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Finite Element Analysis and in Vivo Evaluation of En-Masse Retraction of Maxillary Anterior Teeth Using Palatal TADs and a Clear Appliance

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Abstract

Aim: Among various retraction methods for space closure in first premolar extraction, the palatal approach is preferred to labial appliances in cases having high aesthetic demand. A finite element model and clinical randomized prospective trial was undertaken to determine the possibility of en-masse retraction of maxillary anterior teeth using palatal TAD and a clear aligner-like appliance in patients undergoing extraction of maxillary first premolars and to study the effects of the above using three-dimensional scanned models and lateral cephalograms.
Methods: A finite element model of maxillary dentition with alveolar bone, an acrylic splint on six anterior teeth, palatal implants, and short e-chain were produced to measure shifting when force was applied from three various levels. Thereafter, the finite element analysis findings were applied to 10 patients requiring fixed orthodontic treatment with first premolar extraction and fulfilling the inclusion criteria. Impressions were made and the rate of retraction was evaluated at 4-week intervals by superimposition of scanned models.
Results: En-masse bodily retraction was seen when both canine hooks and palatal TAD was placed at 10 mm distance from the respective gingival margin. Clinically, subjects showed significant retraction at that level and statistically significant results in some cases. The maximum rate of retraction was seen in the first three months (average: 5.310 mm) with p-value <0.0001.
Conclusion: Translational tooth movement was observed when line of force was at the level of the center of resistance.

Keywords: Anterior teeth retraction; Biomechanics; Mini-implants; Three-dimensional finite element.

1. Background

Patients with maxillary protrusion commonly refer to orthodontists for aesthetic reasons (1). Therefore, different methods and mechanics are used to correct protruded maxillary teeth; for example conventional sliding mechanics, loop mechanics, and lingual orthodontics. In all these methods, extraction of maxillary first premolars is usually planned before beginning retraction.

Anchorage is a chief aspect in anterior en-masse retraction and the method of anchorage control determines the success of orthodontic treatment. Various methods of reinforcing anchorage are: headgear, muscular forces, and cortical anchorage, Nance holding appliance, trans-palatal arch, and so forth. However, these methods have their drawbacks such as requiring accurate wire bending, and patient co-operation, as well as being time consuming (2,3,4). The palatal approach is a preferred retraction method over the labial appliances when aesthetic braces and the critical torque control of anterior teeth are required (5). TADs are used in posterior palatal areas in compromised periodontal conditions, non-compliance patients, as well as aesthetic considerations in which clinician cannot use extra-oral anchorage devices or class II elastics (6).

Clear aesthetic appliances or aligners are more acceptable to the patient. However, aligners produce lack of control during retraction over long distances as in extraction cases (7). Hence, clear rigid appliance needs to be designed accordingly and evaluated clinically, so that the individualized appliance model can be evaluated and analyzed based on the Finite Element Method (FEM) principle. FEM allows different force systems to be placed analytically at every point and in every direction. FEM also makes it possible for the quantitative assessment of the distribution of these forces via the wire and affiliated structures (8). Thus, this method was chosen for the current study.

Although there is a deluge of data available on current methods to access retraction of maxillary anterior teeth with palatal TADs, there is a paucity of data on finite element analysis of clinical subjects. In view of aforesaid, the following study was conducted to evaluate en-masse retraction of maxillary anterior teeth with orthodontic mini-implant anchorage by examining different combinations of the height of palatal TADs and anterior retraction hooks, and to validate them on patients acquiring maxillary first premolar extraction using three-dimensional (3D) staged models and lateral cephalograms.

2. Methods

Finite Element Analysis

The study was conducted at the department of orthodontics and dentofacial orthopaedics at SRCDSR, Haryana, India using FEM after obtaining clearance from the institutional ethical clearance board (SRCDSR/ACAD/2016/1917) dated 22/11/2016.

Construction of Geometric Model

The geometric model of maxillary teeth was built based on the dimensions and morphology explained in Wheeler's textbook (Fig. 1). The first premolar was not made so that retraction could be simulated in first premolar extraction cases. To create natural anatomy, periodontal ligament (PDL) was built using an average thickness of 0.25 mm around the roots of all the teeth. Next, the alveolar bone was produced and then the PDL and the teeth were fitted into the bone (Fig. 2). A splint was constructed and placed over six maxillary anterior teeth with biocryl material (1mm thickness) (Scheu-Dental, Germany). Miniscrews (1.8 mm x 10 mm) were placed palatally between roots of the second premolar and first molar. Short continuous e-chain (G&H Orthodontics, Franklin, USA) was used to apply force from the miniscrew to the canine hook (Fig. 3).

