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Original Article

Optimizing Orthodontic Anchorage: Comparative Evaluation of Larger Diameter, Shorter Length Mini-Implants for Enhanced Mechanical Stability

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Abstract

Aim: We aim to assess and contrast the mechanical stability of two mini-implant designs, featuring larger diameters and shorter lengths, for orthodontic anchorage against a conventional group of implants.

Materials and methods: Three groups of mini-implant underwent testing: the implants in Group 1 were 2.5 mm in diameter and 4 mm in length; the implants in Group 2 were 3 mm in diameter and 3 mm in length; and the conventional group implants were 1.3 mm in diameter and 7 mm in length. Both types were Abso Anchor mini-implants (Dentos Inc.). The implants' mechanical stability was assessed using the maximum insertion torque (MIT), the maximum removal torque (MRT), and the angulated lateral displacement tests for compression and tension force vectors. Fourteen mini-implants of each design were used to measure MIT and MRT. Seven mini-implants of each design were tested for lateral displacement.

Results: Torque tests - Group 2 mini-implants showed superior primary stability with higher MIT and MRT values compared to Group 1 and the conventional group implants. Lateral displacement tests - Group 2 mini-implants required significantly greater compressive force than those in Group 1 and the conventional group. Tension force for lateral displacements was similar between the three groups.

Conclusion: Group 2 mini-implants, with larger diameters and shorter lengths, demonstrated superior primary stability over Group 1 implants. Despite the differences in compressive force, all three groups performed similarly under tension in lateral displacement tests.

Keywords

anchorage, compression, lateral displacement, mini-implants, torque, tension

INTRODUCTION

Over the past decade, orthodontic mini-implants have become increasingly popular as a crucial tool for establishing absolute anchorage, achieving mechanical stability, and reducing reliance on patient compliance.[1-3] Improvements in mini-implant design have aimed to maximize orthodontic anchorage while minimizing unwanted tooth movements. These advancements have enabled the successful treatment of complex cases that would be challenging with conventional orthodontics alone.

Conventional mini-implants provide satisfactory stability but are limited in placement due to their larger lengths, which increase the risk of damage to nearby roots during orthodontic treatment. Major stability of mini-implants is obtained from the cortical bone, with maximum cortical bone thickness typically around 2-3 mm.[4-7] Thus, if mini-implants with larger diameters and shorter lengths demonstrate satisfactory stability, they could be used in a wider range of areas and applications without risking damage to adjacent structures. Such experimental designs have the potential to transform the use of mini-implants.[8-10]

This study is designed to evaluate the mechanical stability of mini-implants with larger diameters and shorter lengths. The scope of mini-implants has expanded to include both orthodontic and orthopedic movements.[11,12] For orthodontic tooth movements, a light force of 20–200 g is ideal for various clinical treatments, such as retraction, molar intrusion, extrusion, and open bite correction. In contrast, dentofacial orthopedic movements typically require forces greater than 500 g for maxillary and mandibular growth modification to correct skeletal discrepancies.[13] Traditional orthopedic treatments involve devices like palatal expanders and extraoral appliances, such as headgears and face masks.[14] Recently, mini-implants have been applied with palatal expanders to achieve greater sutural expansion. Given the expanded application of mini-implants in orthodontics, it is essential to examine their stability under various clinical conditions.

This study includes angulated compression and tension tests to simulate the forces applied to mini-implants under diverse clinical conditions. Lateral displacement tests involve applying angulated compression (pushing the implant into the bone) or angulated tension (pulling the implant out of the bone) forces on the implant neck. Primary stability is often measured by the insertion torque, the force required to screw the implant into the bone. Removal torque, reflecting the implant-bone interface during and after long-term orthodontic treatment, evaluates the anchorage capability of mini-implants.

AIM

This study assesses the mechanical stability of experimental mini-implant designs using maximum insertion torque and maximum removal torque.

MATERIALS AND METHODS

This study was conducted to evaluate and compare the mechanical stability of two implant designs with different diameters and lengths.

Materials

1. Experimental implants

Two types of mini-implants were used:

- Group 1: 2.5 mm in diameter and 4 mm in length
- Group 2: 3 mm in diameter and 3 mm long (Abso Anchor, Dentos Inc.)

The implants were made from titanium 6 aluminum 4 vanadium ELI alloy, with a cylindrical shape and self-drilling capability **(Fig. 1)**.

2. Implant driver

A long hand-type implant driver was used, consisting of a handle body with a supporting handle, locking nut, rotating handle, and a torque gauge. The DT-S type handle tip was used for the short head type of implants.

3. Sheep bone

Sheep mandibular bone, cut to 18 mm length and 18 mm width, was employed in the investigation **(Fig. 2A)**. The bone samples were stored in plastic containers and refrigerated before use.

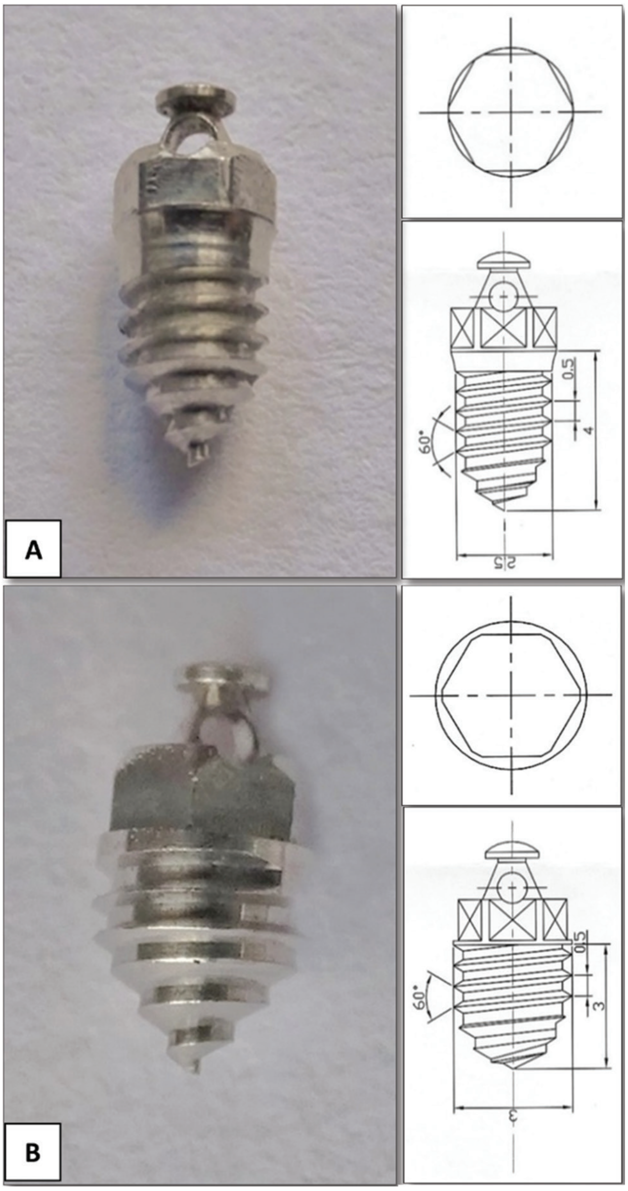

Figure 1. Designs of experimental mini-implants by Dentos Inc. Korea.

