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Original Article

Effect of insertion load on insertion torque value

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KEYWORDS
Dental implant;
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Abstract *Background/Purpose:* This study examined the effect of insertion load on implant primary stability by evaluating the insertion torque and insertion time in various implant designs.
Materials and methods: Four implant designs were tested, including one cylindrical implant standard (S), two hybrid implants tapered effect (TE) and bone level (BL), and one conical implant bone level tapered (BLT). Polyurethane bone models of the maxillary posterior region were used. Insertion torque value (ITV) and insertion time, defined as the duration from implant placement initiation to platform alignment, were recorded under two load conditions, the minimum load and a load of 5.0 newton (N). A torque meter was used to capture torque—time curves, and the mean and standard deviation of ITV were calculated. Data were analyzed using a paired t-test ($P < 0.05$).
Results: The minimum insertion load varied by design: implant S required 2.5 N, implants TE and BL each required 2.0 N, and implant BLT required 1.0 N. At minimum load, insertion torque was 8.68 N cm for implant S, 6.64 N cm for implant TE, 12.29 N cm for implant BL, and 29.52 N cm for implant BLT. Under 5.0 N, the values were 8.12, 7.82, 14.89, and 30.53 N cm, respectively. Insertion time decreased by up to 12.52 % from 1.0 N to 5.0 N, with significant differences in implant BLT.
Conclusion: Hybrid implants are more sensitive to load variations. Optimizing the insertion load based on implant design can enhance clinical outcomes. The insertion load is a critical but often overlooked factor in primary implant stability.

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Introduction

Dental implants refer to a treatment modality designed to restore masticatory function by embedding artificial tooth roots into the jawbone at the sites of missing teeth, followed by the attachment of prosthetic teeth to these roots.[1,2] Currently, screw-type implants are based on the concept of osseointegration, a term introduced by Dr. Per-Ingvar Brånemark to describe the direct structural and functional connections between the bone and implant surfaces.[3] This innovation, supported by the rigorous foundational research over several years, was first applied clinically in 1965 to restore function in edentulous patients.[4] Currently, dental implants are widely used for various edentulism patterns, including single-tooth and partial edentulism, providing a reliable solution for patients with tooth loss.

Extensive research has reported high implant survival rates across diverse patient populations, with the 10-year survival rates ranging from 93.2 to 96.4 %.[5] Despite these impressive outcomes, not all implants achieve successful osseointegration, and several cases of failure have been reported. Implant failures are broadly categorized into four main types: biological failures, mechanical failures, iatrogenic complications, and failures stemming from inadequate patient motivation.[6] Biological failures are further classified into early failures, which fail to gain osseointegration, and late failures, which are characterized by the subsequent loss of osseointegration. Early failures occur at approximately five times the frequency of late failures,[7] highlighting the critical importance of addressing the factors contributing to early implant failure.

Early implant failures have been associated with various factors including inadequate primary stability, reduced bone volume and quality, placement in the maxillary posterior region, type 4 bone quality, suboptimal implant designs, surgical techniques, and infection.[8] Primary stability is particularly important for successful osseointegration. Primary stability depends on mechanical engagement between the implant and surrounding bone, which is achieved by compressing the bone as the implant is inserted into an implant bed smaller than the implant diameter.[9] Over time, stress in the compressed bone is released, or the bone undergoes resorption mediated by osteoclasts, leading to a decrease in primary stability.[10] As part of the natural wound healing process, new bone forms around the implant, progressively increasing fixation. This transition from initial mechanical fixation to biological stability is referred to as secondary stability.[11] Sufficient primary stability is a critical predictor of osseointegration because inadequate stability can result in micromovement, delayed osseointegration, or early implant failure.[12,13] Consequently, quantification of the insertion procedure, which is the final step in implant surgery, is an essential priority in implantology.

