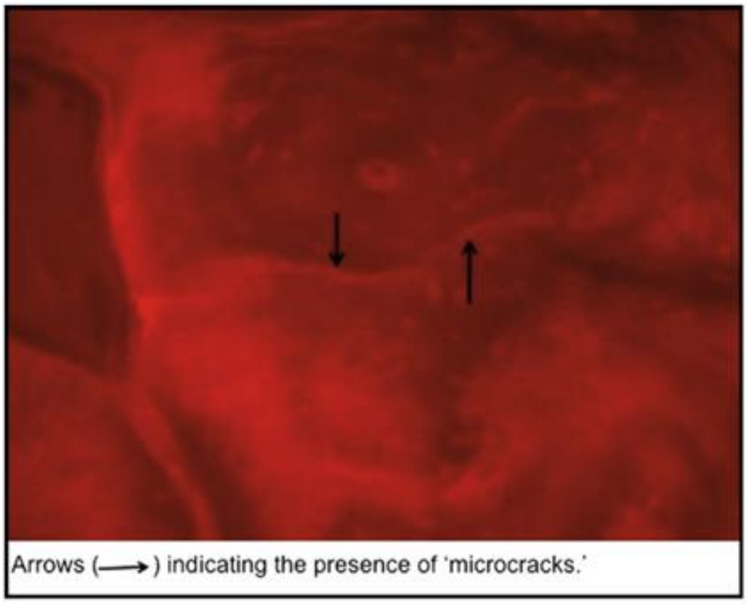
Figure 4 *Schematic of cortical bone microdamage following miniscrew insertion (11).*

The accumulation of such microdamage can produce local ischemia, bone necrosis, bone remodeling, and premature loss of orthodontic miniscrews(12). Microdamage can be repaired via bone remodeling process, induced by microcracks accumulation in and around the bone-implant interface during miniscrew insertion. Thus, this remodeling activity can prevent fatigue fracture, increase stability and longevity of a miniscrew. On the other hand, excessive amount of microdamage can reduce bone stiffness and strength, compromising stability and contributing to the early loosening of miniscrews(10, 53).

Microdamage has been investigated regarding various parameters associated with miniscrews. Two previous studies reported that larger diameter miniscrews generated more microdamage than smaller diameter screws(13, 23). However, the study of Lee and Beak(23) showed greater microdamage in tapered miniscrews compared to cylindrical ones, while Taing-Watson et al(13) reported that tapered miniscrews did not produce more microdamage than cylindrical miniscrews due to the use of pilot drilling. This is supported by Yadav et al(10) who compared between self-drilling and self-tapping miniscrews regarding microdamage accumulation after miniscrew insertion and found that drilling the pilot hole effectively helped reducing the bone damage.

According to the placement site, Nguyen et al(19) found that more microdamage was produced in thicker cortical bone. This might be due to more accumulation of the bone debris between the thread and around miniscrew that can cause more stress to the cortical bone(54). This result was supported by another experiments(11, 55), however, there is a histomorphometric study summarized that there was no relationship between cortical bone thickness and the amount of microdamage(56).

(A)



(B)

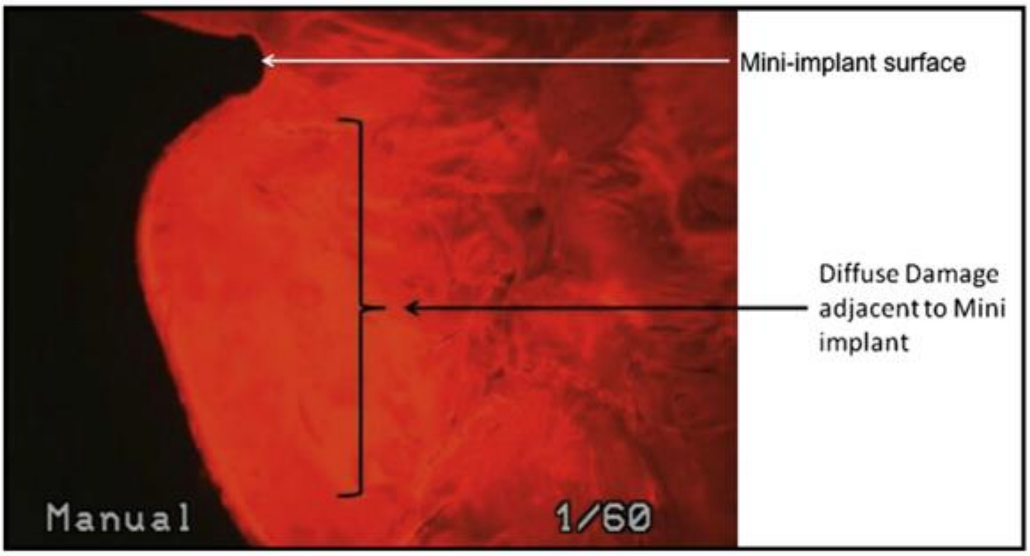


Figure 5 *Fluorescence images of cortical bone microdamage following miniscrew insertion, showing (A) microcracks and (B) diffuse damage in animal model (10).*

2.5 Pilot hole

Making the pilot hole is an effective method of decreasing the resistance encountered during miniscrew placement, thus also reducing the insertion torque(45). Many studies showed that larger pilot hole sizes resulted in lower insertion torques(8, 15, 16, 57). This is because less bone needs to be displaced during miniscrew insertion, leading to minimizing the applied force.

However, some studies showed different results. One of which reported the insertion torque associated with four pilot hole sizes by using a cortical bone screw for rigid fixation and noted that the size that required the highest insertion torque was not from the smallest pilot hole size(17). Another study reported that the insertion torque of a 2.0-mm diameter orthodontic miniscrew was higher when inserted into a larger pilot hole(8). The authors also claimed that a smaller pilot hole size may result in miniscrew fracture. Therefore, the critical pilot hole size, which can provide both appropriate insertion torque and miniscrew stability, should be concerned. Gantous and Phillips(58) stated that the pilot hole size can be increased up to between 80% and 85% of miniscrew outer diameter without a significant loss of holding power when using self-tapping screws with varying pilot hole sizes. Similar results were also reported when evaluated both torque measurement and pullout analysis(45). Using a pilot drill less than 80% was recommended because pilot hole could be enlarged due to wobbling during drilling.

2.6 Stability of the miniscrews

There are two phases of miniscrew stability: primary stability and secondary stability. Primary stability refers to the stability immediately after insertion, which obtained by mechanical retention between miniscrew and surrounding bone. Secondary stability occurs after the healing process, which is a result of bone remodeling at the area of implant-bone surface and surrounding tissue(8). Ure et al(59) placed self-tapping miniscrews in the maxilla of the beagles to evaluate stability changes for an experimental period of 8 weeks. They found that the stability of miniscrew implants significantly declined during the first 3 weeks and increased thereafter, which indicated that the transition point from primary to secondary stability appears at approximately 3 weeks. Kim(60) demonstrated the graph explaining the transition from the primary to secondary stability at the critical period of 3 weeks following the miniscrew insertion (Figure 6). Nevertheless, both primary stability and secondary stability are necessary for the overall retention of miniscrews.

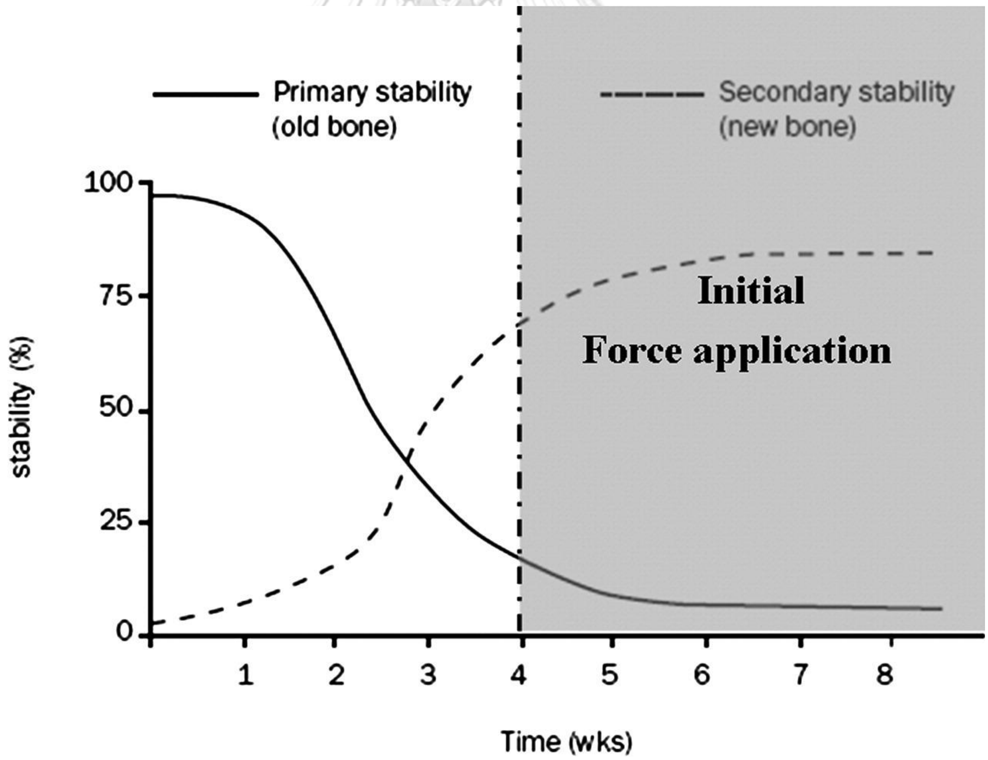


Figure 6 *The relationship between primary stability and secondary stability after miniscrew insertion over time (60).*

Primary stability plays an important role in the success of miniscrews because they do not require osseointegration. Various possible factors can affect miniscrew stability as shown in Table 3(1). With a lack of primary stability, miniscrews tend to easily move, resulting in miniscrew failure(39). Thus, miniscrews can be used for immediate or early loading with adequate primary stability.