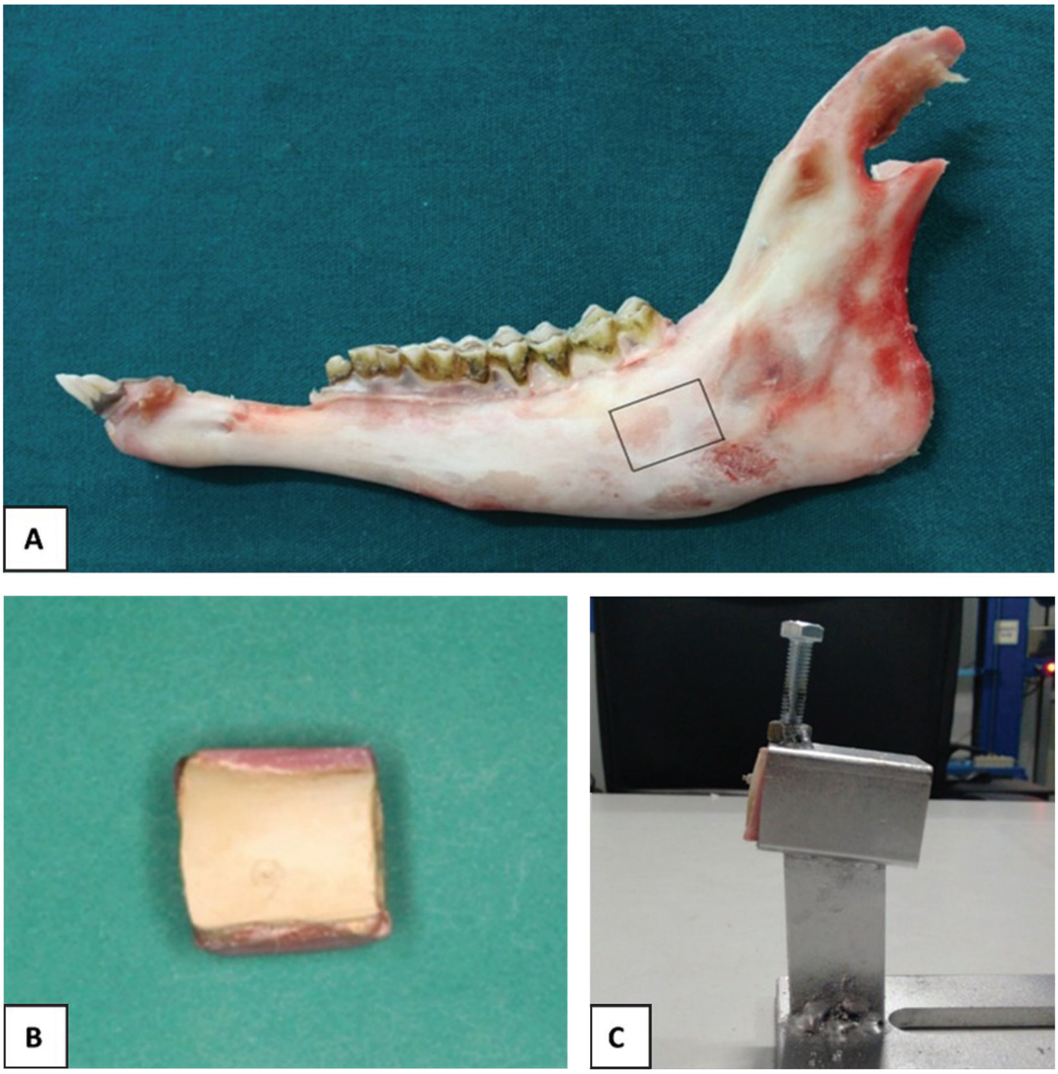

Figure 2. **(A)** Specimen of sheep mandible used for testing. A rectangular box on the sheep mandibular bone shows the region from where the bone samples were obtained; **(B)** The bone sample mounted on acrylic block; **(C)** An angulated vise with secured bone sample.

4. Cold cure acrylic material

Bone samples were mounted in a rectangular block of cold cure acrylic (DPI-RR Cold Cure) **(Fig. 2B)**.

5. Vise

A vise with 10° and 20° angulation was constructed to secure the bone blocks during testing **(Fig. 2C)**.

6. Testing machine

We used a computerized, software-based, universal strength Star system testing machine, model No. STS-248. The apparatus included an upper crosshead with a sharp chisel-shaped rod and a lower holding jig for the mounted bone sample assembly.

7. Other materials

Additional materials included a slow-speed handpiece and air motor, modeling wax, and separating media.

Method of data collection

1. Bone sample preparation

- Twenty-eight bone samples (18×18 mm) were cut from 14 sheep mandibles, stored in plastic containers in refrigerators before the study.
- All samples were mounted on cold cure acrylic using a customized rectangular metal block **(Fig. 3)**.

2. Insertion torque

- Fourteen mini-implants of each design were inserted and removed using a manual implant driver with a torque gauge.
- The maximum insertion torque (MIT) and maximum removal torque (MRT) were measured for each sample **(Fig. 4)**.

3. Angulated lateral displacement test

- Seven new mini-implants of each design were tested at two angles (10° and 20°) for both compression and tension forces.

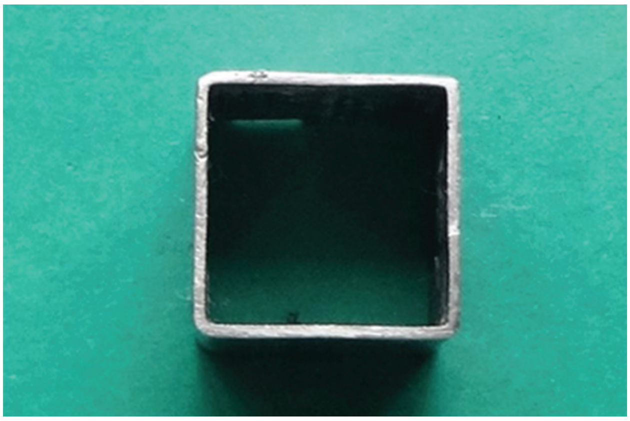

Figure 3. Rectangular metal block used for mounting bone samples.

Figure 4. Implant driver with torque gauge (Absco Anchor LHD DT-S driver) consisting of resisting torque force ranging from 0.5 Kgf.Cm to 2.0 Kgf.Cm.

- Mechanical testing was performed using the Star Testing System (model No. STS-248), which recorded force and displacement data **(Fig. 5)**.

4. Surface area measurement

- The surface area of the threaded region of the mini-implants was measured using a high-resolution work microscope (WM1300 CNC, Dr. Heinrich Schneider Messtechnik, Germany) with SAPHIR software analysis.
- A conventional mini-implant (1.3 mm in diameter, 7 mm long) was included for comparison.

Surface characteristics of mini-implants

The external surface was divided into head and thread regions for measurement and analysis **(Fig. 6)**.

