

# Biomechanical Evaluation of Orthodontic Miniscrews: How Insertion Angle and Number of Insertions Impact Pull-Out Strength

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Received 7 July 2026; 1<sup>st</sup> revision 18 July 2026; 2<sup>nd</sup> revision 12 August 2026; Accepted 19 August 2026;

Published online 28 August 2026

## Keywords:

Biomechanical phenomena, bone screw, materials testing, polyurethanes.

## ABSTRACT

**Background:** This study aimed to analyze the effects of insertion angle and number of insertions on miniscrew pull-out strength in polyurethane bone blocks.

**Method:** In this experimental study, 30 miniscrews (Mico One; 2 mm diameter and 10 mm length) were inserted into Sawbones polyurethane blocks consisting of a 2 mm cortical layer (40 pcf) and an 18 mm trabecular layer (20 pcf). Samples were divided into six groups based on insertion angle (45°, 70°, and 90°) and number of insertions (single vs. repeated). Pull-out strength was measured using a Universal Testing Machine (UTM). Data were analyzed using two-way ANOVA followed by Tukey's HSD post hoc test, with significance set at  $p < 0.05$ .

**Result:** In the single-insertion group, the insertion angle significantly affected pull-out strength ( $p < 0.05$ ). The 70° angle yielded the highest mean pull-out strength ( $339.98 \pm 20.76$  N), which was significantly higher than that of the 90° angle ( $299.93 \pm 20.45$  N;  $p < 0.05$ ). In the repeated-insertion group, the insertion angle did not significantly affect pull-out strength ( $p > 0.05$ ). Although the repeated-insertion group showed a lower mean pull-out strength ( $307.88 \pm 24.78$  N) than the single-insertion group ( $318.34 \pm 25.21$  N), the difference was not significant ( $p > 0.05$ ).

**Conclusion:** Insertion angle significantly influences pull-out strength in single-insertion miniscrews, with 70° providing the highest strength. The number of insertions (single vs. repeated) does not significantly affect pull-out strength. These findings have implications for clinical anchorage strategies and experimental protocols using polyurethane bone analogs.

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doi: <http://dx.doi.org/10.30659/odj.13.2.162-171>.

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Odonto : Dental Journal accredited as **Sinta 3 Journal** (<https://sinta.kemdikbud.go.id/journals/profile/3200>)

How to Cite: Maulani, et al. Biomechanical Evaluation of Orthodontic Miniscrews: How Insertion Angle and Number of Insertions Impact Pull-Out Strength. Odonto: Dental Journal, v.13, n.2, p.162-171, August 2026.

## INTRODUCTION

Temporary Anchorage Devices (TADs), also known as miniscrews, have various applications in clinical orthodontic practice, particularly for anchorage optimization, and have become an essential component of orthodontic treatment.<sup>1</sup> The use of orthodontic miniscrews as absolute anchorage expands treatment possibilities, improves treatment efficiency, and enhances treatment quality.<sup>2,3</sup> Orthodontic miniscrews are considered a preferred method for reinforcing anchorage in patients requiring maximum anchorage and are effective in preventing undesirable dentoalveolar side effects.<sup>3</sup> In addition, orthodontic miniscrews provide excellent mechanical retention and sufficient anchorage, can be used in noncompliant patients, are minimally invasive, and allow easy insertion and removal procedures.<sup>4</sup>

Primary stability is a key determinant of miniscrew success.<sup>5</sup> Miniscrew stability can be quantitatively evaluated using several methods, including Periotest, resonance frequency analysis, pull-out test, and insertion and removal torque measurements (Table 1).<sup>6,7</sup> Miniscrew stability does not depend on osseointegration, but rather on the mechanical interlocking with the surrounding bone tissue established immediately after insertion, enabling the miniscrew to withstand orthodontic loading.<sup>3,8</sup> Therefore, miniscrews must remain stable during orthodontic force application to ensure treatment effectiveness. Miniscrews are inserted into cortical bone at an appropriate angle according to the required orthodontic movement. The trajectory of insertion is largely governed by the structural configuration of the alveolar bone alongside the intended path of orthodontic tooth movement. Insertion techniques, including insertion angle and insertion method, play an important role in achieving primary stability.<sup>5</sup>