Miniscrew characteristics	**Placement site characteristics**	**Loading characteristics**
Miniscrew length	Bone density	Force
Miniscrew diameter	Bone quality	Root injury
Pitch	Cortical bone thickness	
Thread design	Miniscrew orientation	
Fluting	Pilot hole size	
SLA surface treatment		
Shaft design		

Table 3 *Factors associated with the primary stability of miniscrews (1).*

Aside from the pilot hole diameter that was mentioned before, there are still numerous factors related to this study.

2.6.1 Miniscrew length

Figure 7 showed the average sizes of the endosseous screw in today market, ranged from 5 to 15 mm in length and from 1.2 to 2.3 mm in diameter(37). It was believed that using longer and larger size of the screw could enhance miniscrew stability because the bone-to-implant contact was proportionally increased. However, it also produced higher pressure and torque that may cause bone damage and stability impairment(61, 62). Furthermore, long miniscrew is able to penetrate surrounding structures, such as, tooth root or maxillary sinus(63), while short miniscrew provides limited retention. Currently, the effect of miniscrew length on the primary stability is still controversy. Several previous studies have reported that length has a little or no impact on the primary stability compared to other factors(7, 8, 64, 65). Kim(1) also reviewed and summarized that the miniscrew length had a small effect on the long-term stability. In contrast, some articles reported that longer miniscrew was more superior on the primary stability and the success rate(66, 67), and the length of at least 6 mm was recommended to use(63, 67).

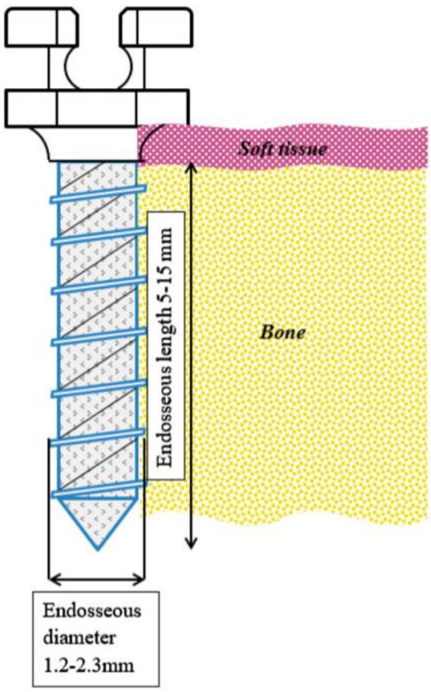


Figure 7 *The endosseous screw with the manufactured dimensions (37).*

2.6.2 Miniscrew diameter

Mostly, miniscrew diameter has been reported to be one of the main factors that considerably affect miniscrew primary stability(20, 49, 66, 68, 69). Lim et al(20) measured the insertion torque regarding the variations of miniscrew shape, diameter and length, and found that all can impact the torque value but the diameter particularly provided a major reinforcement to the primary stability.

Previous studies have also shown that an increase in the diameter of the miniscrew caused higher insertion torque and removal torque(20, 49, 68, 69), higher pull out strength(21, 70, 71), and more loading transmission from the screw to the bone(72). However, the root proximity should be considered when using large diameter miniscrew due to the reason that it may cause root damage and stability impairment(20, 37). Poggio et al(73) suggested to use miniscrew diameter between 1.2 and 1.5 mm for the placement at interradicular area. On the other hand, miniscrew with small diameter, usually less than 1.2 mm, tends to have anchorage loss under heavy orthodontic force(37, 74). The fracture risk was also reported to be higher as the diameter of the miniscrew decreased, especially the inner or core diameter(7, 38, 75).

2.6.3 Fluting

Flute or cutting flute is a recessed area at the tip at the screw or longitudinally throughout the screw length as shown in Figure 8(76, 77).

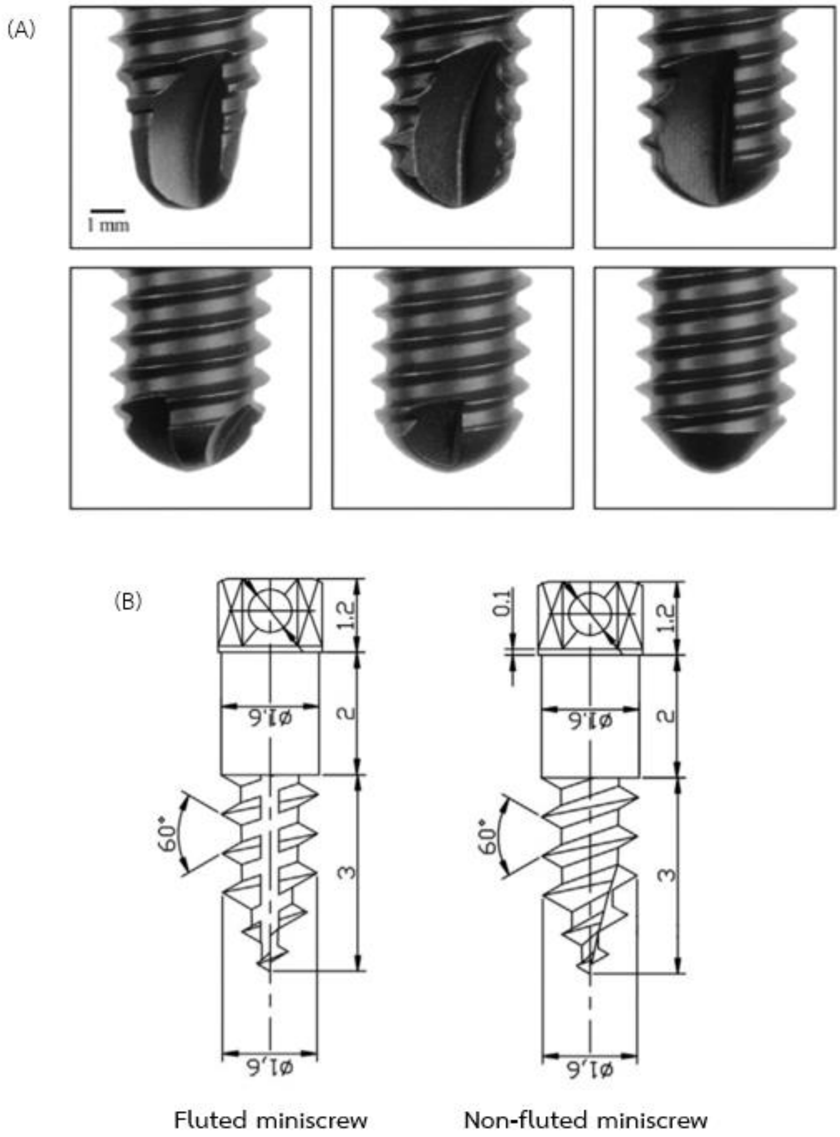


Figure 8 *Images of the cutting flute; (A) placed at the screw tip, and (B) placed through the screw length (76, 77).*

Flute can both increase or decrease the insertion torque value, depending on its dimension and the ability to clear the bone debris during miniscrew insertion(1, 77). Brinley et al(78) measured the insertion torque value and pull-out force compared between longitudinal fluted and non-fluted miniscrews. They found that the cutting flute provided an effectively increase of both parameters because the accumulation of the bone chips around miniscrew threads may increase the friction and resistance to insertion, which in turn, resulting in the primary stability improvement. They also recommended to use fluted miniscrew when placing in thinner or less dense bone than usual.

Conversely, there are previous articles reported a decrease in insertion torque related to having the cutting flute. Wu et al(79) concluded that flute was a major factor that reduce the insertion torque of the endosseuos screws, depending on its shape. Yerby et al(77) reported quite similar results when varying the designs of the cutting flute. They also concluded that smaller cortical bone damage can be found in adding flute numbers and length.

2.6.4 Bone quality and quantity

It has been suggested that both bone quality and quantity, as known as bone density and cortical bone thickness, had a positive relation to the stability of the screw. Kravitz and Kusnoto(80) categorized the quality of the bone into 4 types, using computed tomography (CT) scan measured the density as Hounsfield units (HU), described in Table 4 and Figure 9(37, 80). Previous studies recommended to insert the miniscrews into D1, D2 and D3 regions to acquire greater stability, while D4 region may not appropriate as placement site due to a higher chance of miniscrew failure(80, 81).

Type	Quality of bone	Region	Prognosis of miniscrew
D1	Homogeneous dense cortical bone	Anterior mandible Mid-palate	Greater stability
D2	Thick layer of cortical bone surrounds a core of dense trabecular bone	Anterior maxilla Posterior mandible	Greater stability
D3	Thin layer of cortical bone surrounds a core of dense trabecular bone	Posterior maxilla Posterior mandible Zygoma	Higher failure rate
D4	Thin layer of cortical bone surrounds a core of low-density trabecular bone	Posterior maxilla Tuberosity	Insertion not recommended

Table 4 *Bone density classification (37, 80).*

There is a meta-analysis reported that the failure of the miniscrew was found in the mandible more than the maxilla, owing to its denser bone. The heat generated during screw drilling into dense bone can produce microfractures, ischemia and necrosis, leading to screw impairment, and finally resulting in miniscrew failure.