The geometric model was transformed into a FEM (finite number of elements and nodes) as seen in Table 1. Teeth, PDL, alveolar bone, and acrylic splint were regarded as iso-parametric and homogenous. The material properties used in this study were derived from Chang et al. as mentioned in Table 2.

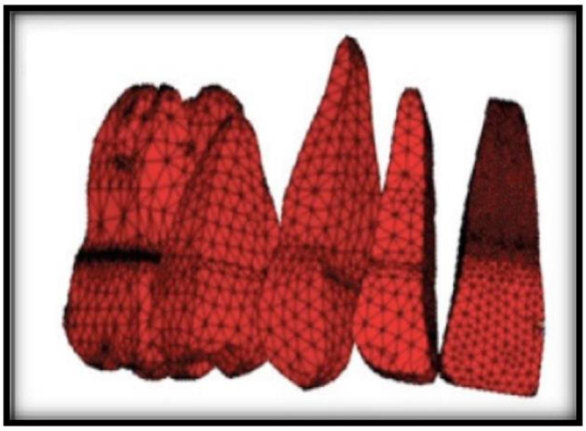

Figure 1. Geometric model of maxillary teeth

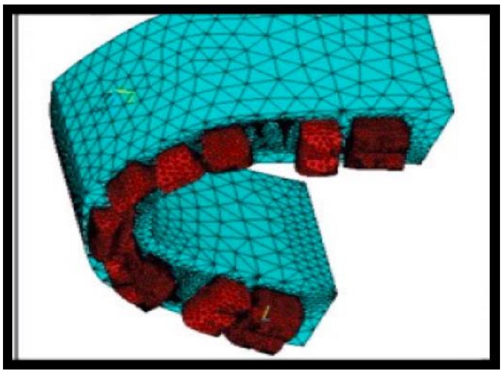

Figure 2. Geometric model of maxillary teeth fitted into the bone

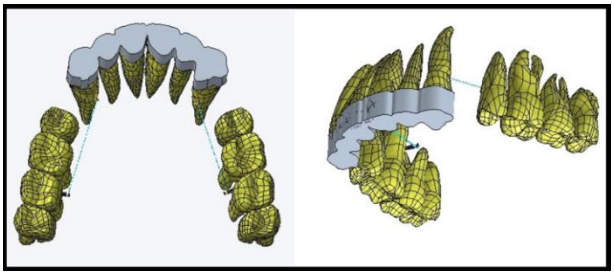

Figure 3. Geometric model depicting retraction using e-chain, TAD and hook incorporated in clear splint

Defining the Boundary Condition

At the affixed nodes between the splint and miniscrew, translational degrees of freedom in the two flexural directions of the splint were combined to contort conjointly, and translational degrees of freedom in the anteroposterior direction related to the splint were unrestrained. Hence, free axial rotation movement of the maxillary anterior six teeth under the splint was allowed, while the force of elastomeric chain from the canine hook to the miniscrew was kept constant. The nodes fixed to the outer surface of the bone were secured in all directions to avoid not to have any free movements.

Application of Forces

Anterior en-masse retraction was done from the palatal side with force vectors at three different levels: high pull implant (12 mm from the gingival margin), medium pull implant (10 mm from the gingival margin), and low pull implant (8 mm from the gingival margin), which were situated palatally between the roots of the second premolar and first molar. Similarly, height of the canine hook was changed to three different levels: from high pull (12 mm from the gingival margin), medium pull (10 mm from the gingival margin), and low pull (8 mm from the gingival margin). Different combinations of vertical heights were considered and were divided into nine groups (Table 3). A force of 150 gm/side was applied from each miniscrew and a 3D force system was generated for each group.

Evaluation of En-masse Retraction

The software ANSYS 11(Swanson Analysis System Inc., Canonsburg, Pennsylvania, USA) was used to do the analysis and movement was calculated (Fig. 4). The movements were shown in Y axis (sagittal plane) and Z axis (vertical plane). Positive value showed distal movement in the Y axis and upward movement in the Z axis. Negative values demonstrated mesial movement in the Y axis and downward movement in the Z axis.