Miniscrews should be inserted at a specific angle relative to the bone surface to increase the bone–miniscrew contact area.<sup>4,9</sup> Miniscrews inserted perpendicular to the tooth axis provide less bone support compared with those inserted at an oblique angle.<sup>10</sup> However, the influence of insertion angle on primary stability remains controversial.<sup>11</sup> Meira et al. evaluated primary stability at insertion angles of 45°, 60°, and 90°, while Raji et al. investigated insertion angles of 45°, 60°, and 75°, concluding that lower insertion angles were associated with increased primary stability.<sup>5</sup> Wilmes et al.<sup>12</sup> reported that insertion angles of 60°–70° produced higher primary stability than a 30° insertion angle. In contrast, Araghbidikashani et al. and Maya et al. found that a 90° insertion angle resulted in the highest primary stability, which decreased as the insertion angle became smaller.<sup>11</sup>

**Table 1. Methods for measuring Miniscrew Stability<sup>7</sup>**

| Invasive Methods                                                | Non-invasive Methods                              |
|-----------------------------------------------------------------|---------------------------------------------------|
| - Evaluated through histological and histomorphometric analyses | - Resonance Frequency Analysis monitoring (RFA)   |
| - Measurement of Cutting Resistance Torque                      | - Computational finite element simulations (FEA)  |
| - Removal Torque Value Evaluation                               | - Radiographic and imaging assessments            |
| - Insertion Torque Evaluation                                   | - Clinical percussion testing                     |
| - <i>Pull-Out Test</i>                                          | - Subjective perception of the clinician/operator |
|                                                                 | - Analysis of pulsed oscillation waveforms (POW)  |
|                                                                 | - Periotest                                       |

One of the main limitations of orthodontic miniscrews is insufficient stability, which may result in loosening or failure before the clinical objectives are achieved. Mandibular insertion sites are associated with a higher risk of miniscrew failure.<sup>13</sup> Hong et al.<sup>14</sup> demonstrated that the stability of miniscrews inserted in the mandible was significantly lower than that of miniscrews inserted in the maxilla, being 2,23 times lower. The failure rate of miniscrews placed in the mandibular vestibular area has been reported to range from 13,5% to 14,3%, indicating a relatively higher risk of failure compared with other insertion sites.<sup>13,15,16</sup> Miniscrew loosening remains frequently encountered in daily clinical practice. Clinicians may modify the treatment plan or perform reinsertion when miniscrews become loose or detached. Primary and secondary miniscrew failure may be caused by several incidental factors, including variations in bone quality at the insertion site, procedural errors by inexperienced operators, and peri-implant tissue infection associated with poor oral hygiene.<sup>17</sup>

Several studies have evaluated the effect of insertion angle variation on the stability of orthodontic miniscrews; however, inconsistent findings have been reported in both experimental and clinical settings. Repeated orthodontic miniscrew insertion is commonly performed in clinical practice, particularly in cases of primary failure or when repositioning is required. Although previous studies have investigated miniscrew reinsertion, no study has specifically evaluated secondary insertion at the same site. Therefore, this study was conducted to analyze the pull-out strength of miniscrews in polyurethane bone blocks based on insertion angle and insertion frequency at the same insertion site. This study aimed to evaluate the differences in miniscrew pull-out strength values in polyurethane bone blocks according to variations in insertion angle (90°, 70°, and 45°) and insertion frequency (single and repeated insertion).

## RESEARCH METHOD

This study was conducted under a Research Permit Letter (No. 6653/UN6.F.1/PT.00/2025) at the Orthodontic Specialist Residency Clinic and Integrated Research Laboratory, Faculty of Dentistry, Universitas Padjadjaran, Bandung, Indonesia. Because this in vitro study utilized synthetic bone blocks and did not necessitate ethical approval, given that the study design excluded both human and animal models. In this study, purposive sampling was employed. A total of 30 miniscrews were divided into six groups based on their number of insertions and insertion angles: K1 (single insertion at 90°), K2 (single insertion at 70°), K3 (single insertion at 45°), R1 (repeated insertion at 90°), R2 (repeated insertion at 70°), and R3 (repeated insertion at 45°) in polyurethane bone blocks.