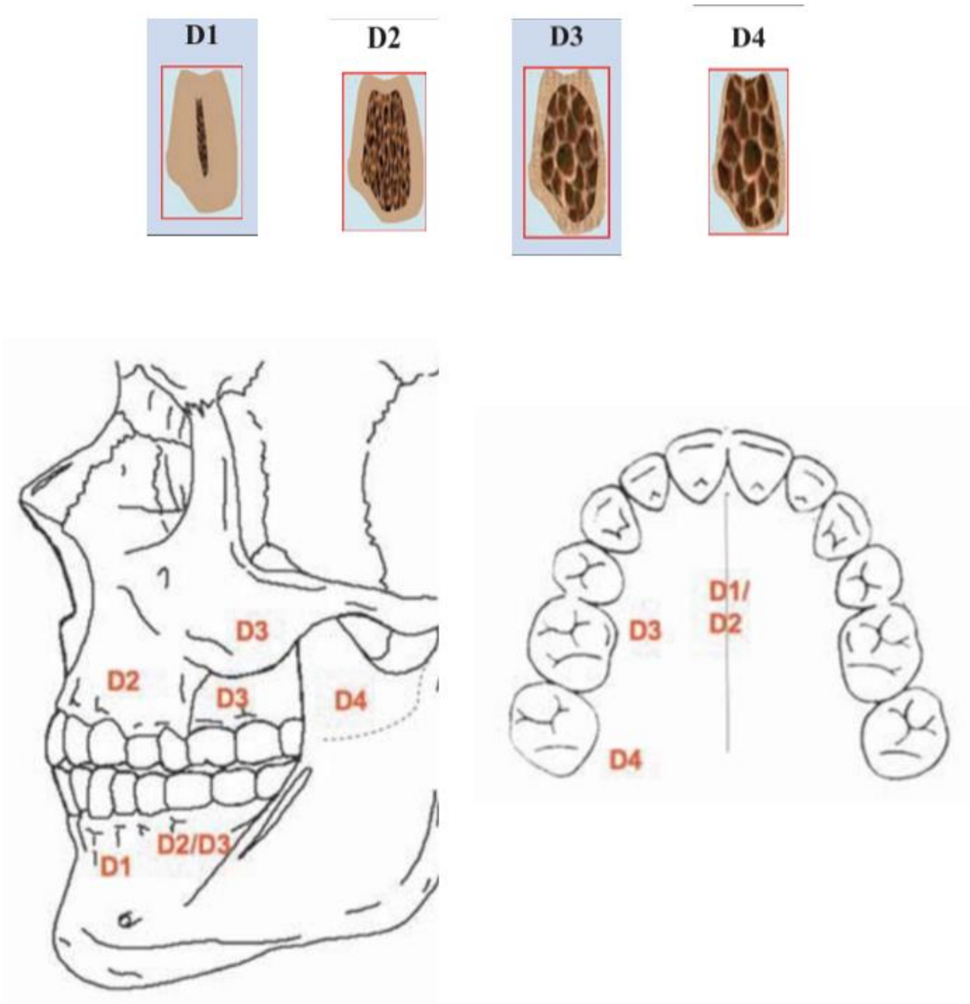


Figure 9 *Bone density classification related to the regions (37, 80).*

2.6.5 Root injury

Root damage can be resulted from unsuitable placement of miniscrew, movement of the screw after loading or tooth movement into contact with the miniscrew by orthodontic force(82). Cho et al(83) evaluated variables that affected the rate and the pattern of root contact during insertion of MSIs and found that the frequency of root contacts produced by inexperienced operators was substantially higher than that of experienced group. Moreover, the implantation site also impacted the risk of root contact. They concluded that most root contacts occurred in the posterior areas.

Root proximity between miniscrew and adjacent root has been investigated to be a major risk factor for the screw failure(84, 85). The main problem is that sufficient interaction between miniscrew thread and surrounding bone cannot be achieved, resulting in the mobility of screw and an increase in failure rate owing to the loss of stability(84, 86, 87). Therefore, it is suggested to use small and short miniscrew with predrilling to avoid root damage when applying in the inter-radicular region(88). Moreover, cone beam computed tomography (CBCT) and surgical stent are recommended to use before and during miniscrew placement to guide accurate positioning(89).

According to the complications on the tooth and periodontium, the healing process of periodontal structure can be started rapidly after removal of the problematic miniscrews. The possible sequence of periodontal repair after root proximity and root contact with the miniscrews is showed in the Figure 10(2). Injured roots generally heal themselves unless that damage reaches the pulp(87). Thus, when root contact is suspected, immediate removal of the miniscrews and reinsertion is strongly recommended.

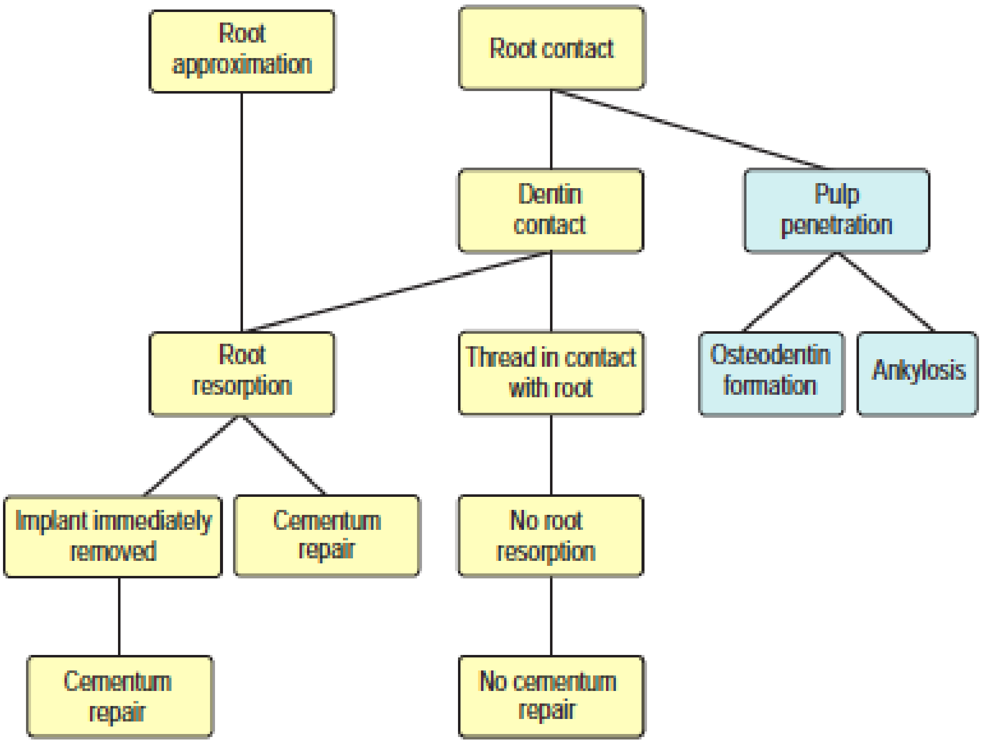


Figure 10 *Sequence after root contact with a miniscrew (2).*

To evaluate the primary stability of miniscrews, a variety of measurement could be used (Figure 11). Histologic and histo-morphometric analyses are used to assess primary stability of implants(90-92), but they are quite invasive and cannot use clinically. Percussion test, measured by Periotest, can be used to examine mobility, which quite related to the miniscrew stability(93, 94). Over recent years, resonance frequency analysis (RFA) has been used as another tool by measuring vibrations of the miniscrew within the bone. It has been used as a successful method to evaluate stability of dental implants over time. In 2006, Wilmes et al(8) stated that RFA was not an appropriate method to evaluate miniscrew stability because of a dramatic difference in size between dental implants and miniscrews. However, with the modification of this equipment, particularly the development of a transducer, specifically designed for orthodontic aspect, RFA has been determined to be a useful method, as equal to percussion test(93) and maximum insertion torque(95). Last but not least, the most common and effective means is torque analysis by measuring insertion torque when tightening miniscrews into the bone(6-8, 21).

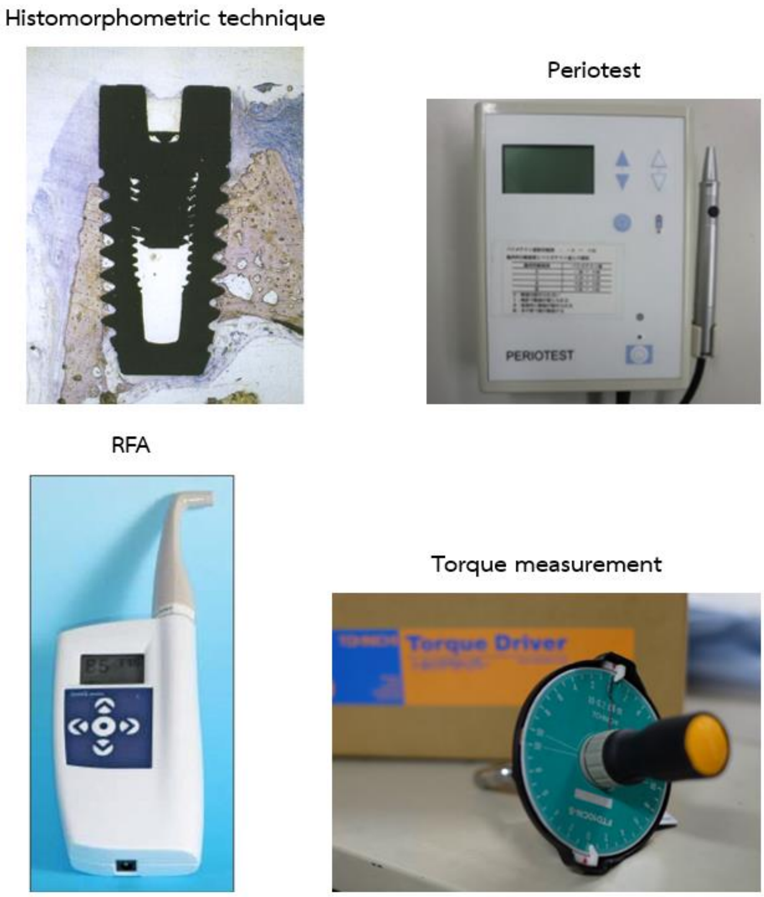


Figure 11 *Technique and tools for miniscrew stability evaluation (91, 93, 94).*

2.7 Insertion torque

Insertion torque or placement torque is defined as the amount of torque during the insertion of miniscrews, which required to overwhelm the resistance of the bone at implantation site(14). It was first introduced in 1995 to evaluate the relationship between titanium implant placement resistance and bone density(96). The authors found a relationship between implant insertion torque and implant-bone interface characteristics and summarized that insertion torque measurement could be a reliable means to evaluate bone quality. Over recent years, it has been frequently used as an indirect method to measure the miniscrew stability and bone characteristics in orthodontic studies(21, 24, 97, 98). Numerous studies have been evaluated the effect of miniscrew associated factors on the insertion torque, summarized in Table 5(1).

