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Original Article

Assessment of stiffness and load deflection of orthodontic miniscrews used for palatal anchorage: An in vitro biomechanical study

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Summary

Objective > The purpose of this study was to evaluate the biomechanical properties of miniscrews of 5 different lengths, 2 different diameters, and different combinations of insertion used for palatal skeletal anchorage.

Materials and methods > Twenty-four different combinations of a total of 120 miniscrews of two different diameters (2.0 mm and 2.3 mm) and five different lengths (9 mm, 11 mm, 13 mm and 15 mm) were tested at different angles of insertion (90° and 45°) and distances from a synthetic bone block (3 mm, 5 mm, 7 mm). Samples were fixed in an Instron Universal Testing Machine and a load was applied in single cantilever mode to the neck of each miniscrew. The stiffness and maximum load before permanent deformation were recorded. Model-based recursive partitioning testing (CART) was used to evaluate differences between groups.

Results > Significantly higher forces were necessary to deform miniscrews of diameter 2.3 mm than those of 2.0 mm, those inserted at an angle of 45° with respect to 90°, and at smaller distances between the miniscrew neck and block; in addition, the maximum load and stiffness increased with increasing screw length.

Conclusion > This in vitro experimental study showed strong correlations between deformation load and miniscrew geometry, insertion angle and distance from the synthetic block, results that should be considered when planning miniscrew insertion in order to reduce the risk of unwanted fracture.

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Introduction

For several years now, miniscrews have attracted considerable interest thanks to their ability to provide greater biomechanical control and, especially, to reduce or even prevent unwanted tooth movement [1]. Hence, numerous studies have been conducted on various clinical situations, showing their usefulness in extrusion [2], intrusion [3], extraction space closure [4], occlusal plane cant correction [5] and uprighting [6]. Furthermore, in addition to more conventional uses, studies have also demonstrated their use alongside devices generally used in combination with dental anchorage [7] in cases of palatal expansion [8–11], distalization [12], mesialization [13] and correction of class III [14], with the aim of minimising adverse effects on the dentition.

The efficacy of miniscrews, in particular, has been amply demonstrated both in vitro [15] and in vivo [2,16–18], and skeletal anchorage, combined with the advanced digital technology now available, has opened new frontiers in orthodontic treatment, enabling ever more predictable results to be achieved [19–21]. However, despite their widespread diffusion and high success rates [22], several authors have reported two major drawbacks; while mini-implant failure (loss of stability) is certainly the most frequent, fracture is undoubtedly the least desirable outcome [23,24]. Thankfully, fracture occurs in a very low percentage of cases but in clinical cases of traditional application it has been seen at loads of less than 5 N [25], as compared to the range observed in vitro, from roughly 43 N to 747 N [26].

Among the possible insertion sites, the palatal vault is finding an increasing number of applications [7–14], and is therefore the focus of great research interest, not only for biomechanical, but also anatomical reasons [27]. This makes the palatal vault a particularly suitable site for miniscrews for both conventional use and in association with devices like distalization or mesialization appliances and palatal expanders [7–14].

That being said, palatal expanders are orthopaedic devices, and therefore miniscrews used to anchor them need to withstand far greater forces than those exploited for orthodontic applications [25,28].

While there are many studies available on the characteristics of orthodontic miniscrews used in conventional approaches [26,29], despite their growing popularity no research has yet been carried out on the biomechanics of miniscrews designed and manufactured to be used in conjunction with devices for orthopaedic applications. This absence of data is concerning, because the greater forces applied in these cases [28,30] are likely to lead to a greater risk of deformation or fracture, a factor of great clinical relevance. Hence, we decided to investigate the biomechanical characteristics of orthodontic miniscrews destined for palatal anchorage for orthopaedic purposes, comparing different lengths and diameters of miniscrew as well as different insertion depths and angles.

Materials and methods

In this study we tested 120 miniscrews made of grade 5 medical titanium alloy (Ti-6Al-4V) (Spider Screw Regular Plus Konic, HDC, Health Development Company, Thiene, Italy), subdivided into 24 different combinations on the basis of three variables:

- miniscrew length: 9, 11, 13 or 15 millimetres;
- angle of insertion in block: 45 or 90 degrees;
- distance from miniscrew head to block: 3, 5 or 7 millimetres (*figure 1*).