Implant insertion is typically achieved by screwing the implant into the implant bed using a handpiece or manual force, referred to as insertion load. In the osteotome technique, which involves bone compression to prepare the implant bed, excessive force can cause microfractures in the trabecular bone, potentially impairing osseointegration.[14] Overcompression can also damage the surrounding bone, emphasizing the need to determine the optimal range of insertion load. However, no standardized guidelines currently exist for the insertion load, and implant insertion largely depends on the surgeon's experience and judgment.

This study aimed to elucidate the influence of insertion load on primary stability, a relationship that remains poorly understood. Simulated experiments were conducted using four implant designs with varying macrogeometries and synthetic bone models to replicate bone density in the maxillary posterior region. This study also aimed to identify the minimum insertion load required for implant insertion and evaluate the effects of varying insertion loads on primary implant stability.

Materials and methods

Implants and drill protocol

Four implant designs with a diameter of 4.1 mm and length of 10 mm were tested, including one cylindrical implant standard (S), two hybrid implants tapered effect (TE) and bone level (BL), and one conical implant bone level tapered (BLT) (Straumann AG., Basel, Switzerland) (Fig. 1). Ten implants were tested for each design. A drill press (Amini Series No. 3100, Enomoto Kogyo Co., Ltd., Shizuoka, Japan) was used to ensure precise socket preparation and prevent axial deviation. The drilling protocol was performed according to the manufacturer's instructions (Fig. 2). In this study, the minimum load related to the drilling sockets was investigated. To scrutinize the drilling socket shape, images were captured using a digital microscope (Digital Microscope RX-100, HIROX Co., Ltd., Tokyo, Japan) and precisely replicated on a computer (Fig. 3).

Artificial bone

Although many studies have used animal bone,[15] this study focused on the effect of insertion load on insertion torque value (ITV), making a uniform material preferable. Artificial bone measuring 18 cm × 4 cm × 13 cm without a cortical structure, simulating the maxillary posterior bone density (0.32 g/cm^3) was used.[16] Solid, rigid polyurethane foam (20 pcf, Sawbones, Pacific Research Laboratories Inc., Vashon, WA, USA) was employed in compliance with the American Society for Testing Materials F-1839-08 standards.

Torque measurement

To obtain analyzable torque–time curves, a high-speed torque meter (PC Torque Analyzer TVRQ-5DRU, Vectrix Corporation, Tokyo, Japan) capable of 1-ms sampling was used. To eliminate the effect of weight of the insertion apparatus on the insertion load, the apparatus was pre-adjusted to zero using a balance scale. Before testing, the torque meter was calibrated by confirming the balance between reference weight and balancing weight and setting the thrust load to zero.

The insertion loads were evaluated under two conditions: a load of 5.0 N and a minimum load. Starting at 5.0 N,

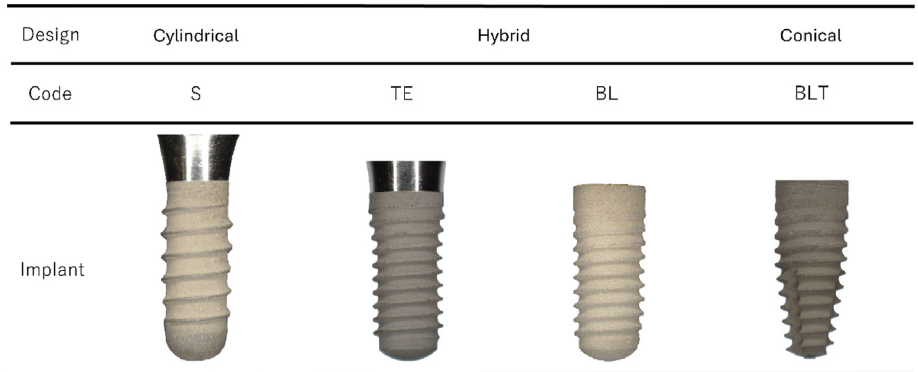

Figure 1 Implants used in this study Implants with an apical parallel region and crestal tapered region have a hybrid design. Implants with both regions parallel are cylindrical, whereas those with both regions tapered are conical. S: Standard, TE: Tapered effect, BL: Bone level, BLT: Bone level tapered.