Characteristics	Insertion torque
Length $\uparrow$	+
Width $\uparrow$	+
Pitch $\downarrow$	+
Thread depth $\uparrow$	++
Fluting	±
SLA surface treatment	-
Bone density $\uparrow$	++
Cortical bone thickness $\uparrow$	++
Pilot holes	-

Table 5 *Insertion torque according to the affected factors (+ = increase, - = decrease)(1).*

It was thought that when the miniscrew insertion torque is higher, the stability would be enhanced because of increased bone-implant contact. It is proved that this is definitely wrong. Excessive or very tight insertion torque can produce high level of stress at the interface between miniscrew and surrounding tissue, causing microdamage and consequently bone necrosis(55, 61, 62, 94). On the other hand, too low insertion torque leads to the mobility of miniscrew implants. These can compromise the stability and result in the failure of miniscrews. Motoyoshi et al(9) evaluated the insertion torque value using self-tapping, tapered titanium miniscrews with a diameter of 1.6 mm and a length of 8 mm in orthodontic patients and recommended the insertion torque ranged from 5 to 10 Ncm to obtain optimum success rate of the miniscrews. However, these values can be varied by miniscrew designs and recipient bone properties. Recently, the study of torque loss after miniscrew insertion has been reported increasingly, summarized that the loss of maximum insertion torque values could be occurred in the first 2 weeks(99, 100), which might be said that the insertion torque value was not able to predict the long-term stability(94).

2.8 Removal torque

Removal torque presents the amount of bone-to-implant contact. Therefore, it can be said that it is the critical torque threshold needed to break the contact to remove the screw from its surrounding bone(101). The removal torque is generally used to evaluate the potential of the anchorage and osseointegration after healing period for both dental implants and orthodontic miniscrews(60, 102, 103). However, Okazaki et al(104) used the removal torque to evaluate the primary stability of the self-tapping miniscrews in beagle model. They found that the removal torque immediately after miniscrew insertion was significantly less than the insertion torque value and significantly decreased up to 6 weeks post-retention. This might be due to the bone remodeling.

Apart from measuring removal torque value in the animal model, Niimil et al(105) measured the removal torque of the endosseous implants in the cadavers to evaluate the initial stability. Moreover, there are some studies evaluated the removal torque using the synthetic bone model. Saeed et al(106) measured the maximum insertion and removal torque values following miniscrew insertion. The results showed that there was a significant correlation between insertion torque and removal torque, which suggested that this type of miniscrew provided better anchorage. Furthermore, it can be clearly seen that the value of removal torque was generally lower than that of insertion torque. This result was also supported by another in vitro study, presented less removal torque value(107).

Chapter 3

Research methodology

3.1 Study design

In-vitro experimental study.

3.2 Overview of this study

The overview of this experiment, including indentation test and miniscrew insertion test, was shown in Figure 12.

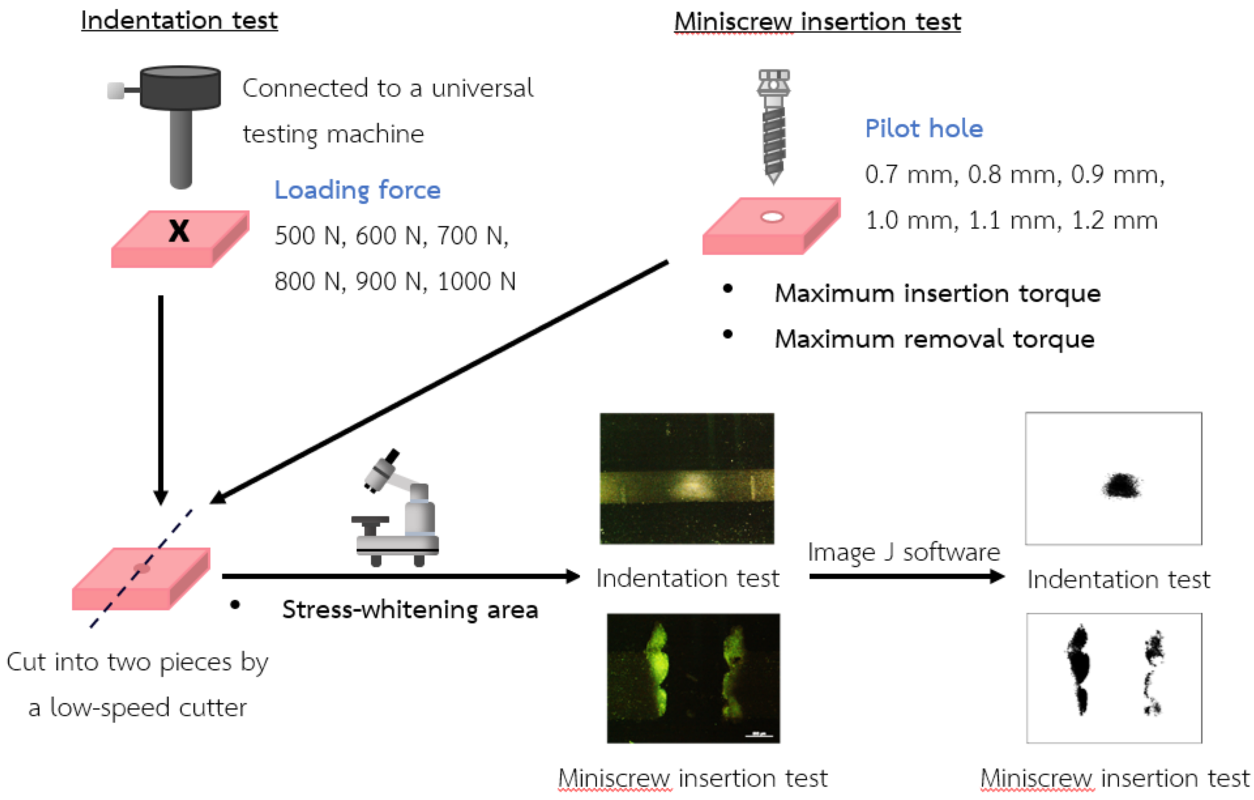


Figure 12 The overview of this study.

3.3 Materials

3.3.1 Synthetic cortical bone

E-glass filled epoxy sheet with 1-mm thickness was used in this study to represent human bone analogue (#3401-07; Sawbones, Vashon, WA, USA; Figure 13). It is a mixture of short E-glass fibers and epoxy resin. Physical and mechanical properties of this material are shown in the Table 6(108).

Figure 13 *a 1-mm thick E-glass filled epoxy sheet (pale pink) used in this experiment (https://www.sawbones.com/sheet-1mm-short-fiber-filled-epoxy-4th-gen-130-x-180-x-1mm-3401-07.html/ accessed on 24 April 2021).*

Material properties	Metric unit
Density	1.7 g/ml
Ultimate tensile strength	90.0 MPa
Modulus of elasticity	12.4 GPa
Compressive yield strength	120.0 MPa
Compressive modulus	7.6 GPa

Table 6 *Physical and mechanical properties of the synthetic cortical bone (108).*

3.3.2 Miniscrew

1.3-mm diameter, 6-mm length Ti6Al4V miniscrews (Jeil Medical Corporation, Seoul, South Korea) were used in miniscrew insertion test as seen in Figure 14.

Figure 14 *An image of Ti6Al4V miniscrew used in this experiment (1 scale = 1 mm).*

3.3.3 Pilot drill

Cylindrical carbide burs of 0.7, 0.8, 0.9, 1.0, 1.1 and 1.2 mm in diameter were used to make pilot hole before miniscrew insertion (Saito Seisakusho, Tokyo, Japan).

3.4 Equipment

- Low-speed precision cutter (IsoMet, Buehler, IL, USA)
- Torque screwdriver (FTD10CN-S; Tohnichi, Tokyo, Japan)
- Light microscope (LV100N POL; Nikon Instruments Inc., Melville, NY, USA)
- Camera connected with computer screen and imaging software (NIS-Elements; Nikon Instruments Inc., Melville, NY, USA)
- ImageJ software program (ImageJ version 1.51r; National Institutes of Health, Bethesda, MD, USA)
- Universal testing machine (AG-X, Shimadzu, Kyoto, Japan)
- Scanning electron microscopy (SEM; S-4500; Hitachi High-Tech, Tokyo, Japan)
- A vice
- A micromotor
- Plaster of Paris
- Black ink

3.5 Sample size estimation

Sample size was estimated using power analysis for analyzing the difference between many means(109). Means and standard deviations from the pilot preliminary test, measuring maximum insertion torque values in six pilot hole sizes, were used to calculate the total sample size.

Mean in group 1 = 7.77

Mean in group 2 = 6.80

Mean in group 3 = 8.87

Mean in group 4 = 7.93

Mean in group 5 = 4.50

Mean in group 6 = 2.13

Standard deviation in group 1 = 0.25

Standard deviation in group 2 = 0.40

Standard deviation in group 3 = 0.31

Standard deviation in group 4 = 0.31

Standard deviation in group 5 = 0.36

Standard deviation in group 6 = 0.12

α error probability = 0.05

Power (1-β error probability) = 0.80

The total sample size from the calculation was twelve. According to the microdamage aspects, the latest previous study used five 1.5 x 6.0 mm self-drilling, cylindrical miniscrew implants per each experiment group to evaluate the effect of miniscrew insertion torque on microdamage of porcine tibia cortical bone(24). Thus, thirty miniscrews were decided as the total sample size (five per one group) for miniscrew insertion test to place miniscrew into six pilot hole sizes.

3.6 Sample preparation

No ethics approval was required because no animal experiments or human studies were involved in this research. Synthetic cortical bone was cut into forty-eight 14-mm x 14-mm pieces, using a low-speed precision cutter. Eighteen test pieces were used for indentation tests, and the remaining test pieces were used for miniscrew insertion tests. The center point of each test piece was marked with a pencil.