Five samples of each of the 24 combinations were tested (*table I*). Each miniscrew was inserted into a polyoxymethylene (POM) block using a manual screwdriver. Each block measured 30 × 30 × 10 mm and was pre-drilled using a benchtop drill press (*figure 2*). POM was chosen as the synthetic bone material due to its excellent properties, which enabled the load testing to be carried out without the block breaking.

A digital caliper with a resolution of 0.01 mm was used to measure the distance from the point of application of the force to the surface of the block for the purposes of checking its distance from the miniscrew head, i.e., the insertion depth. The blocks were clamped to the bench during flexion testing, which was carried out by means of an INSTRON 4467 universal testing machine (Instron Corp. USA) equipped with a 30-kN load cell. The force was applied at the junction of the miniscrew head and transmucosal neck (*figures 3 and 4*), and the load applied at a speed of 1 mm/min via a blade with tip of diameter 1.5 mm until each sample was permanently deformed.

The resulting data were recorded using LabVIEW 8.6 software (National Instruments Corporation, Austin, Texas), directly connected to the INSTRON machine. The same software was used to create a load/deflection curve to describe the biomechanical behaviour of each miniscrew.

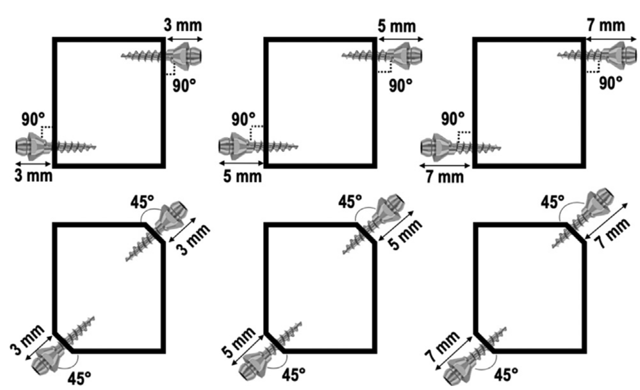

FIGURE 1

Examples of combinations tested

Table I
Combinations tested with respect to the variables miniscrew length, insertion angle and head distance from support

Sample	Length (mm)	Diameter (mm)	Angle (°)	Distance from support (mm)
1	9	2	90	3
2	9	2	90	5
3	9	2	90	7
4	9	2	45	3
5	9	2	45	5
6	9	2	45	7
7	11	2	90	3
8	11	2	90	5
9	11	2	90	7
10	11	2	45	3
11	11	2	45	5
12	11	2	45	7
13	13	2	90	3
14	13	2	90	5
15	13	2	90	7
16	13	2	45	3
17	13	2	45	5
18	13	2	45	7
19	15	2	90	3
20	15	2	90	5
21	15	2	90	7
22	15	2	45	3
23	15	2	45	5
24	15	2	45	7

For each sample the following values were calculated:
- the maximum load before plastic miniscrew deformation (N);
- the stiffness (N/mm).

Statistical analysis

The resulting data were processed using Microsoft Excel software (Microsoft Corporation, Redmond, Wash). A load versus deflection graph was obtained for each sample, an in each graph the initial straight line, i.e., that before the plastic deformation of the miniscrew, was selected. To confirm that the selected values did, in fact, lie on a straight line, the coefficient of determination (R^2) was verified, ensuring that it was close to 1. The trend line of this initial section and the equation of a straight line parallel to the previous one but moved by 0.001 mm were calculated. In this way, it was possible to identify the maximum load at which there is a