The inclusion criteria were polyurethane bone blocks with a cortical layer density of 40 pounds per cubic foot (pcf) equivalent to 0,64 g/cm<sup>3</sup> (2 mm thickness), and a trabecular layer density of 20 pcf equivalent to 0,32 g/cm<sup>3</sup> with an 18 mm thickness, simulating mandibular bone properties. The bone blocks had uniform dimensions (20 mm × 20 mm × 20 mm), intact surfaces without cracks or physical defects, and had not been previously used for miniscrew insertion. Stainless steel miniscrews (2 mm in diameter, 10 mm in length) were employed. All miniscrews were intact and free from fracture or physical defects. The instruments and materials used in this study included a Universal Testing Machine (Ametek Lloyd Instruments, LRX Plus), electric torque driver (Orthonia-111-ED-010), short blade (Mico One Type AS), 90°, 70°, and 45° positioners, ultrasonic cleaner (Klazz 460 MI), saw, hard wire cutter (Hu-Friedy®), Mathieu plier (Hu-Friedy®), polyurethane bone blocks (Sawbones, Pacific Research Laboratories, Vashon Island, WA, USA), miniscrews (2 mm in diameter, 10 mm in length, Mico One), 0,012 inch stainless steel wire (Morelli), and distilled water (Water One). ISO-certified Mico

One miniscrews were selected for their cost-effectiveness, widespread clinical availability, and compliance with study specifications. Additionally, 0.012-inch Morelli stainless steel roll wire was utilized because Mico One does not offer wire in roll form. This wire ensured efficient fixation by providing the necessary rigidity to stabilize the positioner against the bone block during miniscrew insertion while maintaining optimal flexibility for handling. The positioner was attached to each polyurethane bone block and stabilized using stainless steel wire (Fig. 1). Miniscrews were inserted into the bone blocks through 90°, 70°, and 45° positioners using an electric torque driver with an insertion torque of 30 Ncm and high-speed rotation mode (20 rpm), according to the manufacturer's specifications, until all miniscrew threads were fully embedded in the bone block (Fig. 1).

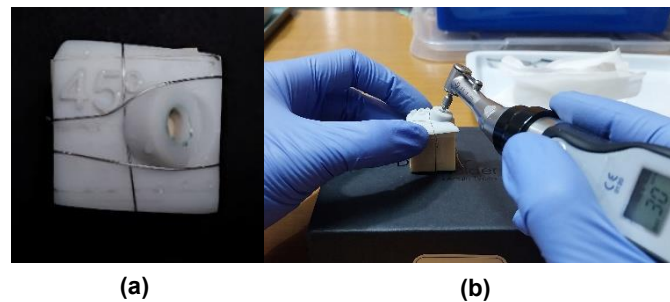


**Figure 1.** Fixation of the positioner onto the bone block (a). Miniscrew insertion into the bone block using an electric torque driver (b).

An electric torque driver was employed to extract the miniscrews from the respective bone blocks, with the device configured at a torque limit of 30 Ncm and a high-speed mode of 20 rpm, in accordance with the manufacturer's specifications for the repeated-insertion sample group. Adhering bone debris was removed from the screw threads using an ultrasonic cleaner (45 Hz) for 6 minutes according to the manufacturer's instructions, followed by rinsing with distilled water and drying (Fig. 2). The miniscrews were then re-inserted into the same location within the bone block using the same procedure as previously described.

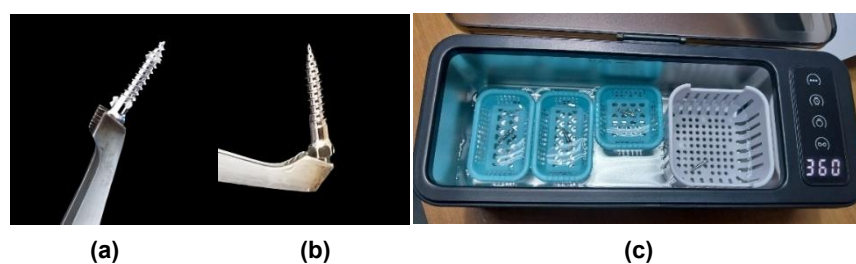


**Figure 2.** Ultrasonic cleaning of the miniscrew to remove adhering bone debris from the threads: (a) bone debris adhering to the miniscrew threads; (b) miniscrew after cleaning; (c) ultrasonic cleaner device.

All miniscrews inserted into the bone blocks (Fig. 3) were mounted onto a Universal Testing Machine (UTM). The bone blocks were positioned to ensure the miniscrews were aligned with the pulling direction of the UTM. It was ensured that the direction of the pull remained parallel to the long axis of the miniscrew to achieve axial loading (Fig. 4). The tensile testing mode was configured with a constant crosshead speed of 10 mm/min. The UTM recorded force-displacement curves throughout the testing process. The maximum load (N) achieved just prior to the dislodgement of the miniscrew was recorded as the pull-out strength. Statistical variations in the

pull-out strength data were assessed using a two-way ANOVA, with subsequent mean comparisons evaluated via Tukey's Honestly Significant Difference (HSD) post-hoc test. The threshold for statistical significance was established at  $p < 0.05$ .