3.7 Experiments

3.7.1 Indentation test

Indentation test was performed in which defined compressive loads were applied to the test pieces of synthetic bone. A universal testing machine was used with a spherical indenter of 5.0-mm-diameter. Forces of 500 to 1000 N in 100-N steps (six experimental groups, three test pieces per group) were loaded on the center of the synthetic bone surface with a crosshead speed of 1 mm/min.

After that, the tested pieces were embedded in plaster of Paris stained with black ink and cut into two pieces using a low-speed cutter to reveal the cross-sectional surface in the center. The cross-sectional surface was imaged using a light microscope at 20× magnification and imaging software under controlled light room conditions.

Each image was processed using the image analysis program (ImageJ) to evaluate the microdamage under the applied load. The region of interest was set at 2.0 mm around the center of the indentation. The original images were converted to grayscale images and then binarized with thresholds of brightness ≥ 20 and particle size ≥ 1000 to quantify the microdamaged area (Figure 15).

To investigate the microdamage of the synthetic bone piece, scanning electron microscopy (SEM) observations were also performed. The tested piece loaded with 1000 N was washed with an ultrasonic cleaner with distilled water for 10 s. After Au coating, the cross-sectional surface was observed with a tube voltage of 15.0 kV.

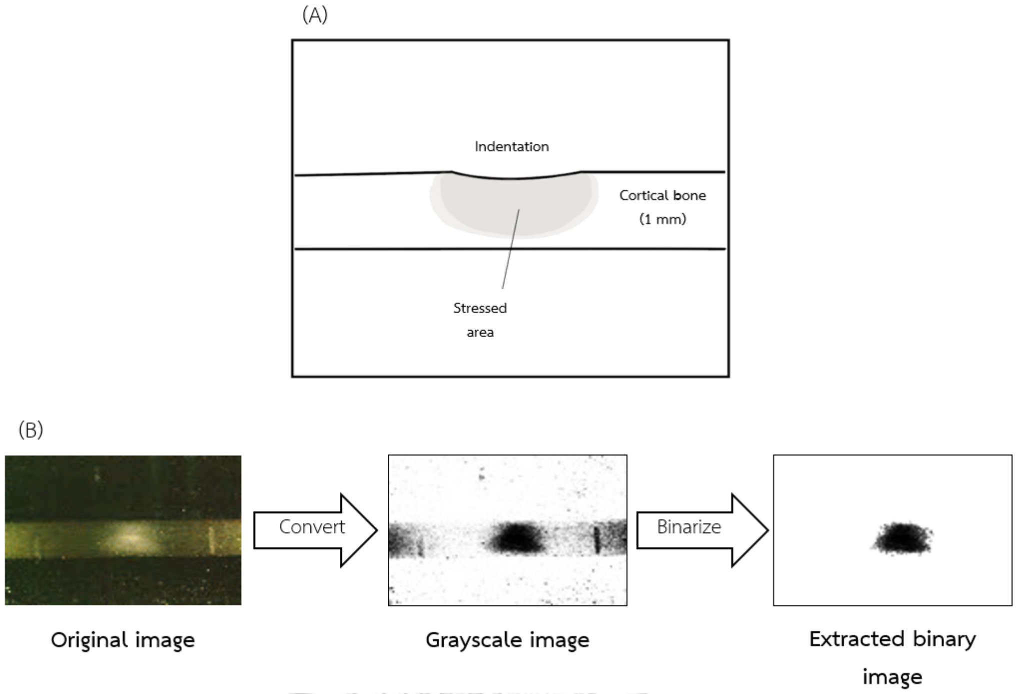


Figure 15 *Stressed-whitened area measurement for the indentation test using Image J software; (A) Schematic description and (B) the procedure to extract the area.*

3.7.2 Miniscrew insertion test

The synthetic bone test pieces with a pilot hole were prepared in which the hole diameter ranged from 0.7 to 1.2 mm in increments of 0.1-mm (six experimental groups, *n* = 5 per group). Each piece of bone was secured in a vice and the pilot hole was made perpendicularly to the bone. All holes were inspected with light microscopy to confirm the accuracy of the hole diameter. A miniscrew was then manually inserted into the test piece hole and removed with a dial-measuring torque screwdriver. Maximum insertion torque and maximum removal torque values were recorded to evaluate the primary stability. At the screw insertion, the final gap between the test piece surface and the bottom of the screw head was regulated to be 1.0 mm.

After removal of the screw, the microdamaged areas were quantified in a similar way as the indentation tests. The cross-sectional surface was imaged at 40× magnification. The region of interest for the insertion test was set to 2.0 mm around the center of the hole. The microdamage area was extracted with a brightness threshold of ≥40 and a particle size of ≥1000 (Figure 16).

3.8 Statistical analysis

The normality test was performed using Shapiro-Wilk test. Some groups did not show normal distribution. Therefore, non-parametric tests were chosen for the analysis. The data from the indentation test was analyzed using Spearman's rank correlation coefficient. The data from the miniscrew insertion test was analyzed using Kruskal-Wallis test and pairwise Wilcoxon rank sum test adjusted with the Hochberg method. All p-values < 0.05 were considered statistically significant. All statistical analyses were carried out using "R" software (version 4.0.2, http://www.r-project.org/ (accessed on 5 July 2020)).

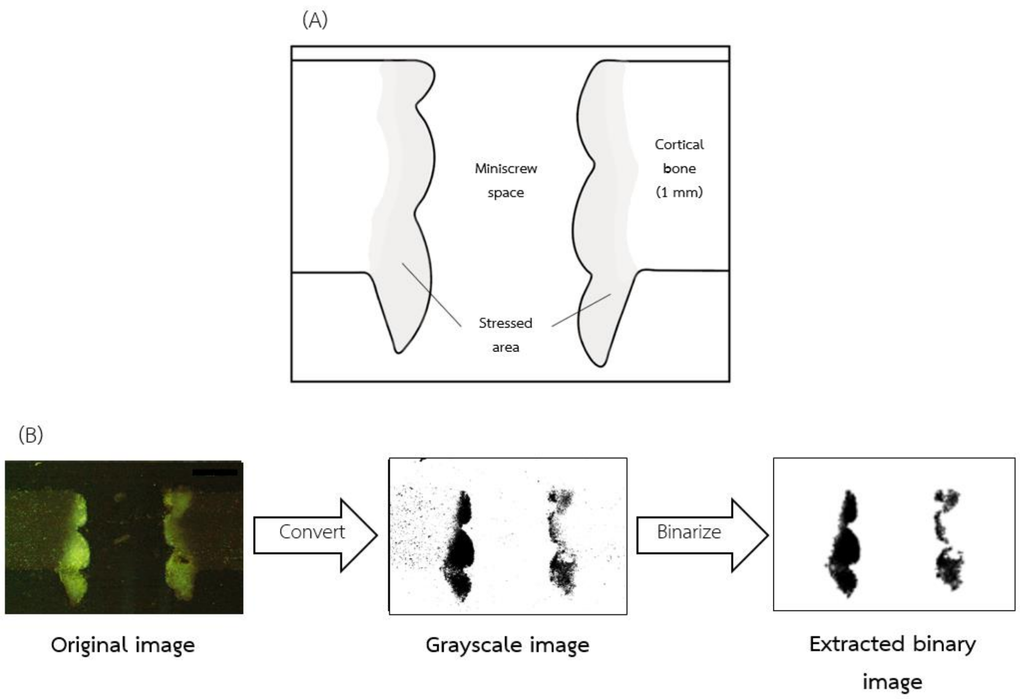


Figure 16 *Stressed-whitened area measurement for the miniscrew insertion test using Image J software; (A) Schematic description and (B) the procedure to extract the area.*

Chapter 4

Results

4.1 Results of indentation test

Although no macroscopic cracks were found in any of the test pieces, optical microscopic observations revealed stress-whitened zones approximately 300 μm below the loaded portion for all loading conditions. The intensity of whitening increased as the loading force increased (Figure 17).

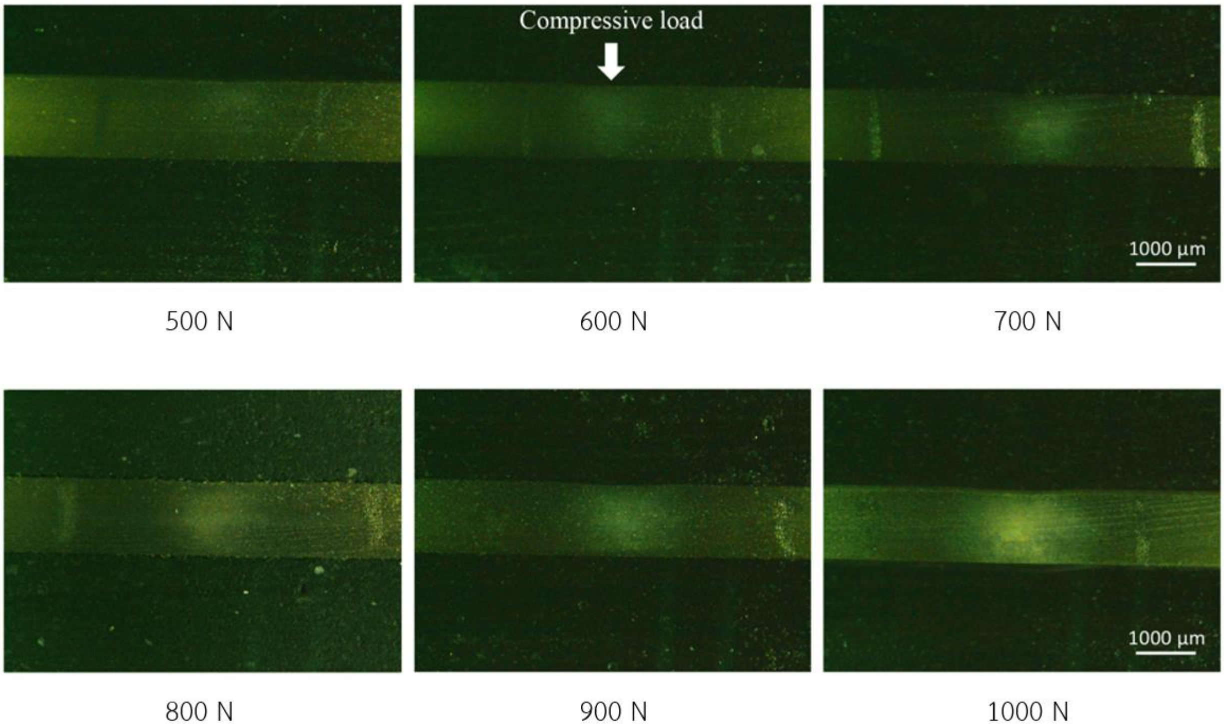


Figure 17 *Light microscopic images of the tested bone pieces in cross-sectional view following indentation test (Bar = 1000 μm).*

According to the SEM images, it is showed that intact rod-shaped glass fibers embedded in the resin matrix at the area distant from the whitened zone (Figure 18, lower left). In the stress-whitened zone, the damaged fibers and cracked matrix with interface failures between them were demonstrated. (Figure 18, lower right).