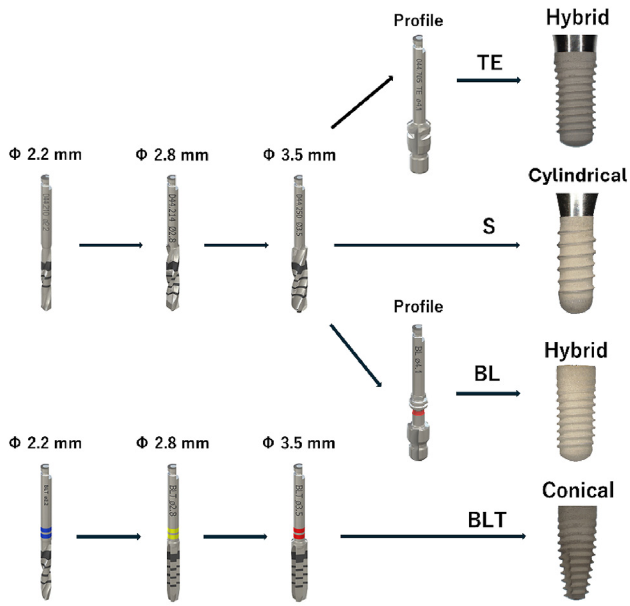

Figure 2 Drilling protocol and implant designs. The drilling protocol begins with a 2.2-mm diameter drill, followed by a 2.8-mm drill, and concludes with a 3.5-mm drill. For hybrid implants, a profile drill is used in the final step. S: Standard, TE: Tapered effect, BL: Bone level, BLT: Bone level tapered.

the applied weight was reduced in 0.5-N steps, and for each load, the torque—time curve was recorded. The minimum insertion load was defined as the lowest load at which all 10 implants produced a torque—time curve without slipping.

For each measurement, weights (Brass with chrome plating, Taisho Balance Mfg. Co., Ltd., Ibaraki, Japan) conforming to the Japanese Industrial Standards B 7609:2008, corresponding to the selected insertion load, were placed on the torque meter. The implants were carefully aligned with the central axis of the artificial bone to ensure accurate rotational alignment and were inserted at a constant speed of 15 revolutions per minute. The analysis was performed by superimposing the 10 torque—time curves, averaging, and evaluating the composite curve. The maximum value reached on each torque—time curve during insertion was defined as the ITV, with the mean values and standard deviations recorded for subsequent analysis. Finally, the torque—time curve was analyzed.

Statistical analysis

Data were analyzed using a paired t-test to compare the minimum load and 5.0 N in each design (JMP4, SAS Institute Japan, Tokyo, Japan). The *P*-value <0.05 was considered to be statistically significant.

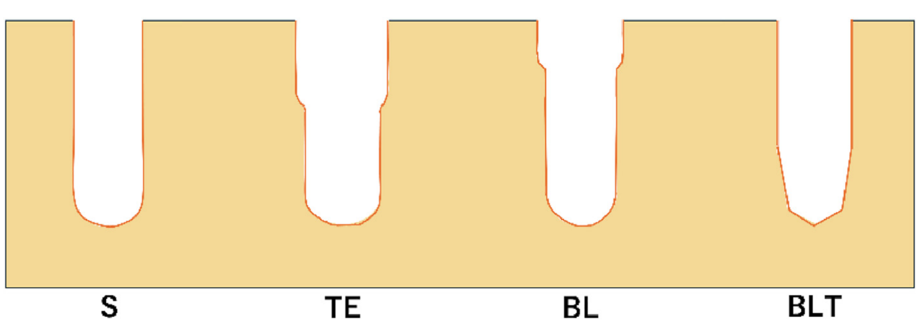

Figure 3 Diagram of the drilling socket. The final drilling socket was imaged at 20 $\times$ magnification using a digital microscope. The acquired images were visualized precisely using a computer. S: Standard, TE: Tapered effect, BL: Bone level, BLT: Bone level tapered.