Statistical analysis

Data was presented as mean and standard deviation (SD). The mechanical stability of two experimental implant designs was evaluated using maximum insertion torque, maximum removal torque tests, and angulated lateral displacement tests. Fourteen samples from each mini-implant group were included in the study. Mean MIT and MRT were compared across implant designs using One-way ANOVA test, while mean force levels for each lateral displacement distance were compared across designs and angulations using the same test. The *p*-value threshold was set to <0.05.

RESULTS

The study evaluated and compared the mechanical stability of two mini-implant designs. Mean and standard deviations (SD) were calculated for various measurements, with differences analyzed using One-Way ANOVA. The *p*-value of <0.05 was considered significant.

Surface area measurement

Mini-implants were scanned using a high-resolution microscope and analyzed with SAPHIR software. The surface area of the threaded region was measured for three designs: conventional (1.3×7 mm), Group 1 (2.5×4 mm), and Group 2 (3×3 mm). The surface areas were 21.480 mm^2 for the conventional implant, 28.289 mm^2 for Group 1, and 29.384 mm^2 for Group 2 **(Table 1)**.

Table 1. Showing surface area of the threaded region of mini-implant designs

Groups	Dimension	Surface area of threaded region
Conventional	1.3×7 mm	21.480 mm^2
Group 1	2.5×4 mm	28.289 mm^2
Group 2	3×3 mm	29.384 mm^2

Torque tests

The comparison of insertion torque among the groups showed a statistically significant difference with a *p*-value of <0.00001. Group 2 exhibited the highest mean insertion torque, followed by Group 1, and the Conventional group had the lowest. The removal torque also showed a statistically significant difference among the groups with a *p*-value of 0.001231. Group 2 had the highest mean removal torque, followed by Group 1, and the Conventional group had the lowest **(Fig. 7, Tables 2, 3)**.

These comparisons **(Table 3)** indicate significant differences in insertion torque between all groups, while for removal torque, significant differences are found between Conventional group and Group 2, and Group 1 and Group 2, but not between Conventional group and Group 1.

Angulated lateral displacement tests

Compression test: At 10° angulation, Group 2 implants required significantly higher mean forces for displacements of 0.01 mm, 0.02 mm, and 0.03 mm compared to Group 1 and Conventional group (*p*=0.017, *p*=0.002, and *p*=0.001, respectively) **(Tables 4, 5)**. At 20° angulation, Group 2 also required significantly higher forces for all displacements (*p*=0.011, *p*=0.002, and *p*=0.001, respectively) **(Fig. 8, Tables 4, 5)**.

Compression Force Tests - *at 10° angulation:*

– 0.01 mm displacement: Conventional group:

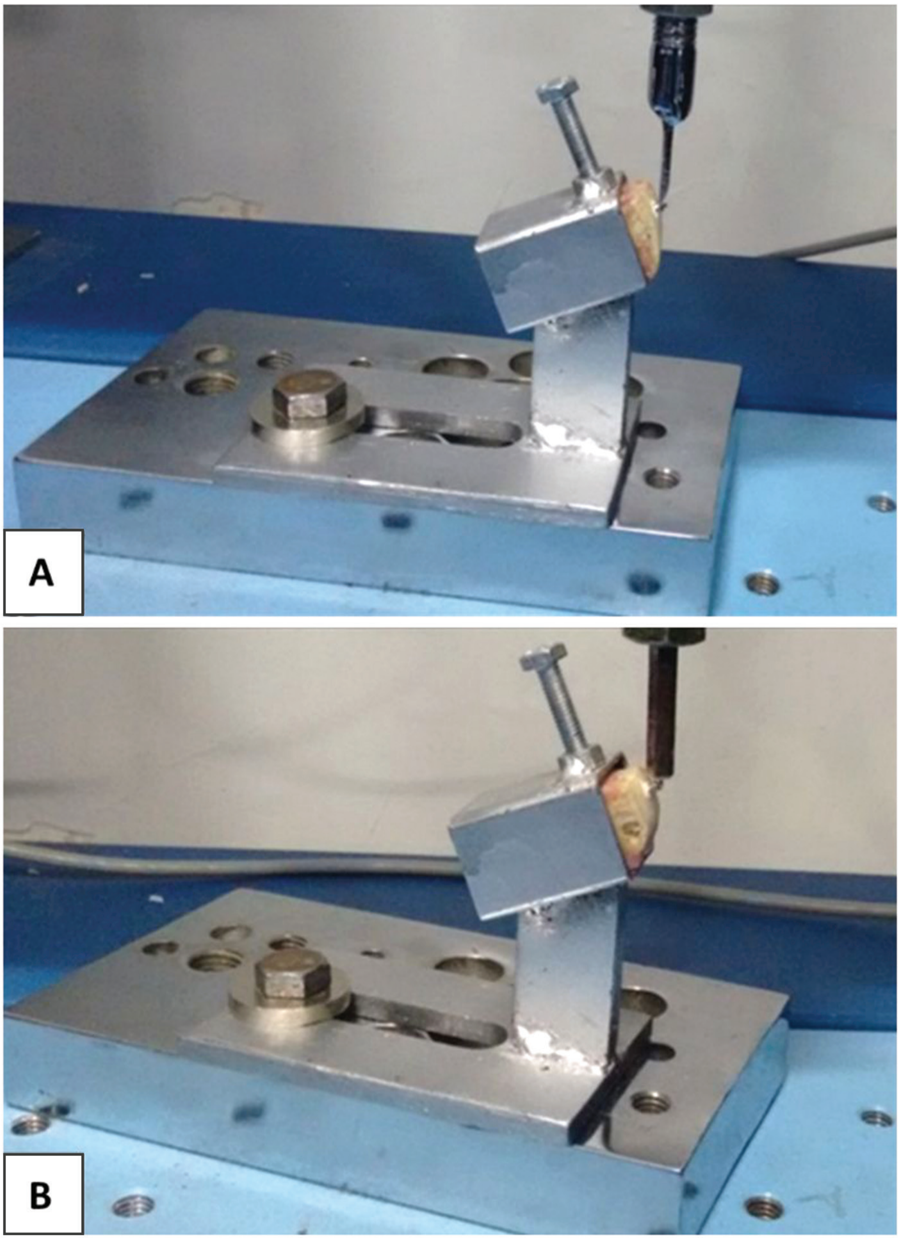

Figure 5. **(A)** Compression force; **(B)** Tension force vectors applied with Star testing System, India (Model no. STS 248).

Table 2. Mean maximum insertion torque (MIT) and mean maximum removal torque (MRT) values for the experimental mini-implants

Measurements	Conventional		Group 1		Group 2		p-value
	Mean	SD	Mean	SD	Mean	SD	
MIT	10.00	1.50	12.95	2.79	16.80	2.70	<0.00001*
MRT	5.05	1.05	5.60	1.15	7.70	1.31	0.001231*

* $p \leq 0.05$;*** $p \leq 0.001$

86±15.15 gm, Group 1: 99.86±20.57 gm, Group 2: 151.57±47.64 gm (p=0.017);

- 0.02 mm displacement: Conventional group: 190±13.00 gm, Group 1: 218.71±20.93 gm, Group 2: 385.43±97.01 gm (p=0.002);
- 0.03 mm displacement: Conventional group: 301±20.00 gm, Group 1: 345.86±43.16 gm, Group 2: 609.43±123.62 gm (p=0.001).