FEM Results

The earliest movement of the teeth at the crown and root tip was calculated on the Y and Z axis. All results were expressed in rad.

Table 1. Number of elements and nodes in the model

Model	Number of nodes	Number of elements
Complete assembly	44568	160587
Canine hook	120	421
E-chain	532	1509
Maxilla	20589	45978
All teeth	8975	21427
Interdental bone	14258	30009

Table 2. Material properties of different structures		
Material	**Poisson ratio**	**Young's modulus (kg/mm3)**
E-chain	0.30	2.3x103
Miniscrew	0.32	110x103
Bone	0.38	1.4 x103
Teeth	0.30	2.0 x103
Maxilla	0.28	3.2 x103

Table 3. Different combinations of vertical heights		
Groups	**Height of implant from gingival margin (mm)**	**Height of hook from gingival margin (mm)**
Group 1	8	8
Group 2	8	10
Group 3	8	12
Group 4	10	8
Group 5	10	10
Group 6	10	12
Group 7	12	8
Group 8	12	10
Group 9	12	12

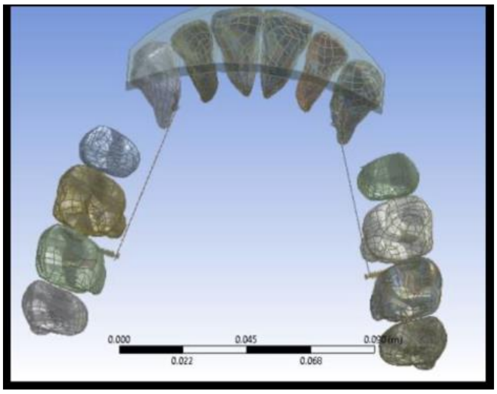

Figure 4. Finite element analysis

Displacement of teeth in the Y axis (Table 4)

In the sagittal plane, when force was applied from the miniscrew at 8 mm (group 1, 2, and 3) to the canine hook at various heights, the following changes were observed:

8 mm: The central incisor, lateral incisor, and canine were tipped lingually. More tipping was observed in the canine and less in the central incisor.

10 mm: Tipping was observed although more tipping was observed than the retraction from 8 mm.

12 mm: Tipping was observed and tipping was higher than that which was noticed from 8 mm and 10 mm.

When force was applied from the miniscrew at 10 mm (group 4, 5, and 6) to the canine hook the following changes were observed:

8 mm: The central incisor, lateral incisor, and canine were tipped lingually. Amount of tipping was more in the canine and least in the central incisor.

10 mm: In all six teeth, the crown tip and root tip was comparable and retraction nearly gave bodily movements.

12 mm: Here tipping was observed and the amount of tipping was more in central incisors and lateral incisors.

Overall, tipping of the six anterior teeth was almost comparable when miniscrew was situated at 8 mm and 10 mm. Group 5 gave bodily movement on en-masse retraction of the six anterior teeth.

When force was applied from the miniscrew at 12 mm (group 7, 8, and 9) to the canine hook the following changes were observed:

8 mm: The central incisor, lateral incisor, and canine tipped almost minimal. Amount of tipping was more in the canine and least in central incisors.

10 mm: In all six teeth, the crown tip and root tip was comparable and retraction nearly gave bodily movements.

12 mm: Pure translation was observed, and there was more movement in the canine as compared to central and lateral incisors.

Displacement of teeth in the Z axis (Table 5):

In the vertical plane, when force was applied:

8 mm (group 1, 2, and 3): Extrusion of the central incisor, lateral incisor, and canine were noticed.

10 mm (group 4, 5, and 6): Intrusion of the central incisor, lateral incisor, and canine were noticed.

12 mm (group 7, 8, and 9): Intrusion was noticed although intrusion amount was greater than the other groups that had miniscrews placed at 8 mm and 10 mm positions.