Results

Minimum load differences among implant design

The minimum load values for the four implant designs were ranked as follows: implant S (2.5 N) > implant TE (2.0 N) = implant BL (2.0 N) > implant BLT (1.0 N) (Fig. 4). By superimposing the implant in Fig. 3, the point where the implant thread first engaged with the implant bed was revealed (Fig. 5). The difference in the minimum load between each implant design was attributed to the position of the implant socket relative to the first thread on the implant.

Insertion torque

Fig. 6 shows the torque—time curves for each implant design. The torque—time curve can be divided into three regions: initial, parallel, and tapered. These regions are defined as follows. The initial region represents the torque measured before the first thread of the implant engages the bone. The parallel region corresponds to the design of the implant in a parallel configuration. The tapered region corresponds to the implant design with a tapered configuration. The torque values for each region were calculated as the ratio of the maximum ITV, which was calculated from $\frac{\textit{each region's torque value}}{\textit{ITV}}$.

Fig. 7 shows the ITV and its distribution across different regions. No statistically significant differences were found between implants S and BLT, whereas implants TE and BL exhibited significant differences in ITV. Raising the load from 2.0 N to 5.0 N increased the ITV by 13.32 % in implant TE and 17.41 % in implant BL. For implant TE, the torque in the initial region increased by 0.58 N cm and that in the crestal tapered region increased by 0.42 N cm. These increases in the initial region accounted for 56.86 % of the total ITV increase, whereas the crestal tapered region contributed 41.18 %. For implant BL, the torque in the initial region increased by 0.92 N cm and that in the crestal tapered region increased by 1.67 N cm. These values represented 35.52 % and 64.47 % of the total change in ITV, respectively, which were calculated as follows: $\frac{\textit{each regions 5N torque value} - \textit{2N torque value}}{\textit{5N ITV} - \textit{2N ITV}}$. The torque rise rates for these two implants were calculated and are summarized in Table 1, organized by the initial, parallel, and tapered regions for both implants TE and BL.

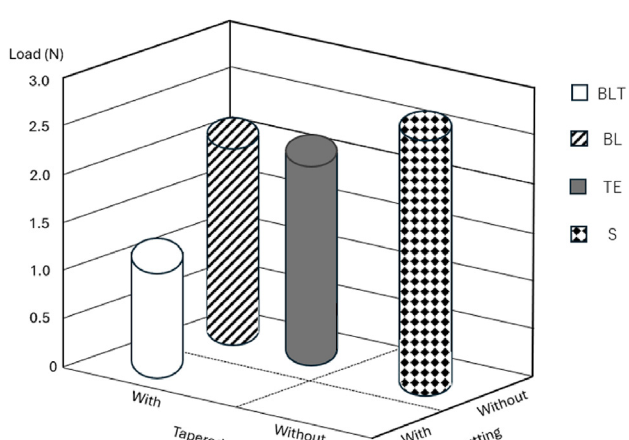

Figure 4 Minimum load values for the four implant designs. The minimum loads were 2.5 N for implant S, 2.0 N for both implants TE and BL, and 1.0 N for implant BLT. S: Standard, TE: Tapered effect, BL: Bone level, BLT: Bone level tapered.