Compression Force Tests - *at 20° angulation:*

- 0.01 mm displacement: Conventional group: 96±20 gm, Group 1: 123.00±40.75 gm, Group 2: 217.00±68.38 gm (p=0.011);
- 0.02 mm displacement: Conventional group:

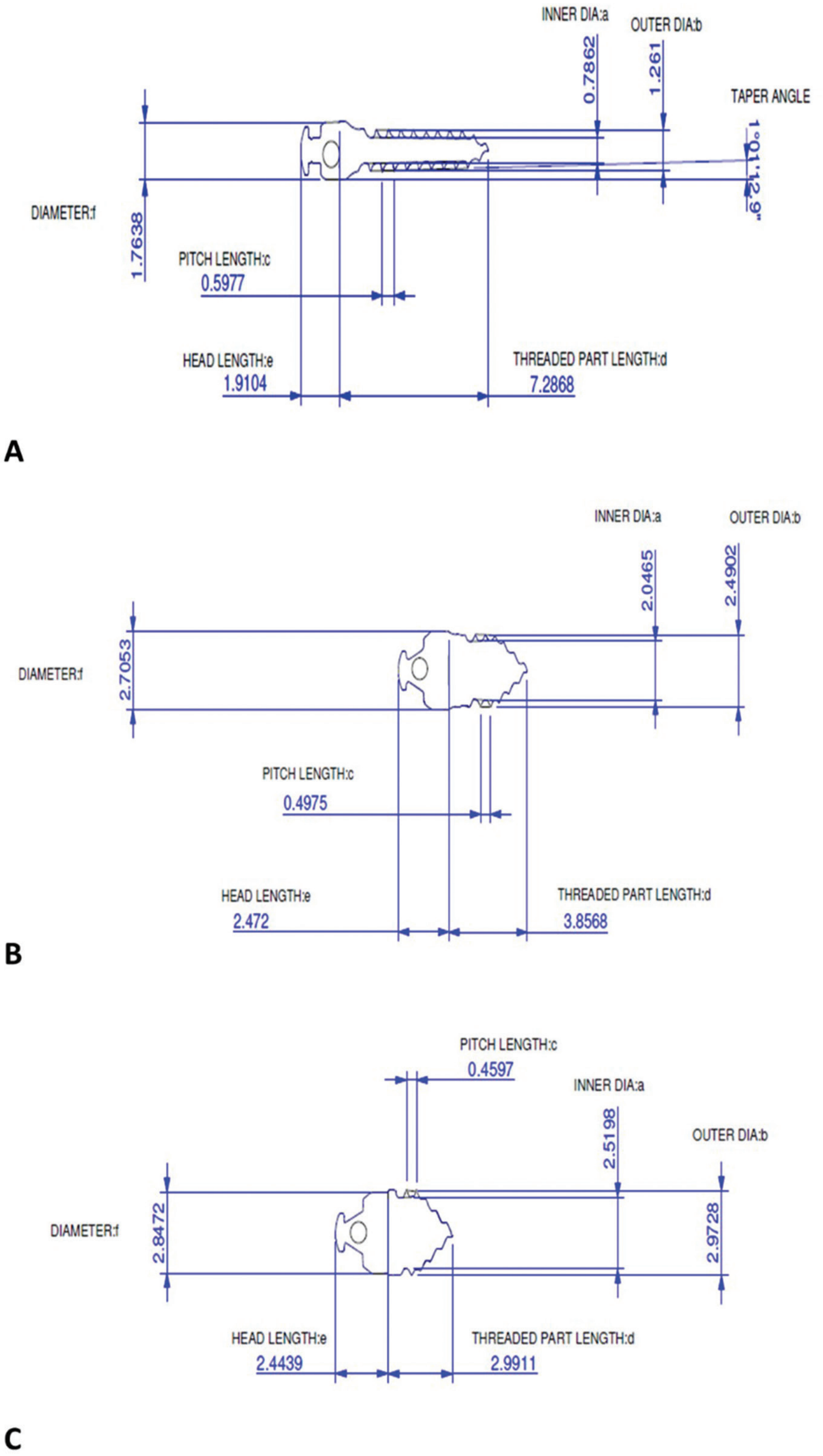

Figure 6. Characteristics of conventional mini-implants **(A)**; Group 1 mini-implants **(B)**; Group 2 mini-implants **(C)**.

203±31 gm, Group 1: 259.14±66.82 gm, Group 2: 426.00±158.89 gm (*p*=0.002);

- 0.03 mm displacement: Conventional group: 312±42 gm, Group 1: 384.57±121.04 gm, Group 2: 704.00±243.37 gm (*p*=0.001).

Table 5 presents the pairwise comparisons of load values at displacements of 0.01 mm, 0.02 mm, and 0.03 mm under angulations of 10° and 20° for three groups: Conventional (Conventional group), Group 1 (Group 1), and Group 2 (Group 2). The mean load values (M), differences in means, Q values, and *p*-values are reported for each comparison.

Tension Test

At 10° angulation, no significant differences were found

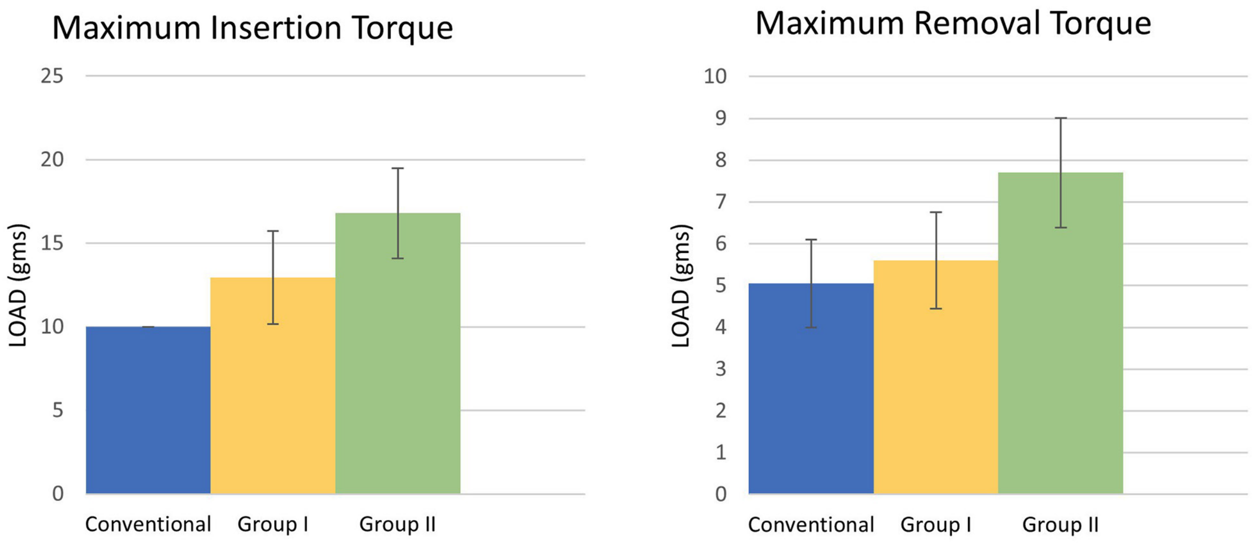

Figure 7. Comparison of maximum insertion torque (MIT) and maximum removal torque (MRT) across all groups. The bar charts display the maximum insertion torque and maximum removal torque for the Conventional, Group 1, and Group 2 treatments. **Left Chart (MIT)**: The mean insertion torque values are shown with error bars representing the standard deviation. Group 2 exhibited the highest mean insertion torque, followed by Group 1 and the Conventional group. **Right Chart (MRT)**: The mean removal torque values are shown with error bars representing the standard deviation. Group 2 had the highest mean removal torque, followed by Group 1 and the Conventional group.