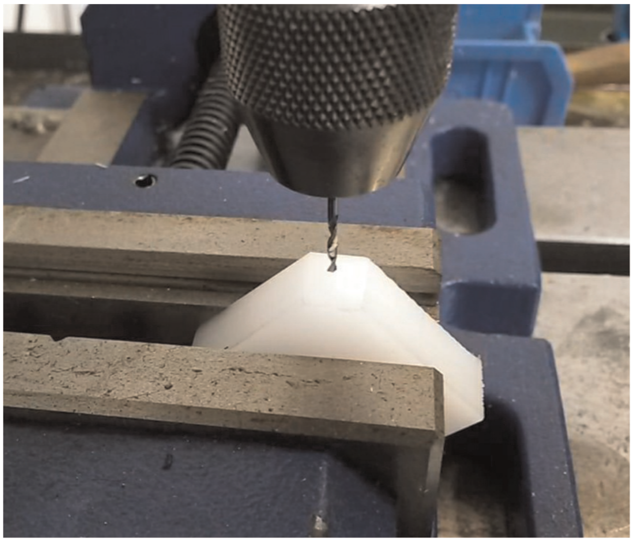

FIGURE 2
Pre-drilling with a benchtop drill press

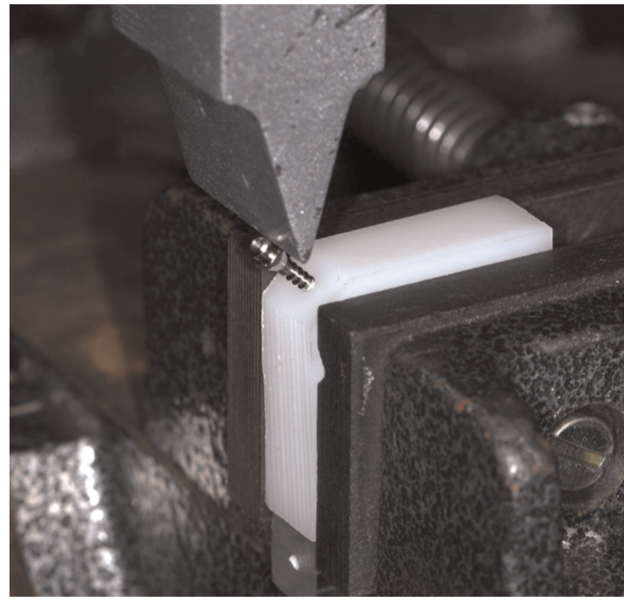

FIGURE 4
Point of load application (45° angle)

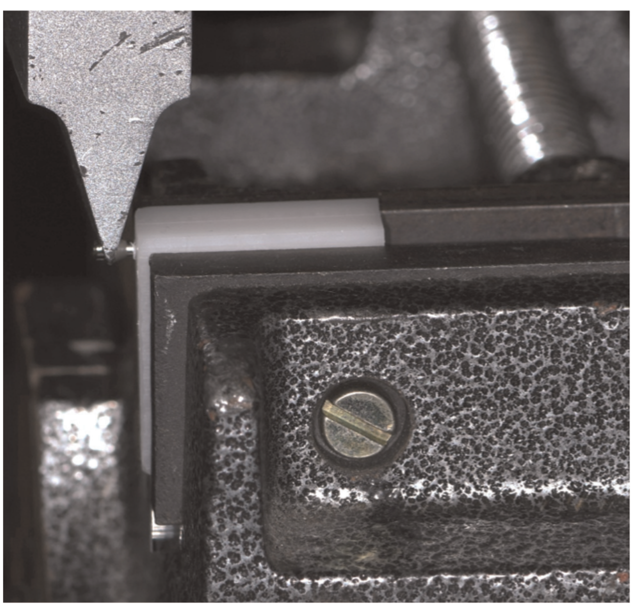

FIGURE 3
Point of load application (90° angle)

deviation from linearity equal to 0.001 mm, therefore comparable as the maximum load (measured in Newtons, N) applied to the sample before it underwent permanent deformation.

The stiffness, measured in Newton/mm (N/mm), was taken as being equal to the angular coefficient of the straight line passing through the initial straight section of the load/displacement graph, thereby representing the slope of that line.
Descriptive statistical analysis was performed (mean, standard deviation, minimum, maximum) for each of the combinations, and both of the parameters investigated were subjected to model-based recursive partitioning testing, a variant of the classification and regression tree (CART) method [31], in order to highlight the most significant relationships among the variables. Statistical procedures were performed using R Statistical software and the level of significance was set at $P < 0.05$.
Finally, to calculate the maximum load F_{max} for a miniscrew diameter equal to 2.3 mm, in relation to the previously described variables, a deterministic approach was used, relying on the following formula:

$$F_{\max} = F_1\left(\frac{D_2}{D_1}\right)$$

where F_{max} is the maximum load, F_1 is the estimated average force for a given combination relative to the diameter of 2 mm, D_1 is the diameter of 2 mm and D_2 is the diameter of 2.3 mm.