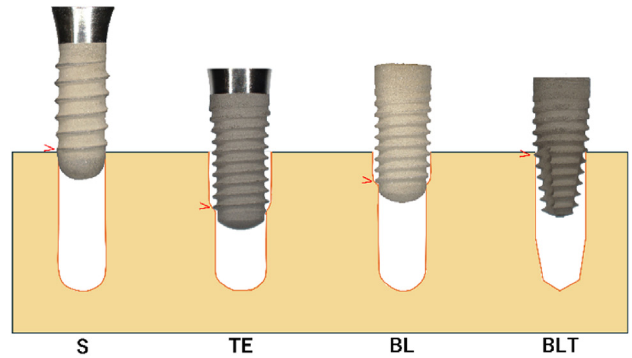

Figure 5 Relative position of the implant socket and first thread. Red points indicate the location of the first thread. In implant S, the first thread is located on the implant socket, resulting in the highest minimum load. In contrast, implants TE and BL have the first thread positioned within the socket, which reduces the minimum load. Implant BLT, with its self-cutting feature and a socket larger than the apical portion of the implant, requires the lowest minimum load. S: Standard, TE: Tapered effect, BL: Bone level, BLT: Bone level tapered.

Insertion time under different loads

Table 2 presents the recorded times, revealing significant differences only for implant BLT under varying insertion loads. A total insertion time variation of 3.74 s was observed between the two load conditions, with the initial region accounting for 90.78 % of the variation. Increasing the insertion load from 1.0 N to 5.0 N reduced insertion time by up to 12.52 %. Microscopic observations of the BLT implant insertion are shown in Fig. 8.

Discussion

Research on insertion load is limited, even in the engineering field, with only one study explicitly documenting both vertical and minimum required loads.[17] According to Matsumoto et al., pressure refers to the vertical load exerted on the driver during screw insertion, which is equivalent to the insertion load during implant insertion. Although Matsumoto et al. did not explicitly discuss the relationship between the insertion load and ITV, their study highlighted that the insertion load is a critical parameter during screw tightening. Furthermore, the study emphasized that a minimum insertion load must be applied when inserting screws. When the insertion load is too low, the force applied is insufficient to properly engage the screw with the female thread member, leading to inadequate tightening torque and compromised thread formation. Conversely, excessive pressure results in the application of