Table 3. Pairwise comparisons of the insertion torque

		MIT	
Pairwise Comparisons		$HSD_{.05}=2.4756$ $HSD_{.01}=3.2261$	$Q_{.05}=3.6093$ $Q_{.01}=4.7034$
Conventional : Group 1	$M_1=10.00$ $M_2=12.94$	2.94	Q=4.29 ($p=0.01862$)
Conventional : Group 2	$M_1=10.00$ $M_3=16.86$	6.86	Q=10.00 ($p=0.00000$)
Group 1 : Group 2	$M_2=12.94$ $M_3=16.86$	3.91	Q=5.71 ($p=0.00213$)
		MRT	
Pairwise Comparisons		$HSD_{.05}=1.6060$ $HSD_{.01}=2.0929$	$Q_{.05}=3.6093$ $Q_{.01}=4.7034$
Conventional : Group 1	$M_1=5.06$ $M_2=5.61$	0.55	Q=1.25 ($p=0.65888$)
Conventional : Group 2	$M_1=5.06$ $M_3=7.72$	2.66	Q=5.98 ($p=0.00140$)
Group 1 : Group 2	$M_2=5.61$ $M_3=7.72$	2.11	Q=4.73 ($p=0.00957$)

between Group 1 and Group 2 for any displacement (**Tables 6, 7**). Similarly, at 20° angulation, the differences in mean forces were not statistically significant (**Tables 6, 7**).

Tension Force Test - *10° angulation:*

- 0.01 mm displacement: Conventional: 78±10 gm, Group 1: 95.29±21.03 gm, Group 2: 83.00±13.57 gm ($p=0.259$)
- 0.02 mm displacement: Conventional: 150±12 gm, Group 1: 176.86±11.61 gm, Group 2: 162.14±21.98 gm ($p=0.259$)
- 0.03 mm displacement: Conventional: 212±14 gm, Group 1: 242.71±15.70 gm, Group 2: 253.57±37.92 gm ($p=0.535$)

Tension Force Test - *20° angulation:*

- 0.01 mm displacement: Conventional: 78±12

Table 4. Mean force levels at various lateral displacements of mini-implants for 10° and 20° angulation

Angulation	Displacement mm	Conventional		Group 1		Group 2		*p*-value
		Load (gm)						
		Mean	SD	Mean	SD	Mean	SD	
10°	0.01	86	15.15	99.86	20.570	151.57	47.648	0.017
	0.02	190	13.00	218.71	20.934	385.43	97.013	0.002
	0.03	301	20.00	345.86	43.164	609.43	123.623	0.001
20°	0.01	96	20	123.00	40.755	217.00	68.384	0.011
	0.02	203	31	259.14	66.829	426.00	158.899	0.002
	0.03	312	42	384.57	121.048	704.00	243.371	0.001

* $p \leq 0.05$,*** $p \leq 0.001$

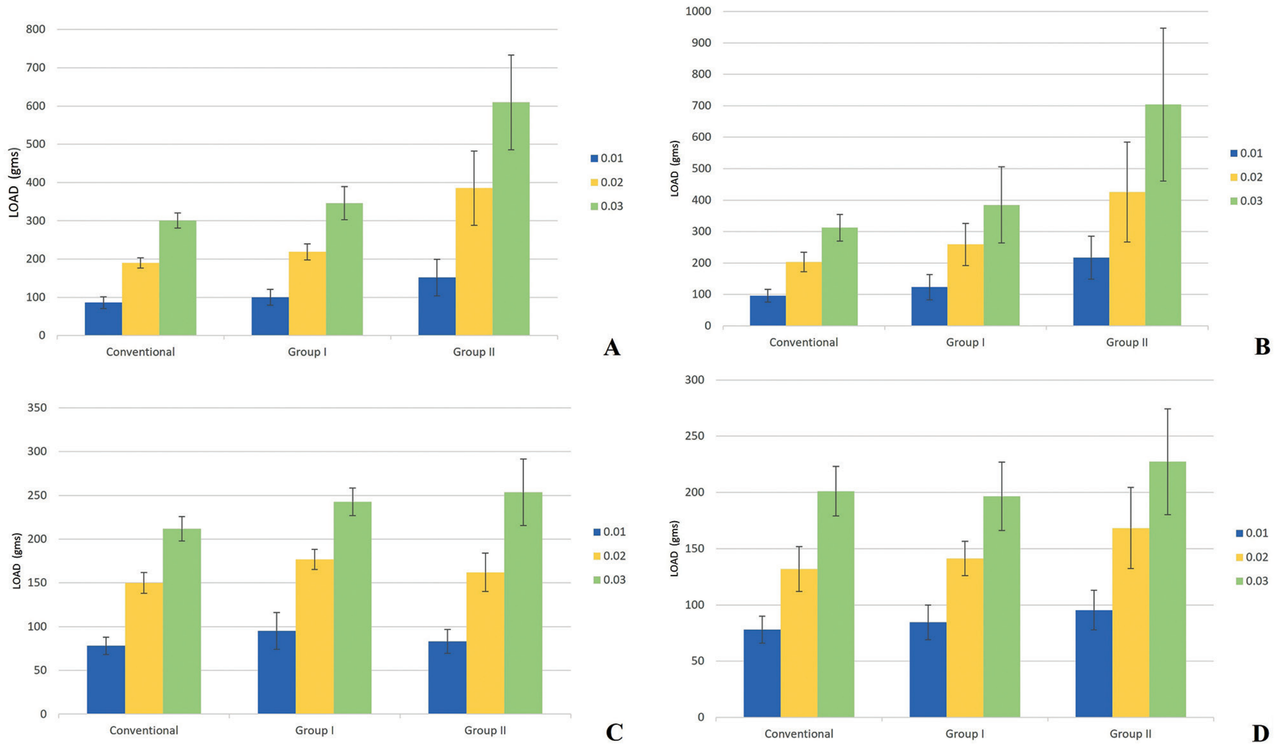

Figure 8. Graphs illustrating the mechanical response of different mini-implant designs under various conditions: **(A) and (B)**: Show the compression performance at angles of 10° and 20°; **(C) and (D)**: Show the tension performance at angles 10° and 20°. Comparisons are made between the conventional mini-implants and Group 1 and Group 2 mini-implants. Lateral displacement was assessed at intervals of 0.01 mm, 0.02 mm, and 0.03 mm to evaluate stability and performance under these mechanical stresses.