Table 4. Displacement of teeth in Y-axis

Group (mm)	**Central incisor**		**Lateral incisor**		**Canine**	
	Crown tip	**Root tip**	**Crown tip**	**Root tip**	**Crown tip**	**Root tip**
8X8	0.13E-03	0.49E-04	0.14 E-03	0.35 E-04	0.18 E-03	0.18 E-04
8X10	0.29E-03	0.35E-04	0.28 E-03	0.25 E-04	0.32 E-03	0.21 E-04
8X12	0.49E-03	0.22E-04	0.39 E-03	0.18 E-04	0.45 E-03	0.38 E-04
10X8	0.13E-03	0.39E-04	0.14 E-03	0.34 E-04	0.17 E-03	0.16 E-04
10X10	0.29E-03	0.33E-04	0.31 E-04	0.27 E-04	0.31 E-03	0.25 E-04
10X12	0.50E-03	0.25E-04	0.50E-03	0.19 E-04	0.29 E-03	0.40 E-04
12X8	0.10E-03	0.11E-04	0.11 E-03	0.12 E-04	0.12 E-03	0.11 E-04
12X10	0.11E-03	0.13E-04	0.11 E-03	0.17 E-04	0.13 E-03	0.20 E-04
12X12	0.46E-03	0.38E-03	0.42 E-03	0.38 E-03	0.49 E-03	0.23 E-03

Table 5. Displacement of teeth in Z-axis			
Group (mm)	**Central incisor**	**Lateral incisor**	**Canine**
8X8	-0.11E-06	-0.11E-06	-0.09E-04
8X10	-0.13 E-06	-0.12 E-06	-0.10E-04
8X12	-0.21 E-06	-0.19 E-06	-0.16 E-06
10X8	0.10E-04	0.11E-04	0.09E-04
10X10	0.11E-04	0.10E-04	0.10E-04
10X12	0.13E-04	0.10E-04	0.14E-04
12X8	0.13E-04	0.12E-04	0.13E-04
12X10	0.17E-04	0.16E-04	0.15E-04
12X12	0.18E-04	0.17E-04	0.15E-04

Table 6. Inclusion and exclusion criteria	
Inclusion criteria	**Exclusion criteria**
Class II dental cases treated by upper premolar extraction	Presence of local pathology in the region of interest
above 17 years of age	Taking any medications that may cause alteration to orthodontic tooth movement
Good general health	
Consent to be part of the study	

In Vivo Evaluation

A randomized prospective clinical trial was undertaken and the study subjects with a chief complain of protrusive teeth were chosen. Patients were treated with maxillary first premolar extractions. The patients were included after obtaining informed consent form. Based on the prevalence of class II malocclusion, a total of 10 cases diagnosed as class II division and class I malocclusion were selected to ensure a power of 80% with 5% significance (9) (Table 6).

Alginate impressions along with lateral cephalograms of all the patients were taken and maxillary clear splint of biocryl material (Scheu-Dental, Germany) incorporating power-arms was fabricated using the Bio-Star machine (Scheu-Dental, Germany). TADs were inserted at the assessed height between the 16-15, 16-17 and 26-25, 26- 27 palatally at 10 mm (between maxillary first premolar and first molar; and maxillary first molar and second molar bilaterally). A force of 150 g from the 10 mm height of the hook in the splint was applied to retract the anterior teeth with the help of the e-chain (G&H orthodontics, Franklin, USA) as was used in finite element analysis. The assessment of retraction was done by measuring the distance between the distal aspect of the canine and second premolars with the help of a vernier calliper (Libral Traders, New Delhi, India), visible changes, superimposition of 3D models; and two landmarks: U1-NF (angle between tip of upper incisor to nasal floor) and U1-NA (both angle and distance between tip of upper incisor and NA line) were analyzed using lateral cephalogram.

Maxillary arch impressions were taken at intervals for every patient up to the period of observation (up to six months) and poured in dental stone. The formed dental models were scanned using an extra oral laser scanner (MaestroTM 3D MDS 400, AGE Solutions, Pontedera, Italy) with an accuracy of 10 microns and resolution of 0.007 mm. The scanned files thus obtained in a STL format were transferred to advanced 3D mesh processing software (Meshlab, CNR-ISTI, Pisa, Italy). Using this software, the digitally scanned models were superimposed on each other with the median end of palatal rugae as well as the palatal slope used as stable surface landmarks, thus making it possible to obtain the only movement of dental units on the maxillary arch (Figs. 5 and 6)