Table II
Descriptive statistics for maximum load parameter (mean value; standard deviation; min; max)

Combinations	Mean (N)	Sd (N)	Min (N)	Max (N)
2 × 9_90°_3	81	41.1	15	120
2 × 9_90°_5	62.2	5.6	53	67
2 × 9_90°_7	36.4	4.9	29	41
2 × 9_45°_3	124.6	23.6	90	150
2 × 9_45°_5	115.6	6.3	105	121
2 × 9_45°_7	91.8	11.1	83	111
2 × 11_90°_3	83.6	24.6	47	111
2 × 11_90°_5	60.4	1.9	57	62
2 × 11_90°_7	40.2	2.3	37	43
2 × 11_45°_3	247.4	46.3	197	299
2 × 11_45°_5	121.6	12.8	104	134
2 × 11_45°_7	116.4	26.7	75	143
2 × 13_90°_3	125.8	4.4	122	131
2 × 13_90°_5	66.2	7.4	55	75
2 × 13_90°_7	47.4	2.7	44	51
2 × 13_45°_3	249	36.9	222	310
2 × 13_45°_5	138.4	17	118	157
2 × 13_45°_7	103.4	30.9	78	153
2 × 15_90°_3	102.6	8	91	110
2 × 15_90°_5	52.6	7.6	41	61
2 × 15_90°_7	41.8	6	37	52
2 × 15_45°_3	217.6	49.7	134	266
2 × 15_45°_5	126.2	18.3	96	133
2 × 15_45°_7	121	21	94	140

SD: standard deviation; Min: minimum value; Max: maximum value.

Results

The *tables II and III* show the descriptive statistics for the maximum load and stiffness values and the boxplot *figure 5* show an overview of the measurements. The highest average maximum load value, 249 N (± 36.9 N), was recorded for miniscrews with a length of 13 mm inserted at an angle of 45° with their heads a distance of 3 mm from the block. The lowest load, 36.4 N (± 4.9 N), was recorded for miniscrews with a length of 9 mm, inserted at an angle of 90° with their heads at a distance of 7 mm from the block.

Table III
Descriptive statistics for stiffness parameter (mean value; standard deviation; min; max)

Combinations	Mean (N/mm)	Sd (N/mm)	Min (N/mm)	Max (N/mm)
2 × 9_90°_3	134	69.3	90	256
2 × 9_90°_5	78.2	5.4	73	87
2 × 9_90°_7	12.4	3	9	17
2 × 9_45°_3	402.8	116	273	535
2 × 9_45°_5	203.8	30.2	155	230
2 × 9_45°_7	66.8	22.5	38	95
2 × 11_90°_3	121.8	25.5	100	163
2 × 11_90°_5	88.4	9.3	80	104
2 × 11_90°_7	37	2	35	40
2 × 11_45°_3	700.2	138.8	618	947
2 × 11_45°_5	331.4	34.2	287	364
2 × 11_45°_7	79.8	15.6	63	95
2 × 13_90°_3	254.8	23.9	220	276
2 × 13_90°_5	94.8	6.9	86	105
2 × 13_90°_7	40.8	3.3	36	45
2 × 13_45°_3	864.4	176.2	574	997
2 × 13_45°_5	374.6	49.3	338	454
2 × 13_45°_7	138	59.6	102	241
2 × 15_90°_3	260	72.4	155	300
2 × 15_90°_5	87.6	9.2	78	99
2 × 15_90°_7	45	10.4	34	57
2 × 15_45°_3	749.6	213.5	447	1044
2 × 15_45°_5	323.2	38.8	292	384
2 × 15_45°_7	188.2	87.4	128	339

SD: standard deviation; Min: minimum value; Max: maximum value.

Similarly, the highest average stiffness value, 864.4 N/mm (± 176.2 N/mm) was measured for miniscrews with a length of 13 mm, inserted at an angle of 45° with a head-to-block distance of 3 mm, while the lowest average stiffness, 12.4 N/mm (± 3 N/mm) was found for miniscrews of 9 mm length, 90° insertion angle and 7 mm head-to-block distance.