gm, Group 1: 95.43±17.67 gm, Group 2: 84.57±15.41 gm (*p*=0.456)

- 0.02 mm displacement: Conventional: 132±20 gm, Group 1: 168.29±36.06 gm, Group 2: 141.29±15.28 gm (*p*=0.073)
- 0.03 mm displacement: Conventional: 201±22 gm, Group 1: 227.29±47.10 gm, Group 2: 196.57±30.40 gm (*p*=0.165)

Table 7 presents the pairwise comparisons of load values at displacements of 0.01 mm, 0.02 mm, and 0.03 mm under angulations of 10° and 20° for three groups: Conventional (Conventional), Group 1 (Group 1), and Group 2 (Group 2). The mean load values (M), differences in means, Q values, and *p*-values are reported for each comparison.

Statistical conclusions

1. The surface area was 21.48 mm^2 for Conventional group, 28.28 mm^2 for Group 1, and 29.38 mm^2 for Group 2 mini-implants.
2. Group 2 mini-implants demonstrated significantly higher MIT (16.80±2.70 Ncm) and MRT (7.70±1.31 Ncm) compared to Group 1 (MIT: 12.95±2.79 Ncm, MRT:

Table 5. Pairwise comparisons of load at various displacements and angulations

At 10° angulation				
Displacement mm	**Pairwise comparisons**		HSD$_{.05}$=30.2413 HSD$_{.01}$=39.4084	Q$_{.05}$=3.6093 Q$_{.01}$=4.7034
0.01	Conventional: Group 1	M_1=86.14 M_2=99.90	13.76	Q=1.64 (*p*=0.49061)
	Conventional: Group 2	M_1=86.14 M_3=151.60	65.46	Q=7.81 (*p*=0.00009)
	Group 1: Group 2	M_2=99.90 M_3=151.60	51.70	Q=6.17 (*p*=0.00104)
	Pairwise comparisons		HSD$_{.05}$=59.7623 HSD$_{.01}$=77.8783	Q$_{.05}$=3.6093 Q$_{.01}$=4.7034
0.02	Conventional: Group 1	M_1=190.03 M_2=218.67	28.64	Q=1.73 (*p*=0.45526)
	Conventional: Group 2	M_1=190.03 M_3=385.69	195.66	Q=11.82 (*p*=0.00000)
	Group 1: Group 2	M_2=218.67 M_3=385.69	167.01	Q=10.09 (*p*=0.00000)
	Pairwise comparisons		HSD$_{.05}$=81.8968 HSD$_{.01}$=106.7224	Q$_{.05}$=3.6093 Q$_{.01}$=4.7034
0.03	Conventional: Group 1	M_1=301.00 M_2=345.97	44.97	Q=1.98 (*p*=0.36109)
	Conventional: Group 2	M_1=301.00 M_3=609.57	308.57	Q=13.60 (*p*=0.00000)
	Group 1: Group 2	M_2=345.97 M_3=609.57	263.60	Q=11.62 (*p*=0.00000)
At 20° angulation				
	Pairwise comparisons		HSD$_{.05}$=54.4749 HSD$_{.01}$=70.9880	Q$_{.05}$=3.6093 Q$_{.01}$=4.7034
0.01	Conventional: Group 1	M_1=96.00 M_2=123.01	27.01	Q=1.79 (*p*=0.43197)
	Conventional: Group 2	M_1=96.00 M_3=217.01	121.01	Q=8.02 (*p*=0.00006)
	Group 1: Group 2	M_2=123.01 M_3=217.01	94.00	Q=6.23 (*p*=0.00095)
	Pairwise comparisons		HSD$_{.05}$=108.5173 HSD$_{.01}$=141.4125	Q$_{.05}$=3.6093 Q$_{.01}$=4.7034
0.02	Conventional: Group 1	M_1=203.00 M_2=259.15	56.15	Q=1.87 (*p*=0.40240)
	Conventional: Group 2	M_1=203.00 M_3=426.01	223.01	Q=7.42 (*p*=0.00015)
	Group 1: Group 2	M_2=259.15 M_3=426.01	166.86	Q=5.55 (*p*=0.00272)
	Pairwise comparisons		HSD$_{.05}$=169.0670 HSD$_{.01}$=220.3169	Q$_{.05}$=3.6093 Q$_{.01}$=4.7034
0.03	Conventional: Group 1	M_1=312.00 M_2=384.58	72.58	Q=1.55 (*p*=0.52889)
	Conventional: Group 2	M_1=312.00 M_3=704.00	392.00	Q=8.37 (*p*=0.00004)
	Group 1: Group 2	M_2=384.58 M_3=704.00	319.43	Q=6.82 (*p*=0.00038)

HSD$_{.05}$: honest significant difference at the 0.05 significance level; HSD$_{.01}$: Honest Significant Difference at the 0.01 significance level; Q$_{.05}$: Q value threshold at the 0.05 significance level; Q$_{.01}$: Q value threshold at the 0.01 significance level; M: Mean load value in grams; Q: Test statistic for Tukey's HSD test; *p*: p-value indicating the significance of the difference between groups.

Table 6. Mean force levels at various lateral displacements of Group 1 and Group 2 mini-implants at 10° and 20° angulation

Angulation	Displacement (mm)	Conventional		Group 1		Group 2		*p*-value
		Load (gm)						
		Mean	SD	Mean	SD	Mean	SD	
10°	0.01	78	10	95.29	21.037	83.00	13.577	0.259
	0.02	150	12	176.86	11.611	162.14	21.988	0.062
	0.03	212	14	242.71	15.703	253.57	37.925	0.003
20°	0.01	78	12	84.57	15.415	95.43	17.672	0.056
	0.02	132	20	141.29	15.283	168.29	36.063	0.060
	0.03	201	22	196.57	30.408	227.29	47.102	0.535

* $p \leq 0.05$,*** $p \leq 0.001$

5.60±1.15 Ncm) with $p=0.001$ and $p=0.0001$, respectively.

3. Group 2 required significantly higher forces for all displacements for the compression test at 10° and 20° angulations.
4. For the tension test at both 10° and 20° angulations, there was no significant difference observed amongst the three groups.

DISCUSSION

The conventional mini-implant (1.3×7 mm) had a surface area of 21.480 mm^2, while the Group 1 (2.5×4 mm) and Group 2 (3×3 mm) mini-implants had surface areas of 28.289 mm^2 and 29.384 mm^2, respectively. Group 2 mini-implants had the largest surface area, followed by Group 1 and the conventional mini-implant. According to Christensen[15], stability can be enhanced by maximizing the interlocking surface area (SA) between the bone and implant, essentially the surface area of the threaded region. Group 2 mini-implants required a higher mean MIT of 16.80±2.70 Ncm and a higher MRT of 7.70±1.31 Ncm compared to Group 1 mini-implants, which required a mean MIT of 12.95±2.79 Ncm and a mean MRT of 5.60±1.15 Ncm. The larger diameter (3×3 mm) of Group 2 mini-implants resulted in significantly higher MIT and MRT values, consistent with Hong et al.'s findings.[16] Hong's study on five mini-implant designs showed that the design with the largest diameter (4.1×2.6 mm) required the greatest MIT and MRT. The mean torque values in the present study were higher than those in Hong's study, likely due to the use of sheep mandibular bone instead of biosynthetic bone. According to Newman et al.[17], sheep bone has higher density compared to human bone, while simulated biosynthetic bone has cortical bone density similar to that of human bone.