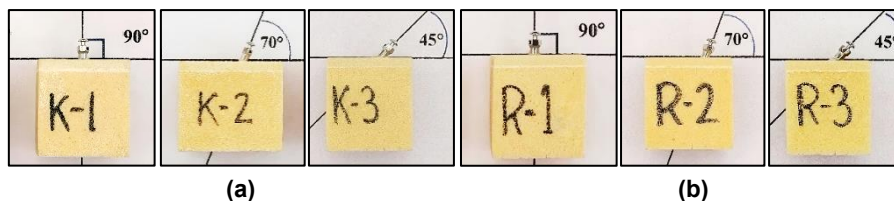


**Figure 3.** Miniscrew insertion into the polyurethane bone block: (a) single insertion; (b) re-insertion.

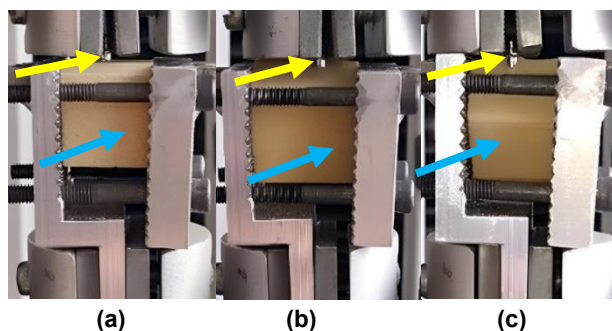


**Figure 4.** Mounting of the miniscrew samples embedded in the bone blocks onto the Universal Testing Machine (Ametek Lloyd Instruments, LRX Plus): (a) 90° insertion angle; (b) 70° insertion angle; (c) 45° insertion angle. Yellow arrows indicate the miniscrew and blue arrows indicate the polyurethane bone block.

## RESULTS

In the single-insertion group, the lowest pull-out strength was observed at an insertion angle of 90° (279,8290 N), while the highest value occurred at 70° (359,9817 N) (Table 2). In the repeated-insertion group, the lowest pull-out strength was similarly observed at 90°, whereas the highest occurred at 70° (Table 3). Figure 5 illustrates the pull-out strength testing results, where the maximum force obtained was defined as the pull-out strength. The greatest slope on the graph represents the steepest load-increase phase, reflecting the initial mechanical resistance between the miniscrew threads and the polyurethane bone block.

**Table 2. Pull-out strength results of the single-insertion miniscrew group**

| Sample Number | Pull Out Strength value (Newton) |          |          |
|---------------|----------------------------------|----------|----------|
|               | 90°                              | 70°      | 45°      |
| 1             | 310,3030                         | 353,5399 | 331,5551 |
| 2             | 329,8719                         | 345,9855 | 338,2424 |
| 3             | 284,3215                         | 332,8378 | 294,4578 |
| 4             | 295,3091                         | 359,9817 | 304,6416 |
| 5             | 279,8290                         | 307,5385 | 306,6767 |

**Table 3. Pull-out strength results of the repeated-insertion miniscrew group**

| Sample Number | Pull Out Strength value (Newton) |
|---------------|----------------------------------|
|---------------|----------------------------------|

|   | 90°      | 70°      | 45°      |
|---|----------|----------|----------|
| 1 | 298,1175 | 319,7145 | 307,8808 |
| 2 | 312,1644 | 334,9526 | 321,0728 |
| 3 | 237,1244 | 330,6739 | 322,9939 |
| 4 | 317,3189 | 291,4074 | 280,7906 |
| 5 | 331,8749 | 307,5261 | 304,5752 |