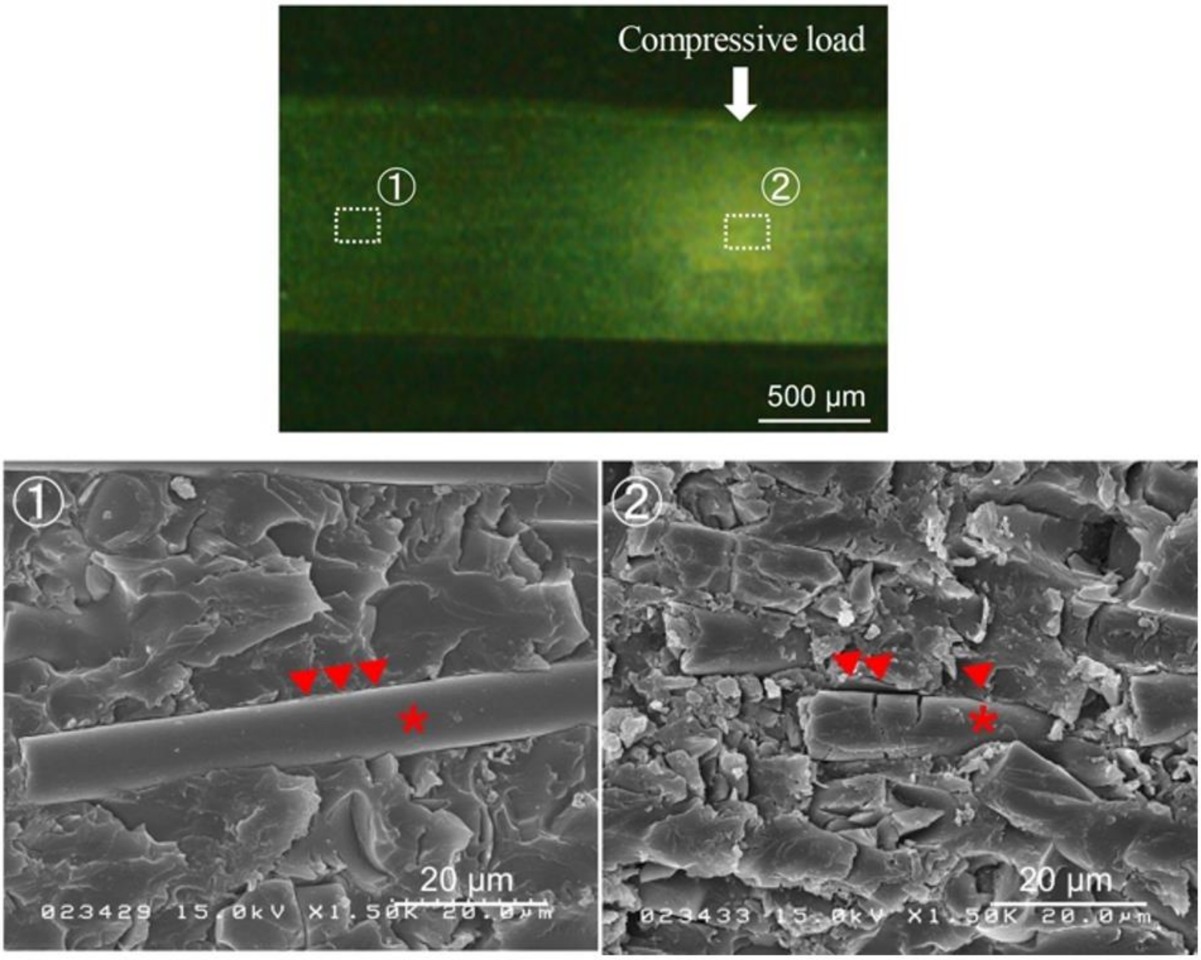


Figure 18 *SEM images of the synthetic bone after the loading of force, compared between the ① intact and ② stress-whitened area (Bar = 20 µm). The asterisk represents the glass fiber, and the arrowhead indicates the border between the resin matrix and the glass fiber.*

The relationship between the loading force and the area of the stress-whitened zone exhibited a sigmoid curve with a significant increase in the range from 600 to 800 N (Figure 19). The calculated Spearman's rank correlation coefficient was

0.95, indicating a high positive relationship between the loading force and the stress-whitened zone ($p < 0.001$).

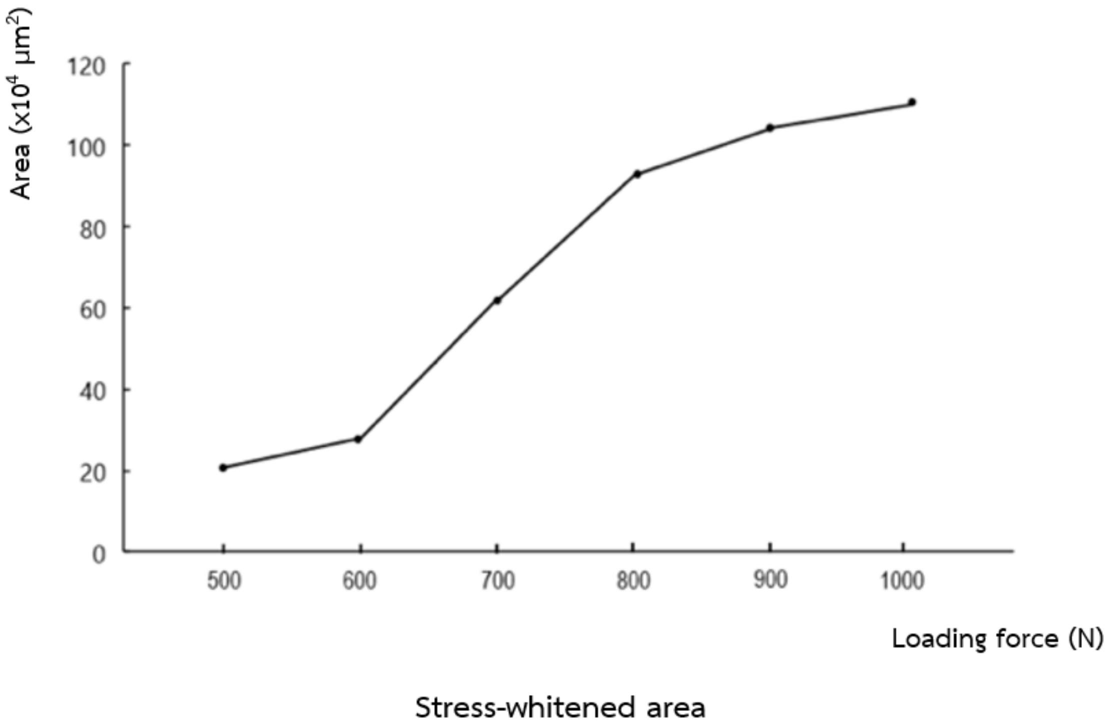


Figure 19 *A line graph of the mean values of area under stress for each level of force applied.*

4.2 Results of miniscrew insertion test

Fractures of the screw and macroscopic cracks of the tested pieces were not observed in any of the samples. At pilot holes with diameters 0.7 and 0.8 mm, synthetic bone chips came out from the screw hole as the tapping proceeded. In particular, more synthetic bone chips were found with insertion in a pilot hole with a diameter of 0.7 mm.

During optical microscopic observations, thread dents associated with miniscrew insertion were observed in the synthetic cortical bone around the screw hole. The lower margin of the synthetic bone around the screw hole protruded. A stress-whitening zone was observed in the synthetic bone between the dents of the screw thread. These phenomena were clear in the 0.7 – 0.9 mm diameter group, but unclear in the remaining diameter groups (Figure 20).