Chen et al.[18] observed that the insertion torque range of 3.28 to 14.65 Ncm is within physiological limits. Group 1 mini-implants had a mean MIT of 12.95±2.79 Ncm, within the physiological limit, while Group 2 mini-implants exceeded this limit with a mean MIT of 16.80±2.70 Ncm. Sotto-Maior et al.[19] emphasized that insertion torque needs to be within physiological limits, as high insertion torque can cause tensile and compressive stress to bone tissue, potentially causing irreversible damage. Low insertion torque may result in insufficient stability.

Nam-Ki Lee and Seung-Hak Baek[20] found that removal torque should be high to prevent unscrewing and is a better measurement of stability. Their investigation showed a significant increase in MIT with increased diameter, which aligns with the present study's observations. However, their study used tibia bones of New Zealand white rabbits, which may have resulted in comparatively lower torque values. The present study used cylindrical implants, while Nam-Ki Lee and Seung-Hak Baek's study included both tapered and cylindrical implants.

The lateral displacement test measures the force applied in a transverse direction, similar to how mini-implants are used during orthodontic treatment. This test may more accurately assess mechanical stability than torque testing.

At a 10° angulation Group 2 mini-implants required higher mean compression forces of 151.57±47.64 gm, 385.43±97.01 gm, and 609.43±123.62 gm for the same displacements. There was a significant difference in compression force values for 0.01 mm and 0.02 mm displacements, with a highly significant difference for 0.03 mm displacement between Group 1 and Group 2 mini-implants.

At a 20° angulation Group 2 mini-implants required higher mean compression forces for the same displacements compared to Group 1. Significant differences were noted for 0.01 mm and 0.02 mm displacements, with a highly significant difference for 0.03 mm displacement between the groups.

As the angulation increased from 10° to 20°, the compressive force required to displace mini-implants increased for all distances in both groups. However, this increase was not significant. Group 2 mini-implants, with a larger diameter and greater surface area, required significantly greater compressive forces for 0.01 mm and 0.02 mm displacements and highly significant forces for 0.03 mm displacements compared to Group 1 mini-implants.

Table 7. Pairwise comparisons of load at various displacements and angulations

Displacement (mm)	**Pairwise comparisons**		HSD$_{.05}$=17.8412 HSD$_{.01}$=23.2494	Q$_{.05}$=3.6093 Q$_{.01}$=4.7034
		At 10° angulation		
0.01	Conventional: Group 1	M_1=78.00 M_2=95.29	17.29	Q=3.50 (*p*=0.05833)
	Conventional: Group 2	M_1=78.00 M_3=83.01	5.01	Q=1.01 (*p*=0.75704)
	Group 1: Group 2	M_2=95.29 M_3=83.01	12.29	Q=2.49 (*p*=0.21200)
	Pairwise Comparisons		HSD$_{.05}$=16.1783 HSD$_{.01}$=21.0825	Q$_{.05}$=3.6093 Q$_{.01}$=4.7034
0.02	Conventional: Group 1	M =150.00 M_2=176.87	26.87	Q=5.99 (*p*=0.00137)
	Conventional: Group 2	M_1=150.00 M_3=162.15	12.15	Q=2.71 (*p*=0.16285)
	Group 1: Group 2	M_2=176.87 M_3=162.15	14.72	Q=3.28 (*p*=0.07818)
	Pairwise comparisons		HSD$_{.05}$=27.4779 HSD$_{.01}$=35.8073	Q$_{.05}$=3.6093 Q$_{.01}$=4.7034
0.03	Conventional: Group 1	M_1=212.00 M_2=242.72	30.72	Q=4.03 (*p*=0.02717)
	Conventional: Group 2	M_1=212.00 M_3=253.57	41.57	Q=5.46 (*p*=0.00312)
	Group 1: Group 2	M_2=242.72 M_3=253.57	10.86	Q=1.43 (*p*=0.58117)
		At 20° angulation		
	Pairwise comparisons		HSD$_{.05}$=15.1409 HSD$_{.01}$=19.7306	Q$_{.05}$=3.6093 Q$_{.01}$=4.7034
0.01	Conventional: Group 1	M_1=78.00 M_2=84.58	6.58	Q=1.57 (*p*=0.52117)
	Conventional: Group 2	M_1=78.00 M_3=95.44	17.44	Q=4.16 (*p*=0.02270)
	Group 1: Group 2	M_2=84.58 M_3=95.44	10.86	Q=2.59 (*p*=0.18802)
	Pairwise Comparisons		HSD$_{.05}$=29.3027 HSD$_{.01}$=38.1853	Q$_{.05}$=3.6093 Q$_{.0}$ =4.7034
0.02	Conventional: Group 1	M_1=132.00 M_2=141.29	9.29	Q=1.14 (*p*=0.70223)
	Conventional: Group 2	M_1=132.00 M_3=171.62	39.62	Q=4.88 (*p*=0.00764)
	Group 1: Group 2	M_2=141.29 M_3=171.62	30.32	Q=3.74 (*p*=0.04186)
	Pairwise Comparisons		HSD$_{.05}$=37.2244 HSD$_{.01}$=48.5083	Q$_{.05}$=3.6093 Q$_{.01}$=4.7034
0.03	Conventional: Group 1	M_1=201.00 M_2=196.57	4.43	Q=0.43 (*p*=0.95065)
	Conventional: Group 2	M =201.00 M_3=227.29	26.29	Q=2.55 (*p*=0.19702)
	Group 1: Group 2	M_2=196.57 M_3=227.29	30.72	Q=2.98 (*p*=0.11671)

HSD$_{.05}$: honest significant difference at the 0.05 significance level; HSD$_{.01}$: honest significant difference at the 0.01 significance level; Q$_{.05}$: Q value threshold at the 0.05 significance level; Q$_{.01}$: Q value threshold at the 0.01 significance level; M: Mean load value in grams; Q: Test statistic for Tukey's HSD test; *p*: p-value indicating the significance of the difference between groups.

The greater stability of Group 2 mini-implants can be attributed to their larger diameter and enhanced mechanical interlocking with the cortical bone due to a greater surface area. As the angle of compression force increased, more underlying bone support was provided against further compressive force, necessitating higher compressive forces to displace Group 2 mini-implants. These findings suggest that Group 2 mini-implants have the potential for clinical application in achieving both orthodontic and orthopedic correction.