Statistical Analysis

Data was not normally distributed based on the Kolmogorov-Smirnov test results (p-value < 0.05). Therefore, analysis was performed using the non-parametric Friedman test for comparing more than

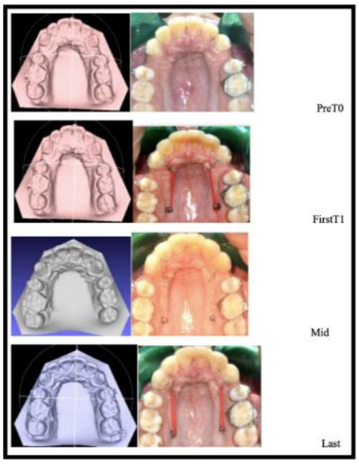

Figure 5. Scanned files used for measurements and clinical intraoral photographs at pre, mid and last appointments

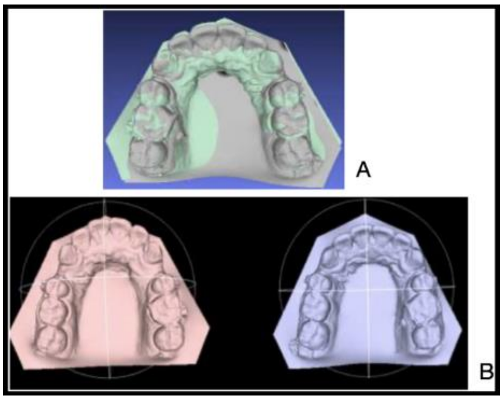

Figure 6. A) Superimposition, B) Comparison of scanned models of pre and last appointment

two groups at different intervals and the Wilcoxon signed rank test for post hoc pairwise comparison. Level of statistical significance was p-value < 0.05.

3. Results

Among the 10 subjects, mean distance between maxillary anterior teeth and second premolars after extraction was found to be 5.31±1.30mm. During the third and sixth month it was 3.36±1.2mm; and 1.05±1.33mm. When this mean difference was compared using the Friedman test, it was found to be statistically significant and maximum retraction of maxillary anteriors were noticed after sixth months. When post-hoc pairwise comparison was done using Wilcoxon signed rank test, significant retraction was noticed from the time extraction was done until the sixth month (Table 7).

When the difference in mean NF-UI angle and U1-NA(degree/mm) after extraction and at the sixth month was compared using the Wilcoxon sign ranked test, no significant difference was found.(Table 8 and 9).

Table 7. Mean (SD) Rate of retraction (mm) at different intervals when miniscrew was placed at 10 mm

	N	MEAN	STD. DEVIATION	MINIMUM	MAXIMUM
T0 (1)	10	5.310	1.3085	3.2	7.2
T3 (2)	10	3.360	1.2140	2.8	6.6
T6 (3)	10	1.050	1.3360	0.92	2.4
P value	<0.0001 S				
Post hoc pairwise comparison	1-2 S 2-3 S 1-3 S				

S- Statistically significant

Table 8. Mean NF-UI angle during first and sixth month after premolar extraction when miniscrew was placed at 10 mm

	N	MEAN	STD. DEVIATION	MINIMUM	MAXIMUM
NF-U1 at T0	10	132.3333	2.51661	130.00	135.00
NF-U1 at T6	10	110.6667	1.15470	110.00	112.00
P value	0.109 NS				

NS- Not statistically significant

Table 9. Mean NA-UI during first and sixth month after premolar extraction when miniscrew was placed at 10 mm

	N	MEAN	STD. DEVIATION	MINIMUM	MAXIMUM
NA-U1 at T0	10	37.0 and 12 mm	4.35890	34.00	42.00
NA-U1 at T6	10	27.0 and 7 mm	1.00	26.00	28.00
P value	0.102 NS				

NS- Not statistically significant

4. Discussion

The science of orthodontics has seen much advancement in many aspects such as diagnosis, treatment planning, and better understanding of biomechanics. One such advancement in orthodontics that has gained attention in recent years is use of clear aligners or aesthetic treatment procedures. So keeping aesthetics in mind, this study was initiated to evaluate and compare the en-masse retraction of maxillary anterior teeth using palatal mini-implant anchorage and clear aligners such as retraction appliance covering maxillary anterior teeth.