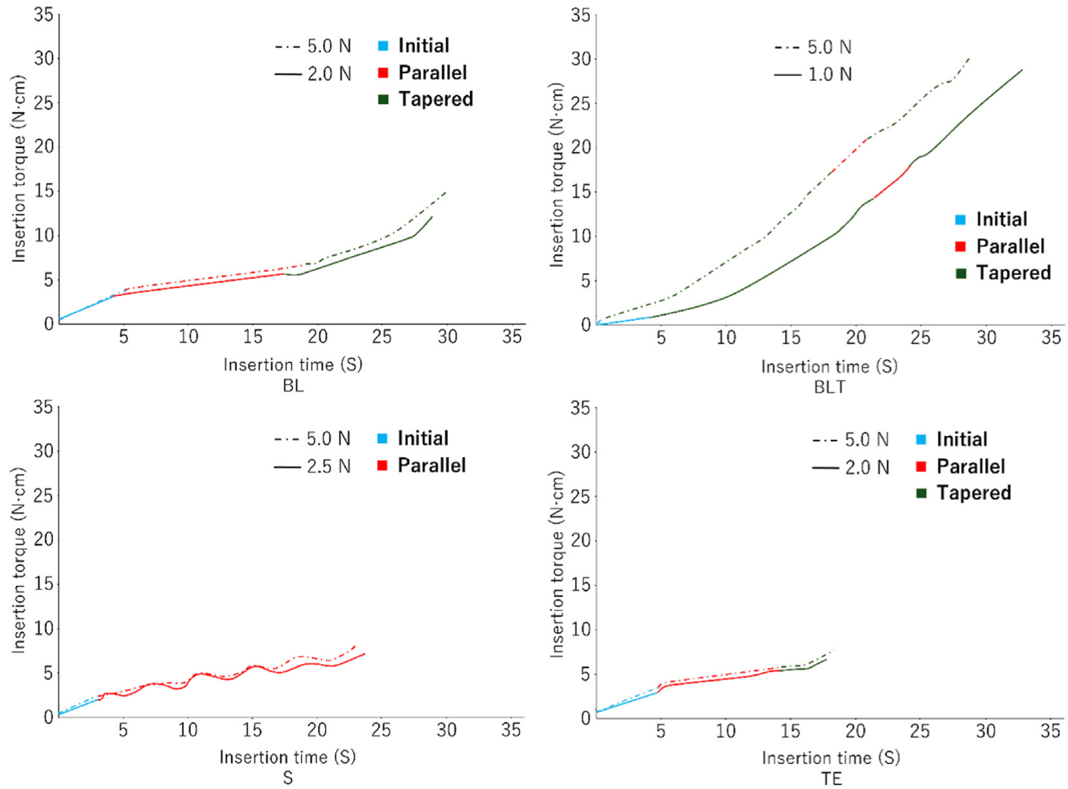

Figure 6 Torque-time curves of the four implants The torque—time curves are presented with distinct line styles for each region. Dotted lines indicate a fixed 5-N insertion load, and solid lines denote the minimum insertion load for each implant. S: Standard, TE: Tapered effect, BL: Bone level, BLT: Bone level tapered.

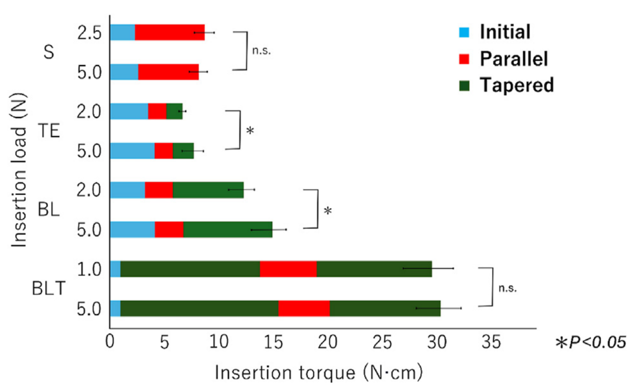

Figure 7 Maximum insertion torque and distribution across different regions Maximum insertion torque and distribution across different regions of the implant. Blue, red, and green represent the initial, parallel, and tapered regions, respectively. S: Standard, TE: Tapered effect, BL: Bone level, BLT: Bone level tapered, n.s.: non significance.

excessive force, which not only risks damaging the workpiece and screw but also increases operator strain and can induce undesirable vibrations, thereby degrading the overall quality of the tightening process.[17]

As optimal and acceptable insertion load ranges are defined through experiments, a significant point emerges: despite its critical role, insertion load applied during implant insertion remains largely operator-dependent and has not been rigorously investigated.

Artificial bone is widely used as a standard material for the mechanical testing of orthopedic implants owing to its consistent properties and ease of availability. Polyurethane used in this study overcomes the limitations associated with biological bones, such as specimen variability and accessibility challenges, making it ideal for biomechanical testing.[18]

This study selected ITV not only because of its high resolution but also because accurate torque—time curves are essential for the analysis of implants. Several methodologies have been proposed to assess implant stability, including Periotest values, resonance frequency analysis (RFA), and torque measurements.[19] Periotest values are limited by their low resolution, poor sensitivity,[20] and susceptibility to operator variability. Furthermore, although RFA is widely recognized as an objective method for monitoring changes in stability over time,[21] previous studies have reported that ITV is more sensitive than RFA for evaluating implant stability.[22]

For cylindrical implants, increasing the load from 2.5 N to 5.0 N did not affect the insertion time or ITV. Hybrid implants showed differences in ITV when the load was altered, with load changes predominantly affecting the initial and crestal tapered regions of the implant. It was hypothesized that, in the initial region, although the apical portions of implants S, TE, and BL were all parallel, both implants TE and BL had a profile on the implant bed. Thus, during implant insertion, an increase in load enhances the contact between the implant and implant bed, leading to an increase in torque in the initial region. In the

Table 1 Torque rise rate on implants TE and BL.