At a 10° angulation **(Table 5)**, Group 1 mini-implants required mean tension forces of 95.29±21.03 gm, 176.86±11.61 gm, and 242.71±15.70 gm for displacements of 0.01 mm, 0.02 mm, and 0.03 mm, respectively. Group 2 mini-implants required mean tension forces of 83.00±13.57 gm, 162.14±21.98 gm, and 253.57±37.92 gm for the same displacements. There was no significant difference in tension force values between the groups for any displacement.

At a 20° angulation **(Table 6)**, Group 1 mini-implants required mean tension forces of 95.43±17.672 gm, 168.29±36.063 gm, and 227.29±47.102 gm for displacements of 0.01 mm, 0.02 mm, and 0.03 mm, respectively. Group 2 mini-implants required mean tension forces of 84.57±15.41 gm, 141.29±15.28 gm, and 196.57±30.40 gm for the same displacements. Again, there was no significant difference in tension force values between the groups.

The mean tension force increased as displacement increased from 0.01 to 0.02 mm and from 0.02 to 0.03 mm. As the angulation increased from 10° to 20°, the tension force required to displace mini-implants of both groups increased for 0.01 mm displacement but decreased for 0.02 mm and 0.03 mm displacements. The likely explanation for the decrease in tension force is that initial movement may have enlarged the bony socket or created microfractures, reducing mechanical retention and requiring less force for further displacement.

The mean tension force required to displace Group 2 mini-implants was generally less than that for Group 1 mini-implants, except for the 10° angulated tension force vector for 0.03 mm displacement, which was not statistically significant. Tension force pulls the mini-implant away from the bone, and the shorter length of Group 2 compromises its ability to withstand displacement as the force vector angulation increases. With less supportive bone mass, less tension force was needed for lateral displacement, suggesting superior stability of Group 1 mini-implants during the application of tension force vectors.

Hong et al.[16] found that during the application of tension force at low angulations, the novel mini-implant design (3 mm diameter, 2 mm length) displayed superior stability to the conventional design (1.5 mm diameter, 6 mm length). However, at higher angulations, the force required for displacement was less for the novel design. In this study, Group 2 mini-implants (3 mm in diameter, 3 mm long) required less tension force for displacement than Group 1 mini-implants (2.5 mm in diameter, 4 mm long) for both angulated tension vectors at all displacements except for the 10° angulated tension force vector for 0.03 mm displacement.

Overall, the Group 2 mini-implants demonstrated greater stability under compressive forces compared to Group 1 mini-implants for all distances. The torque analysis data supported the enhanced primary stability of Group 2 mini-implants. Despite their shorter length, the MIT and MRT values were higher for Group 2, supporting Hong et al.'s[16] assertion that primary stability depends more on increased surface area and mechanical interlocking in cortical bone than on implant length. Group 2 mini-implants, with their larger surface area, demonstrated improved stability and the potential for clinical use in achieving both orthodontic and orthopedic corrections. The shorter length of Group 2 mini-implants also minimizes risks to nearby anatomical structures and allows for convenient placement without the limitation of inter-radicular space. Future clinical trials and in vivo studies are needed to confirm these findings.

CONCLUSIONS

1. Group 2 mini-implants demonstrated a larger surface area (29.38 mm^2) compared to Group 1 (28.28 mm^2) and conventional mini-implants (21.48 mm^2), indicating a potential advantage in mechanical interlocking with bone tissue.
2. Torque tests revealed that Group 2 mini-implants exhibited superior primary stability over Group 1 mini-implants, as evidenced by significantly higher mean maximum insertion torque (16.80±2.70 Ncm vs. 12.95±2.79 Ncm) and mean maximum removal torque (7.70±1.31 Ncm vs. 5.60±1.15 Ncm).
3. Under lateral displacement at 10° angulation, Group 2 mini-implants required significantly higher compression forces than Group 1 mini-implants for all displacement distances, indicating superior stability under simulated clinical conditions.
4. Similarly, at 20° angulation, Group 2 mini-implants demonstrated significantly greater resistance to lateral displacement compared to Group 1 mini-implants, reaffirming their enhanced stability in challenging orthodontic scenarios.
5. The tension forces required for lateral displacement were comparable between Group 1 and Group 2 mini-implants at both 10° and 20° angulations, suggesting similar resistance to forces pulling the implants away from the bone.

In summary, Group 2 mini-implants, with their larger surface area and superior stability under compressive forces, present a promising option for orthodontic and orthopedic corrections, potentially minimizing risks to adjacent anatomical structures while providing reliable support during treatment.

Limitations

The sample size in this study could have been larger to improve statistical power and generalizability of the findings. Due to constraints, live tissues could not be utilized for the study, potentially limiting the ability to fully replicate in vivo conditions and interactions.

Author contributions

Swapnil Junnarkar: conceptualization, methodology, investigation; *Anand Sabane*: data curation, writing - original draft preparation, conceptualization; *Amol Patil*: visualization, investigation, supervision, project administration; *Meenal Tepan*: supervision, writing - original draft preparation; *Tanisha Rout*: data curation, writing - reviewing and editing; *Sonakshi Sharma*: writing - reviewing and editing, data curation; *Arati Gholap*: writing - reviewing and editing.

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Competing Interests

The authors have declared that no competing interests exist.

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Оптимизация ортодонтической фиксации: сравнительная оценка мини-имплантатов большего диаметра и меньшей длины для повышения механической стабильности

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Резюме

Цель: Мы стремимся оценить и сравнить механическую стабильность двух конструкций мини-имплантатов, отличающихся большим диаметром и меньшей длиной, для ортодонтической фиксации по сравнению с обычной группой имплантатов.

Материалы и методы: Три группы мини-имплантатов прошли испытания: имплантаты в группе 1 имели диаметр 2.5 mm и длину 4 mm; имплантаты в группе 2 имели диаметр 3 mm и длину 3 mm; а имплантаты обычной группы имели диаметр 1.3 mm и длину 7 mm. Оба типа представляли собой мини-имплантаты Abso Anchor (Dentos Inc.). Механическая стабильность имплантатов оценивалась с использованием максимального момента установки (MIT), максимального момента удаления (MRT) и угловых испытаний бокового смещения для векторов силы сжатия и растяжения. Для измерения MIT и MRT использовались четырнадцать мини-имплантатов каждой конструкции. Семь мини-имплантатов каждой конструкции были испытаны на боковое смещение.

Результаты: Тесты на крутящий момент – мини-имплантаты Группы 2 показали превосходную первичную стабильность с более высокими значениями MIT и MRT по сравнению с Группой 1 и имплантатами обычной группы. Тесты на боковое смещение – мини-имплантаты Группы 2 потребовали значительно большей силы сжатия, чем в Группе 1 и обычной группе. Сила растяжения для боковых смещений была одинаковой между тремя группами.

Заключение: Мини-имплантаты Группы 2 с большим диаметром и меньшей длиной продемонстрировали превосходную первичную стабильность по сравнению с имплантатами Группы 1. Несмотря на различия в силе сжатия, все три группы показали схожие результаты при растяжении в тестах на боковое смещение.

Ключевые слова

фиксация, компрессия, боковое смещение, мини-имплантаты, крутящий момент, натяжение