The *figure 6*, respectively, and the *table III* show the statistically significant effects on both investigated parameters exerted by the insertion angle and the distance between the miniscrew head and the block. Specifically, a more acute angle caused an increase in the maximum expected load values, and the same occurred for the insertion depth variable. Likewise, as far as stiffness is concerned, the two most influential variables were the head–block

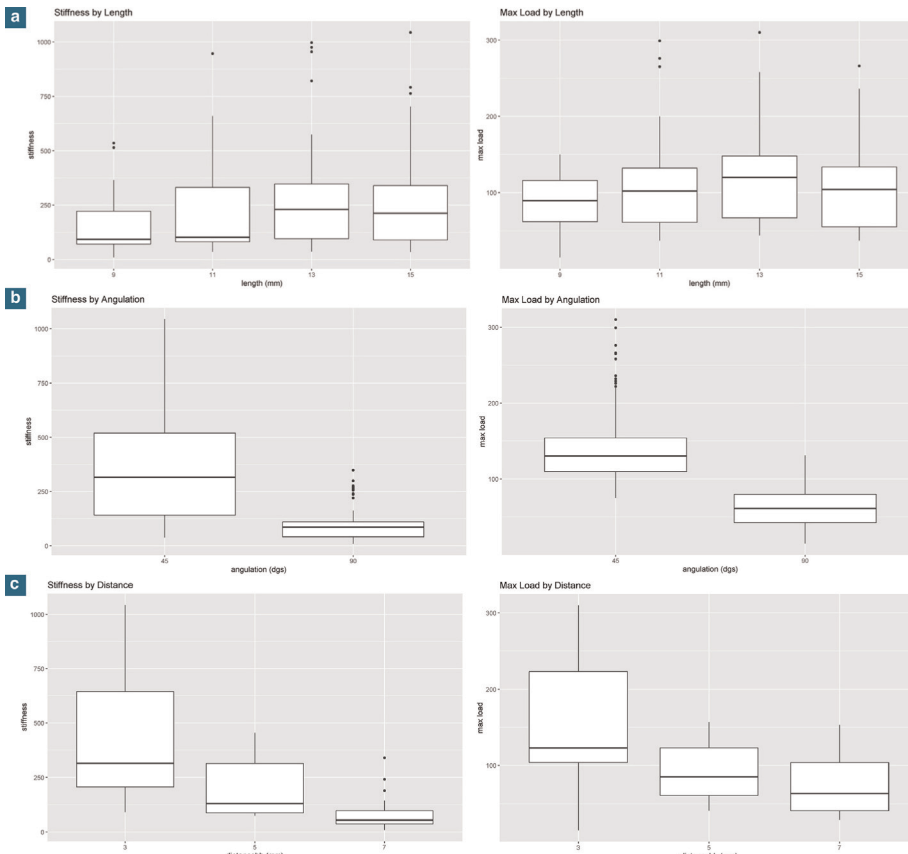

FIGURE 5

Boxplot graphs displaying stiffness and max load values in relation to the variables: a: "miniscrew length"; b: "angle of insertion"; c: "distance from miniscrew head to block"

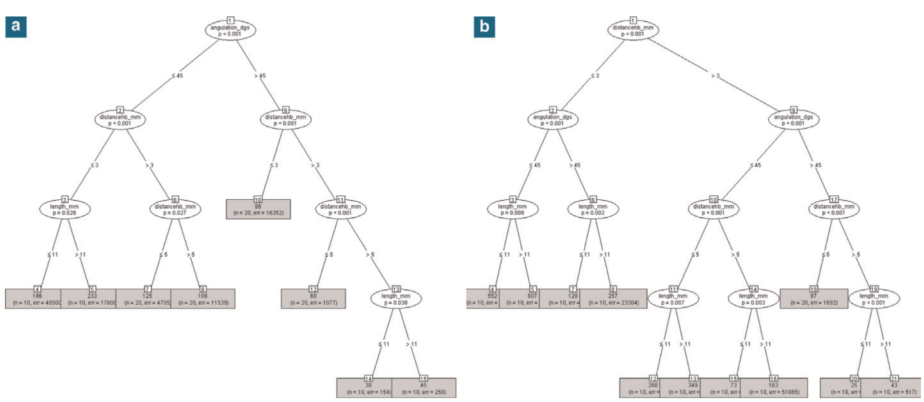

FIGURE 6

a–b: CART diagram for maximum load and stiffness parameters. The plot below displays the hierarchical splits from which it can be seen what are the most important features and relative values for optimal splits. The final node displays the prediction for such combination of predictors (in parenthesis the number of cases and values): a: the two most important values are the "angle of insertion" (with splits ≤ 45 and > 45) and the "distance head/block" (with initial splits ≤ 3 > 3)