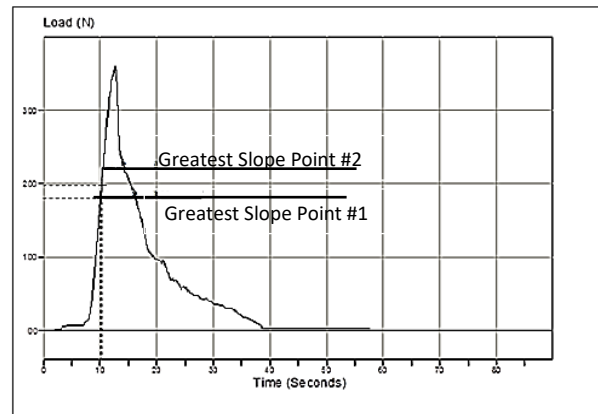


**Figure 5.** Pull-out strength testing graph of the miniscrew.

The statistical analysis using two-way ANOVA (Table 4) revealed that the insertion angle substantially influenced the mechanical pull-out strength of the miniscrews ( $p = 0,032$ ). In contrast, the number of insertions (single insertion vs. repeated insertion) did not significantly influence the pull-out strength ( $p = 0,224$ ), and there was no significant interaction between the insertion angle and number of insertions ( $p = 0,541$ ). As summarized in Table 4, within the single-insertion group, 70° angle yielded the highest mean pull-out strength ( $339,98 \pm 20,76$  N). Post-hoc analysis using the Tukey HSD test indicated that for the single-insertion protocol, the pull-out strength at a 70° angle was significantly higher than at a 90° angle ( $p < 0,05$ ). However, no statistically significant differences were observed when comparing the 70° and 90° angles to the 45° angle ( $p > 0,05$ ). Regarding the repeated-insertion group, although the 70° angle also exhibited the highest numerical value, the various insertion angles exhibited no statistically significant variations. ( $p > 0,05$ ).

**Table 4.** Mean pull-out strength (N) of miniscrews at different insertion angles and number of insertions.

| Insertion Angle        | Single Insertion<br>(Mean $\pm$ SD)  | Re-Insertion<br>(Mean $\pm$ SD) | $p$ -value (Angle) |
|------------------------|--------------------------------------|---------------------------------|--------------------|
| 90°                    | 299,9269 $\pm$ 20,4521 <sup>a</sup>  | 299,3200 $\pm$ 36,8052          | 0,032              |
| 70°                    | 339,9767 $\pm$ 20,7573 <sup>b</sup>  | 316,8549 $\pm$ 17,7572          |                    |
| 45°                    | 315,1147 $\pm$ 18,7934 <sup>ab</sup> | 307,4627 $\pm$ 16,9290          |                    |
| $p$ -value (Frequency) |                                      | 0,224                           | Interaction: 0,541 |

Notes:

SD: Standard Deviation.

Values with different superscript letters (<sup>a</sup>,<sup>b</sup>) indicate a statistically significant difference ( $p < 0,05$ ) between insertion angles within the same frequency group based on Tukey's HSD test.

$p$ -values are derived from Two-Way ANOVA analysis.

## DISCUSSION

From a mechanical perspective, achieving optimal primary stability during miniscrew placement aims to secure maximum interdigitation between the miniscrew threads and the surrounding bone tissue, while generating controlled compressive forces on the bone.<sup>18</sup> The contact between bone and miniscrew, termed primary stability, plays a crucial role in the success of implantation, particularly during the initial phase prior to bone remodeling and healing.<sup>19,20</sup> Primary stability is derived from a combination of bone displacement and compaction during miniscrew insertion, resulting in a tight mechanical interlocking between the miniscrew and the bone.<sup>21</sup> An optimal balance between achieving high primary stability and minimizing micro-damage to the bone tissue is a key factor in ensuring the long-term success of miniscrew applications.<sup>19</sup>

The pull-out test simulates the stress on a miniscrew by applying a controlled force counter to its insertion path. The force required to dislodge the miniscrew indicates its stability level.<sup>7</sup> In the pull-out strength test of this study, the miniscrew was aligned with the axis of the mechanical testing machine (axial direction); thus, the contact between the miniscrew and the cortical bone resulting from the calculated angle differences was accounted for.<sup>4</sup> Higher test values indicate greater stability.<sup>18</sup> The pull-out test (axial direction) is widely used in orthodontics to evaluate the biomechanical performance of miniscrews, although orthodontic forces are clinically not applied parallel to the long axis of the miniscrew.<sup>4</sup> In this study, a tensile force was applied axially to the miniscrew to assess its stability based on the degree of contact between the miniscrew and the cortical bone. Although tangential loading is considered more representative of the clinical conditions of orthodontic forces, this method was not employed in the present study due to limitations in standardization and reproducibility. Technical difficulties in cantilever bending tests have the potential to produce wide and inconsistent data variations.<sup>4</sup>