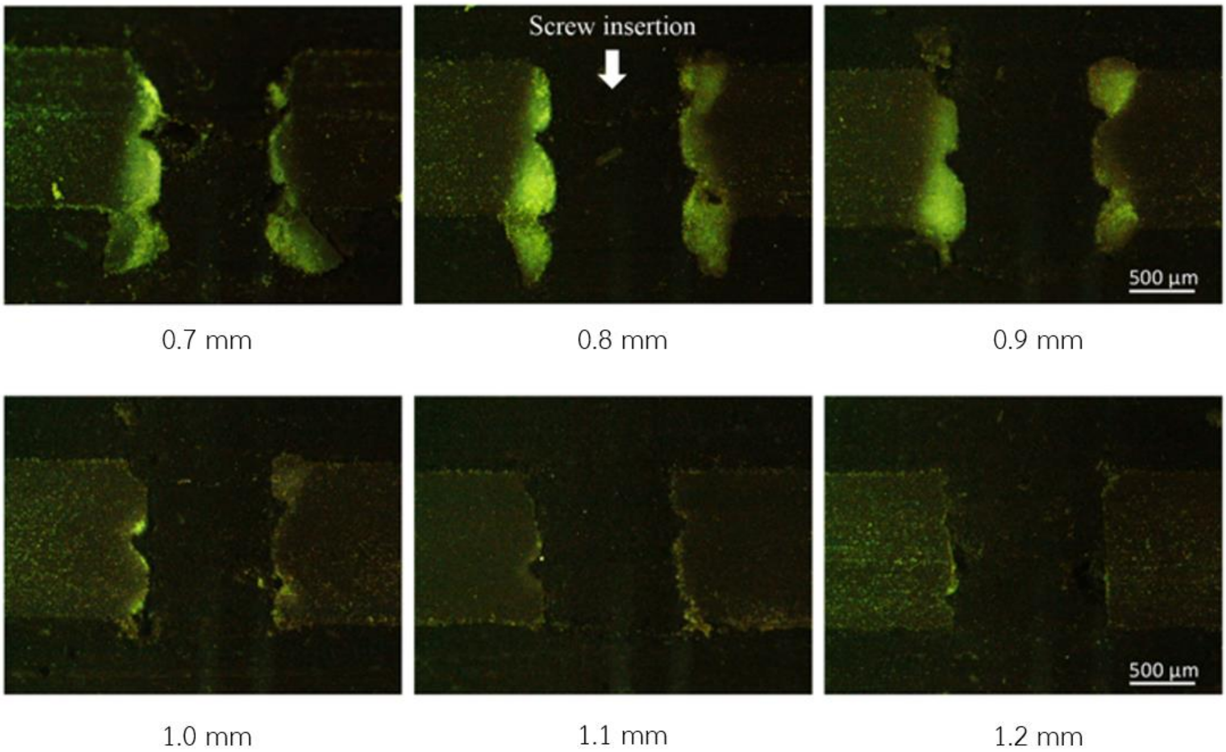


Figure 20 *Light microscopic images of the tested bone pieces in cross-sectional view following miniscrew insertion test (Bar = 500 µm).*

In regard to the relationship between pilot hole diameter and the area of stress-whitening, the area of the stress-whitening zone decreased with the increase in pilot hole diameter, except for in the 0.7 mm pilot hole group. The 0.7 mm pilot hole group showed a smaller area (non-significant) than the 0.8 mm pilot hole group (Figure 21A). The pilot holes with 0.7–0.9 mm diameters showed significantly ($p < 0.05$) larger areas than the other diameter groups.

Insertion torque results revealed significant differences among all groups ($p < 0.05$). Pilot holes with diameters of 0.7 and 0.8 mm had a lower insertion torque than the 0.9 mm pilot hole. In the group with a diameter larger than 0.9 mm, the insertion torque decreased with the increase in pilot hole diameter (Figure 21B).

In the results of removal torque, pilot holes with 0.9- and 1.0-mm diameters showed approximately the same values, which were higher than those of other groups. Except for this point, the removal torque showed the same tendency as the insertion torque (Figure 21C). In every pilot hole diameter, the removal torque values were lower than the insertion torque values.

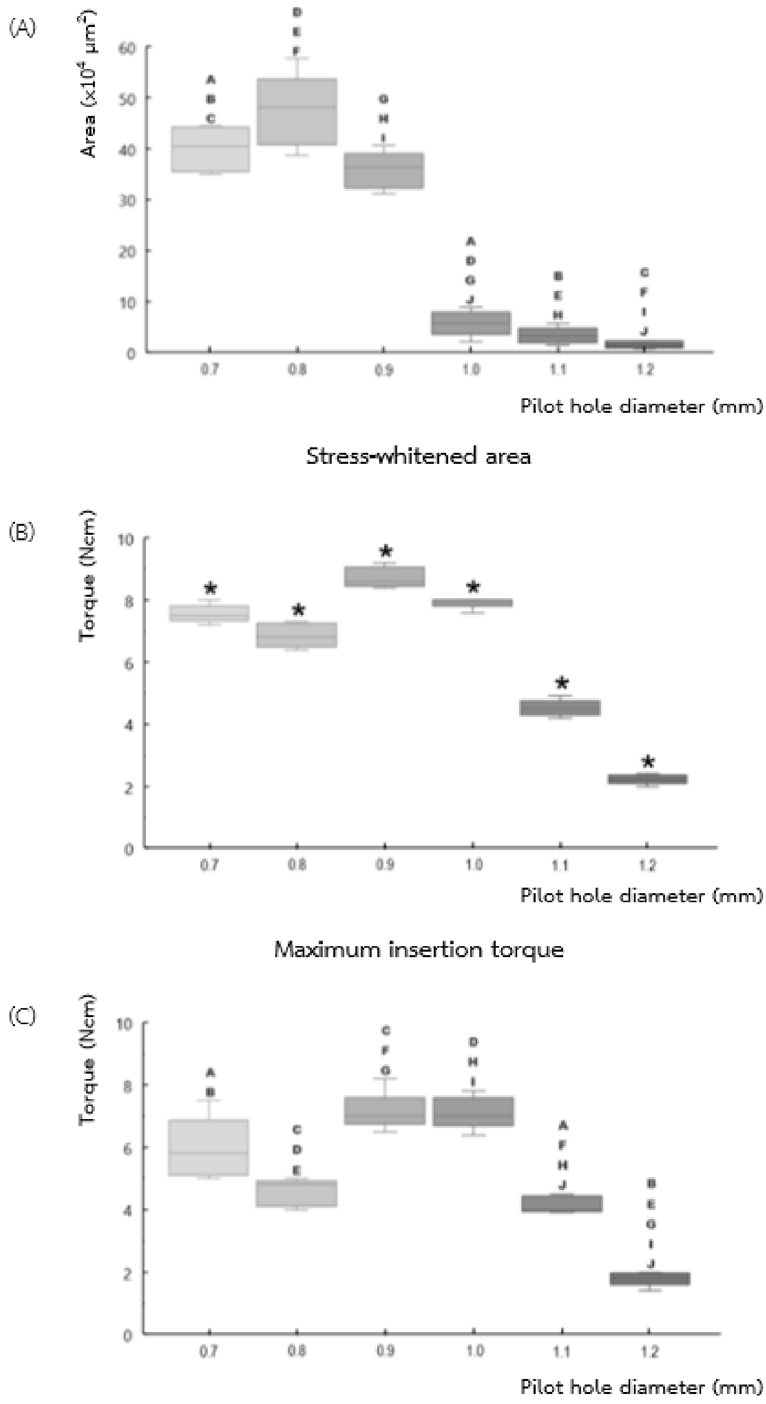


Figure 21 *Box-plot graphs showing the median values of (A) stress-whitened area, (B) maximum insertion torque, and (C) maximum removal torque. The asterisk represents significant differences among all groups ($p < 0.05$). A-J in graph (A) and (C) indicate significant differences ($p < 0.05$) between respective pairs of plots.*

Chapter 5

Discussion

The purpose of the present study was to evaluate the microdamage and primary stability to estimate the critical diameter of the pilot hole that could minimize the screw loosening risk by using 1.3-mm diameter miniscrews inserted into 1.0-mm thick synthetic cortical bone with six different pilot hole sizes. Many studies have reported that screw-root contact due to root proximity is one major factor that affect miniscrew stability, leading to miniscrew failure(84, 110, 111). This is because of insufficient interaction between miniscrew thread and its surrounding bone. Kuroda and Tanaka(88) suggested to use small and short miniscrew with predrilling to avoid root damage when applying in the inter-radicular region. Moreover, miniscrews with a diameter of 1.2 mm and over were found to have favorable success rates and reduce an opportunity of screw loosening under the loading of orthodontic heavy force(66). Thus, miniscrews with 1.3 mm in diameter was chosen as a testing material.

During attempts to evaluate cortical bone microdamage around the orthodontic miniscrew and primary stability of the miniscrew, two distinct approaches have been employed. Many studies have attempted animal experiments(8, 10-13, 18, 19, 39, 112), whereas several others carried out dry bench tests(67, 113). Each research method involves inherent limitations in mimicking the clinical situation; however, ethical aspects arise as serious issues in the former approach. Russell and

Burch claimed the philosophy of the 3Rs: Refinement, reduction, and replacement, regarding the use of animals in scientific experiments(114). According to such principles, researchers must be concerned with reducing animal experimentation. Furthermore, since synthetic bones providing similar mechanical properties of human bones are available nowadays, the dry bench test appears to be a more favorable approach.

As a consequence, the objective of this study was to evaluate cortical bone microdamage around the miniscrew and primary stability of the miniscrew to estimate the optimal pilot hole size that could minimize the risk of screw loosening by using a human bone analogue. Noticing the fact that the microdamage and the primary stability are the dominant factors in screw loosening, the strategy minimizes bone microdamage while providing primary stability. Here, the microdamage is a permanent deformation of the bone microstructure(10), and the corresponding words in the terminology of mechanics, or the terms applicable to artificial materials, is plastic deformation. The antonyms of these words are reversible deformation and elastic deformation, respectively. Hence, our optimization strategy is the minimization of plastic deformation without the reduction of primary stability in the dry bench test with the use of a human bone analogue.

As a human bone analogue, we used synthetic cortical bone made from glass fiber reinforced polymer (GFRP). When GFRP is subjected to a load that exceeds the yield strength, local congregated crazes and debonding between the fiber and polymer are induced. The outcome of such plastic deformations is the increase in the refractive index of GFRP, which may be observed as stress whitening(115). In our indentation tests, cross-sectional images of the synthetic bone demonstrated a stress-whitened area, which spread with an increase in the applied load. SEM image of the stress-whitened area revealed damaged fibers and cracked matrix with interface failures between them, i.e., the evidence of the plastic deformation. Considering that the compressive yield strength and elastic modulus of the synthetic cortical bone are the same as those of the human cortical bone(116), it was concluded that the stress-whitening zone in the synthetic cortical bone corresponds to the microdamaged portion in human cortical bone. Therefore, the magnitude of the bone microdamage could be evaluated by measuring the area of the stress-whitening zone induced in the synthetic cortical bone.