A lower angle leads to a higher expected max load; the same appears also for the "distance head/block" (at least in the initial split); b: the other splits at a lower hierarchical level are: "miniscrew length" (splits ≤ 11 > 11), "distance head/block" (≤ 5 > 5). A distance < 3 is associated to generally a higher expected stiffness; the applies are the same than for the "angle of insertion" (the split ≤ 45 is associated with a higher expected value). Interactions with "distance head/block" and "miniscrew length" are observed at lower values.

Table IV

Expected values for maximum load and stiffness

Length (mm)	Diameter (mm)	Angle (°)	Distance_headtoblock (mm)	Maxload_pred (N)	Stiffness_pred (N/mm)
9	2	90	3	98	128
9	2	90	5	60	87
9	2	90	7	38	25
9	2	45	3	186	552
9	2	45	5	125	268
9	2	45	7	108	73
11	2	90	3	98	128
11	2	90	5	60	87
11	2	90	7	38	25
11	2	45	3	186	552
11	2	45	5	125	268
11	2	45	7	108	73
13	2	90	3	98	257
13	2	90	5	60	87
13	2	90	7	45	43
13	2	45	3	233	807
13	2	45	5	125	349
13	2	45	7	108	163
15	2	90	3	98	257
15	2	90	5	60	87
15	2	90	7	45	43
15	2	45	3	233	807
15	2	45	5	125	349
15	2	45	7	108	163

Maxload_pred: expected values for maximum load; Stifness_pred: expected values for stiffness.

distance and the load application angle with respect to the tested sample. Generally speaking, greater stiffness was associated with a decrease in insertion depth; the same applies to the insertion angle, as at 45°, the predicted stiffness was greater.

The *table IV* shows the predicted values for both the investigated parameters in all the different combinations, while the *table V* shows the expected values for the same combinations but investigating a diameter of 2.3 mm, instead of 2 mm, relative to the parameter maximum load. All combinations involving a miniscrew of diameter 2.3 mm displayed higher predicted values as compared to the same combinations featuring a miniscrew of diameter 2 mm.

Table V
Expected values for maximum load considering the combinations featuring miniscrews of diameter 2.3 mm

Length (mm)	Diameter (mm)	Angle (°)	Distance_headtoblock (mm)	Maxload_pred (N)
9	2.3	90	3	113
9	2.3	90	5	69
9	2.3	90	7	44
9	2.3	45	3	214
9	2.3	45	5	144
9	2.3	45	7	124
11	2.3	90	3	113
11	2.3	90	5	69
11	2.3	90	7	44
11	2.3	45	3	214
11	2.3	45	5	144
11	2.3	45	7	124
13	2.3	90	3	113
13	2.3	90	5	69
13	2.3	90	7	52
13	2.3	45	3	268
13	2.3	45	5	144
13	2.3	45	7	124
15	2.3	90	3	113
15	2.3	90	5	69
15	2.3	90	7	52
15	2.3	45	3	268
15	2.3	45	5	144
15	2.3	45	7	124

Maxload_pred: expected values for maximum load.

Discussion

The aim of this study was to investigate the biomechanical characteristics of orthodontic miniscrews designed and manufactured for use in conjunction with devices relying on skeletal anchorage, first and foremost the rapid palatal expander. We therefore tested various parameters, directly linked to the construction features of miniscrews (length and diameter) and their insertion (depth and angle) in order to determine the maximum load borne and the stiffness of each in vitro system.

This revealed that the miniscrews with the greatest length and diameter (15 mm length and 2.3 mm diameter) inserted at a more acute angle and less distance from the support (45° inclination and 3 mm distance from the block) were able to withstand the highest maximum predicted load value, 268 N. Indeed, the same combination, as tested at an insertion angle of 90°, presented a maximum expected load value of 112.7 N; it therefore follows that miniscrews inserted at an angle of 45° are able to bear higher maximum load values than those inserted at an angle of 90°, regardless of the combination tested.