Salmória et al. reported that the pull-out strength of miniscrews is at its highest immediately following insertion. Leung et al. demonstrated that implant dimensions and design play a critical role in determining mechanical retention.<sup>7</sup> However, the pull-out test has certain limitations; this testing procedure causes damage to the miniscrew site, making it unsuitable as a routine assessment method for evaluating mechanical retention between the miniscrew and the bone.<sup>7</sup> Our findings demonstrated that the 70° insertion angle optimized primary stability within the single-insertion protocol, whereas the 90° angle consistently resulted in the lowest mechanical retention. These findings align with the research by Meira et al., which concluded that from a biomechanical perspective, miniscrews placed at an inclination to the bone surface provide higher primary stability than those placed perpendicularly.<sup>22</sup> While Meira et al.<sup>23</sup> found the 45° angle to be superior, this study identified 70° as the optimal angle. This discrepancy may be attributed to the fact that smaller insertion angles result in shallower penetration depths, potentially reducing resistance to pull-out forces. Shallower penetration increases the distance between the miniscrew head and the cortical bone, making the exposed neck and head more susceptible to movement and increasing the risk of failure.<sup>4</sup>

Furthermore, Araghbidikashani et al. reported that while oblique insertion (45° to 90°) enhances stability under shear loads, the 90° angle provides the highest stability under tensile (pull-out) forces.<sup>9</sup> The difference observed in our study (70° being superior) is likely due to the direction of the applied force; Araghbidikashani et al. applied forces perpendicular to the alveolar surface, whereas this study applied forces parallel to the miniscrew's long axis. Our findings are consistent with Wilmes et al., who recommended an insertion angle of 60°–70° for optimal primary stability based on insertion torque measurements.<sup>12</sup> Similarly, Min et al. and Deguchi et al. reported that oblique insertion increases cortical bone contact area, leading to better initial stability.<sup>22,24</sup>

These findings also support the results of Xu et al., which identified 50° and 70° as the most optimal angles for initial stability.<sup>25</sup>

Early failure of miniscrews is primarily attributed to factors related to weak integration between the miniscrew and bone, leading to inadequate primary stability.<sup>26</sup> The re-insertion of a miniscrew may become mandatory as a secondary orthodontic procedure if the initial mechanical stability is inadequate. In certain cases, repositioning the miniscrew is required, and the potential for recycling miniscrews can reduce treatment costs while enhancing outcomes.<sup>27</sup> In instances of early failure, re-insertion may be an option provided the material has not undergone structural or functional changes.<sup>27</sup> Based on the number of insertions in this study, the mean pull-out strength for repeated insertion was lower than that for single insertion (Table 4), although the difference was not statistically significant ( $p > 0.05$ ). The wear on miniscrew threads due to reuse can reduce thread depth and the surface area between the miniscrew and bone, thereby decreasing mechanical embedding properties. This condition may lead to reduced bone-miniscrew contact and subsequently impact the mechanical strength.<sup>26</sup> These results are consistent with the study by Hergel et al., which concluded that miniscrews could be re-inserted, particularly in cases of early failure, for a second time without significant changes to their mechanical and structural properties.<sup>27</sup> Similarly, Aarash et al. concluded that using miniscrews up to two times does not significantly affect mechanical strength or result in adverse clinical impacts.<sup>22</sup> A primary limitation of this study is that the applied axial pull-out force does not fully replicate the complex dynamic loading and multidirectional stresses encountered in the oral cavity. Future studies should consider modifying the loading direction or incorporating tangential force models to more accurately represent clinical orthodontic conditions, as well as utilizing real bone models, larger sample sizes, and mini-implants with varying diameters and lengths

## CONCLUSION

This study concludes that an insertion angle of 70° provides optimal primary stability for orthodontic miniscrews, significantly outperforming the 90° angle. Additionally, the number of insertions does not significantly diminish pull-out strength, indicating that miniscrew repeated insertion is a biomechanically acceptable procedure in clinical practice. While this research offers valuable guidance for optimizing anchorage, its reliance on static axial loading remains a limitation. Future studies should incorporate dynamic force models to better simulate the complex multidirectional stresses of the oral environment.

## ACKNOWLEDGEMENT

The authors would like to express their gratitude to the Faculty of Dentistry, Universitas Padjadjaran, Bandung, Indonesia, for granting the necessary institutional backing and laboratory resources required to successfully conduct this study.

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