Favorable control in retraction of anterior teeth at the time of space closure is critical because the initial phase permits the height of the line of action of the force to be revised (10,11). Using hooks in retraction phase permits adjusting the height of the line of action of the force via different lengths of soldered hooks (12,13). According to the finite element analysis, concerning the inclination attained by the incisors during retraction, group 3 had the highest amountfollowed by groups 2 and 1 respectively. Hence, the farther the distance from the force to the center of resistance (CR), the greater the inclination obtained by the incisors. In groups 1 to 6, there was a moment of inclination generated by the one-couple system, due to force applied by the hook in the splint in the anterior region to the TAD (the longer the hook, the greater the effect and more the height of TAD, more the effect). However, when the force was applied from the 10 mm height of the hook in the splint to the CR, (TADs placed at 10 mm), most movements were practically translation. When comparing the quantity of extrusion reached by the incisors during retraction, it was observed that when force was applied from the 8 mm height of the hook to the CR, greater extrusion was presented than 10 mm and 12 mm respectively. This could be due to the vertical position of the line of action of the force being farther away from the CR, leading to increased incisor inclination.

The slight decrease in extrusion caused in 10x10 mm (hook height) compared with 10 (TAD placement) x8 mm (hook height) is due to the placement of the hook even higher (10 mm from the gingival margin) in the palate, which reached more proximity of the line of action of the force to the CR of the anterior segment, allowing more control of palatal inclination of the incisors. Hence, when the force's line of action is nearer to the CR, more extrusion can be controlled.

The results of this study are justified with an analysis proposed by various authors (14,15) who demonstrated that the center of rotation changed apically from the center of the root when the height of force application moved toward the apex. If force application height was over the CR in the incisal direction, the CR was displaced in the incisal direction.

Therefore, tooth inclination and extrusion would depend on the direction of force application. To achieve this purpose clinician could bond accessories in a more cervical direction by using longer hooks soldered to the appliance or arch or to the distal wing of the bracket, or use sliding jigs instead of fixed orthodontics. However, a recent FEM analysis concluded that anterior teeth demonstrated translation movement when the line of force infiltrated the CR. However, if the line of action was not perpendicular to the long axis of the anterior teeth, the anterior teeth moved bodily with an abrupt infiltration although the force was sent horizontally (16).

To manage movement of the anterior teeth, clinician must be aware of the association between force direction and CR. However, predicting tooth movement remains challenging because it also depends on each individual characteristic of the PDL. Therefore, it is problematic to determine an ideal combination of anchor screw positions and lever arm heights to obtain a favorable movement pattern. In clinical settings, movement patterns should be intently studied and if necessary the force direction should be altered if an unwanted movement of the anterior teeth occurs (16).

Palatal rugae have been determined by many researchers to be a stable landmark over time and even after orthodontic treatment (17,18). Choi et al (19). found that 3D superimposition of dental casts using palatal rugae as well as palatal slope serves as a reliable method for analyzing tooth movement. Thus, it is used as an important landmark in evaluating anterior teeth retraction.

The appliance design eliminated the role of frictional resistance during en-masse retraction on both sides, but it resulted in certain loss of control of tooth movement during retraction, resulting in rotation (mesial out and distal in), and tipping, which was clinically significant in a few cases. This can be a limitation when compared to fixed orthodontic appliances and palatal TADs. The force decay of the e-chain was not considered in the study. A larger sample size would also be required to negate some of the aberrant readings that may have resulted in the present study. The materials with linear elastic (homogeneous and isotropic) properties were used according to numerical convergence, so creep properties of the model’s components could not be considered.

Conclusion

Within the limitations of the study, the following conclusions can be drawn:

The en-masse retraction of maxillary anteriors was found to be possible using a clear aligner-like appliance and TADs.

Although clinically significant changes were observed in mean UI-NA and NF-UI values, statistically it failed to reach the level of significance.

Significant en-masse retraction of maxillary anteriors was observed in the study sample (N) from the first to the fourth month. After that, slow retraction was observed.

Translational tooth movement was observed when the line of force application was at the level of the center of resistance (i.e, 10x10 mm distance of TADs), and hooks attached to clear splint respectively in both FEM and in vivo evaluation.

In both FEM and in vivo evaluation, when force was applied from a variable height of the hook, above and below the level of CR, more tipping as well as rotation was observed.

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