In contrast, the lowest predicted maximum load value, 38 N, was observed for miniscrews of length 9 mm, diameter 2 mm, insertion angle 90° and distance 7 mm between the miniscrew head and the block. The same combination tested with a head-to-block distance of 3 mm had a predicted maximum load of 98 N, thereby demonstrating that a reduction in distance from the support leads to an increase in the system's ability to withstand loading without deforming.

It is difficult to compare these values with those in the literature, as there is scarce data yet available regarding miniscrew systems for orthopaedic applications [32]. However, it is interesting to note that Scribante et al. [29] reported a maximum load value of 58 N, recorded at a deflection of 0.1 mm and angle of 90°, for a stainless steel miniscrew sample of diameter 2 mm and length 10 mm, and 53 N for the same combination using a grade 5 titanium alloy (Ti-6Al-4V) miniscrew of the same length and diameter; those values are similar to the miniscrew combinations of the same diameter and similar length we tested at 90°. Sfondrini et al. [26] also tested miniscrews of 2-mm diameter and 10-mm length, but found a mean value of 85.4 N; although this value is apparently greater than that recorded in this study, it may be explained by the fact that their miniscrews were tested at a 0.5-mm distance from the support. Indeed, if we consider our finding that the maximum load and stiffness increase as the distance from the support is reduced and the miniscrew length increases, that figure is in line with ours.

As regards to the stiffness parameter, like the maximum load, this appears to be mainly influenced by the distance from the support and the insertion angle; specifically, the stiffness increased as the former decreased from 7 mm to 3 mm and the latter from 90° to 45°. The highest and lowest stiffness values were recorded for the same combinations as the highest and lowest maximum loads. Florvaag et al. [33] reported mean stiffness values of between 627.0 (± 405.8) N/mm (Orlus mini-implant) and 1025.0 (± 337.1) N/mm (tomas®-pin), a range similar to that seen in our sample when taking into consideration miniscrews of similar length and diameter.

Likewise, the length parameter, although having a less significant influence than the insertion angle and distance from the support, did display values that are in line with those reported in the literature. We can therefore confirm previous findings that miniscrews of greater length are likely to guarantee better success rates [15].

The present study has the limitation of having investigated the biomechanical characteristics of the miniscrews without considering the structural components of the equipment connected to them, thereby preventing us from evaluating such systems as a whole. However, it would be complex to simulate the biomechanical behaviour of different systems in vitro due to the wide range of appliances currently available. Despite this limitation, the results of the study seem to suggest important considerations to bear in mind when relying on miniscrews to provide skeletal anchorage for orthopaedic treatment. In particular, the clinical forces generated by a rapid palatal expander range from 7.54 to 15.8 kg [34], and in this regard it is important to bear in mind that among the miniscrews examined, those most at risk of deformation were of length 9 mm and 11 mm tested at an insertion angle of 90°; these showed, respectively, maximum load values of between 36.4 and 81 N (3.7 and 8.2 kg) and 40.2 and 83.6 N (4 and 8.5 kg), regardless of the head distance from the support. However, when the head distance from the support was greater than or equal to 5 mm, the miniscrews of length 13 mm and 15 mm displayed average maximum load values of between 41.8 and 66.2 N (4.2 and 6.7 kg), and therefore an increased risk of deformation during the application of orthopaedic forces during the skeletal expansion of the maxilla.

Although on the one hand our results suggest that the ideal choice of insertion angle is 45° rather than 90°, in addition to a longer miniscrew and the least possible involvement of the soft tissues (represented by the distance from the block), on the other we must carefully assess the anatomy of each individual patient. The thickness of the soft tissues directly affects the distance between the bone and the head of the miniscrew and presents a considerable interindividual variability [35].

Conclusions

The design of miniscrews and their means of insertion have a statistically significant effect on the biomechanical properties of the system.

The maximum load and stiffness parameters increase in a statistically significant fashion in relation to increasing insertion depth and decreasing angle with respect to the support material.

In correspondence of an increase in the length of the miniscrew, an increase in the maximum load and stiffness values is observed, but this has a lesser influence than that of the other two variables examined.

In order to reduce the risk of deformation, it is advisable to use an insertion angle of 45°, rather than 90°, and the greatest possible miniscrew length, diameter and insertion depth compatible with the biomechanics required and the anatomical characteristics of the patient.

Disclosure of interest: the authors declare that they have no competing interest.

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