The primary stability represents the resistance capacity against the forced displacement under the applied load at the time just after insertion. If the forced displacement is small, the stability of the screw is said to be high. The dominant factors that affect the primary stability are considered to be the area of screw–bone contact and the magnitude of compressive stresses at the screw-bone interface(117), since the grip strength of the surrounding bone onto the inserted miniscrew depends on them. However, these factors are difficult to measure experimentally, so the insertion torque or removal torque was utilized instead(101, 118, 119). In the case of a dry bench test with a bone analogue, such usage of the torque can be justified by the following arguments based on elementary mechanics. Firstly, the above-mentioned screw-bone contact and compressive stress generate the frictional force, according to Coulomb’s law(120), as:

$$\text{friction force} = \mu \times \text{compressive stress},$$

in which μ is the coefficient of friction and the compressive stress is created by elastic deformation in the bone analogue. If the screw is made to rotate, the friction generates the torque as:

$$\text{torque} = \text{friction force} \times \text{screw's radius},$$

and the total sum of such torque over the entire surface of the screw constitutes the torque needed to rotate the screw. Here, the insertion torque involves the torque required for the material cutting, whereas the removal torque does not; hence, the removal torque of the screw is directly related to the magnitude of compressive stresses at the screw-bone interface. Therefore, the degree of the primary stability could be evaluated by the magnitude of the removal torque of the screw inserted in the bone analogue.

In the screw insertion tests, the 1.0–1.2 mm diameter pilot hole groups showed almost no stress-whitening zone, which implies that the deformation induced in the bone analogue was mainly elastic, and almost no plastic deformation was present. Among these groups, the elastic deformation became smaller as the pilot hole diameter increased, so the removal torque decreased, and the primary stability also decreased. Thus, 1.0 mm was the optimum diameter among them. On the other hand, the 0.7–0.9 mm diameter pilot hole groups showed significant areas of the stress-whitening zone, i.e., the plastic deformation was predominant. On these groups, it should be noted that the smaller pilot holes did not ensure larger removal torques. This phenomenon might be due to the fact that the plastic deformation was not recoverable and, hence, compressive stresses at the screw-bone interface decreased as the plastically deformed area increased. Thus, the optimum among them was a 0.9 mm diameter pilot hole group with the smallest stress-whitening zone and the highest removal torque. Therefore, comparing these two optimums of two gatherings of groups, the optimum among all groups was 1.0 mm diameter group.

Under the circumstances, from the evaluation of the corresponding microdamage and primary stability in the human bone analogue, we estimated that the optimum pilot hole diameter was 1.0 mm for miniscrews of 1.3 mm diameter. In the case of such diameter pilot holes, the screw-bone compressive stress during screw insertion was slightly below the yield stress of the cortical bone, and the elastic deformation was maximized. Hence, the plastic deformation of the cortical bone, that is, the microdamage, was minimized, and the removal torque, that is, the primary stability, was maximized. This result is consistent with a previous investigation. Namely, a study utilizing the rat tibia model reported that the optimum pilot hole diameter is approximately 69%–77% of the screw's outer diameter(18), whereas our results were 76.9% of the outer diameter.

Supplementally, a small stress-whitened area, observed in the 0.7 mm diameter pilot hole group, should be examined. A possible cause was the effect of the self-tapping flute of the miniscrew. Additional micro-CT observation of the screw head, using a tube voltage of 75 kV, tube current of 55 μA, and voxel size of 7 μm (micro-CT; InspeXio SMX-100CT; Shimadzu, Kyoto, Japan), revealed that the scoop angle of the cutting edge was approximately zero at the 0.7 mm diameter part, whereas it was negative at the 0.8- and 0.9-mm diameter parts (Appendix, Figure A, B). Thus, in the case of the 0.7 mm diameter pilot hole group, the generation of the cutting chip and the deformation of the materials took place simultaneously during screw insertion, which might have resulted in a decrease in the plastically deformed area of the bone analogue. On the other hand, this mechanism created the thickest plastically deformed region in the 0.8 mm diameter pilot hole group. This region might constitute the structure supporting the compressive stresses from the surrounding elastic region, resulting in the relatively smaller insertion and removal torque observed in the 0.7- or 0.9-mm diameter pilot hole group.

The potential limitations of this study come from the differences between living tissues and artificial materials. Plastic deformations in synthetic cortical bones cannot distinguish linear cracks or diffuse damage in natural bones, although each microdamaged bone would be repaired or resorbed in different ways(53). Therefore, further investigations through clinical experience are required to determine the optimum insertion technique for orthodontic miniscrews.

Chapter 6

Conclusion

Synthetic cortical bone can be utilized as a human bone analoge to evaluate cortical bone microdamage around the orthodontic miniscrew and primary stability of the miniscrew. The estimated pilot hole diameter that could minimize the risk of screw loosening was 1.0 mm for a 1.3 mm diameter miniscrew.

APPENDIX

To investigate the effect of the cutting flute, the scoop angle of the cutting edge was examined for 0.7–0.9 mm diameter using miniscrew cross-sectional images from micro-computed tomography scans (micro-CT). The cutting flute along the screw head evaluated as a light microscopic image and cross-sectional micro-CT images at 0.7 - 0.9 mm in diameter was shown in Figure A and Figure B, respectively. The upper panel in each set shows the whole cross-sectional image. The Red circle indicates the outer circumference of the screw, and the black cross indicates its center. The open arrow indicates the direction of rotation when the screw is inserted. Each apex of the cutting edge and the center is connected by a black line. The lower panel in each set shows its magnified view around the cutting edge. The asterisk indicates the scoop angle of the cutting edge.

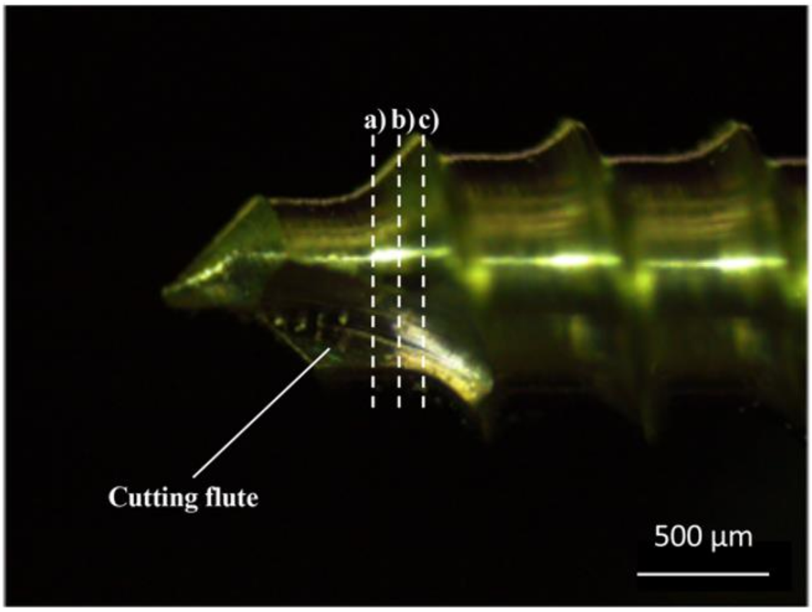
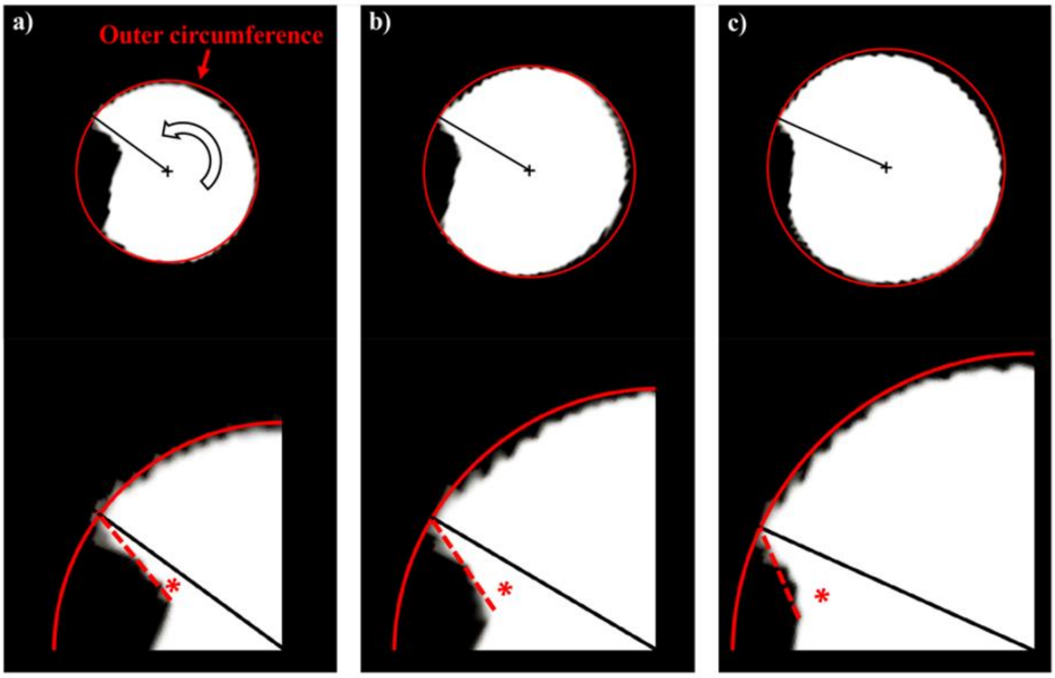


Figure A *A light microscopic image of the cutting flute (Bar = 500 µm).*



0.7 mm 0.8 mm 0.9 mm

Figure B *Cross-sectional micro-CT images of the cutting flute at (a) 0.7, (b) 0.8, and (c) 0.9 mm.*

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