Implant		TE		BL	
Load (N)		2.0	5.0	2.0	5.0
Torque rise rate(N·cm/s)	Initial	0.64	0.70	0.72	0.80
	Parallel	0.17	0.18	0.17	0.19
	Tapered	0.41	0.53	0.65	0.77

Torque rise rate for each region on TE and BL was calculated as follows: $\frac{torque\ change\ for\ each\ region}{time}$. TE: Tapered effect, BL: Bone level.

Table 2 Mean insertion time and standard deviation of each implant.

Implant	S	TE	BL	BLT
Insertion time (s)				
Minimum load	23.84 ± 1.69	21.65 ± 1.50	28.84 ± 1.65	32.92 ± 1.66
5.0 N	22.99 ± 1.29	19.12 ± 0.94	29.71 ± 0.82	28.80 ± 0.71

Insertion time was defined as the duration from the initiation of implant placement to the alignment of the platform with the artificial bone margin. S: Standard, TE: Tapered effect, BL: Bone level, BLT: Bone level tapered.

crestal tapered region, the tapered implant core and profile formation result in greater compression of the surrounding implant bed as the load increases, causing a corresponding increase in torque.[23] Regarding torque increase rates, implant BL exhibited a higher increase in the crestal tapered region than did implant TE. According to the manufacturer's guidelines,[24] the contour of implant BL is closer to parallel than that of implant TE; thus, it results in a more pronounced compression of the implant bed relative to implant TE. These findings are clinically significant because they underscore the effect of load adjustment on primary stability. This study further identified that the compression of the surrounding bone during insertion load varies with implant design. Hybrid implants exhibited variable responses to changes in the insertion load. Conical implants compress the bone during insertion and generate higher torque than that by cylindrical implants, providing an advantage in cases of low bone density.[25] However, both implants were less affected by changes in insertion load.

Only the conical implant showed differences in the insertion time, a phenomenon attributed to the drilling socket design of implant BLT. Fig. 8 shows that threads do not fully engage the implant socket initially, thereby increasing the insertion load and promoting deeper engagement during implant insertion.[26]

No studies have focused on the insertion load of implants. To the best of our knowledge, this study is the first to clarify the existence of both a minimum load and the influence of insertion load on implant insertion. Currently, the insertion load is determined solely based on the dentist's experience and tactile feedback. It has not been incorporated into the training of surgeons. Future training should incorporate systematic load management to enhance the primary stability of implants.

Introduced in 2017, the YOMI robot (Neocis, Miami, FL, USA) is the only FDA-approved dental robot. Although currently serving as a haptic guidance system, drilling and implant insertion are still performed by surgeons.[27] With advances in robotic technology, the introduction of semi-or fully active systems is anticipated.[28] Currently, the human tactile sensation cannot precisely control the insertion load. However, robotic systems allow accurate load

Figure 8 Microscopic observations of BLT implant insertion. Cutting chamber of implant BLT, which is approximately 5 mm in length, does not engage with the implant socket. BLT: Bone level tapered.

control, making optimization of the insertion load a key factor in ensuring precise and reliable implant insertion.[29]

This study was limited to testing only two load conditions, a single bone quality, and four implant designs. Future research should explore a wider range of loads, bone qualities, and implant designs. Moreover, the manufacturer's protocol did not effectively utilize the cutting chamber, rendering its effects unclear. The drilling method must be modified to clarify the effect of the cutting chamber, thereby providing a more comprehensive understanding of the relationship between load and primary stability.

In conclusion, the minimum load required varied according to the implant design. For the implant S, no differences in ITV or insertion time were observed between 2.5 N and 5 N. For the implants TE and BL, increasing the load from 2.0 N to 5.0 N corresponded to a rise in ITV, while insertion time remained unchanged. For the implant BLT, although increasing the load from 1.0 N to 5.0 N did not affect ITV, it resulted in a reduction in the insertion time. This study demonstrated that both ITV and insertion time are influenced by the load in certain implant designs, and these effects depend on the position of the first thread relative to the drilling socket.

Declaration of competing interest

The authors report no conflicts of interest related to this study.

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