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Dear Editor:

Thank you for your kind and detailed review of our manuscript. It is our pleasure to resubmit the revised paper to you for publication in *The Journal of Visualized Experiments*. We found reviewers' comments to be extremely helpful, and hope that our responses adequately address their concerns. The authors tried to make the article concise and simple. To ensure compliance with the journal guidelines, we tried to eliminate jargon and incorrect terms. We would be very honored if the manuscript could be published in your journal.

Thank you in advance for your kind considerations and we look forward to hearing a positive reply from you soon.

Best regards,

Ji-Man Park, DDS, MSD, PhD

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TITLE:

Measuring the Complete-Arch Distortion of an Optical Dental Impression

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KEYWORDS:
Dental, technology, dental impression, intraoral scanner, accuracy, distortion, coordinate system, complete-arch scan

SUMMARY:
Here, we present a protocol to measure the degree of distortion at each part of the compete-arch digital impression acquired from an intraoral scanner with 3D-printed metal phantom with standard geometries.

ABSTRACT:
Digital workflows have actively been used to produce dental restorations or oral appliances since dentists started to make digital impressions by acquiring 3D images with an intraoral scanner. Because of the nature of scanning the oral cavity in the patient's mouth, the intraoral scanner is a handheld device with a small optical window, stitching together small data to complete the entire image. During the complete-arch impression procedure, a deformation of the impression body can occur and affect the fit of the restoration or appliance. In order to measure these distortions, a master specimen was designed and produced with a metal 3D printer. Designed reference geometries allow setting independent coordinate systems for each impression and measure *x*, *y*, and *z* displacements of the cylinder top circle center where the distortion of the impression can be evaluated. In order to evaluate the reliability of this method, the coordinate values of the cylinder are calculated and compared between the original computer-aided design (CAD) data and the reference data acquired with the industrial scanner. The coordinate differences between the two groups were mostly less than 50 µm, but the deviations were high due to the tolerance of 3D printing in the *z* coordinates of the obliquely designed cylinder on the molar. However, since the printed model sets a new standard, it does not affect the results of the test evaluation. The reproducibility of the reference scanner is 11.0 ± 1.8 µm. This test method can be used to identify and improve upon the intrinsic problems of an intraoral scanner or to establish a scanning strategy by measuring the degree of distortion at each part of the complete-arch digital impression.

INTRODUCTION:

In the traditional dental treatment process, a fixed restoration or a removable denture is made on a model made of gypsum and impregnated with a silicone or irreversible hydrocolloid material. Because an indirectly made prosthesis is delivered in the oral cavity, a lot of research has been done to overcome the errors caused by a series of such manufacturing processes[1,2]. Recently, a digital method is used to fabricate a prosthesis through the CAD process by manipulating models in the virtual space after acquiring 3D images instead of making impressions[3]. In the early days, such an optical impression method was used in a limited range such as a dental caries treatment of one or a small number of teeth. However, as the base technology of the 3D scanner was developed, a digital impression for the complete arch is now used for the fabrication of large-scale fixed restorations, removable restorations such as a partial or full denture, orthodontic appliances, and implant surgical guides[4–7]. The accuracy of the digital impression is satisfactory in a short region such as the unilateral arch. However, since the intraoral scanner is a handheld device that completes the entire dentition by stitching together the image obtained through a narrow optical window, the distortion of the model can be seen after completing the U-shaped dental arch. Thus, an appliance of a large range made on this model might not fit well in the patient's mouth and require a lot of adjustment.

Various studies have been reported on the accuracy of the virtual impression body obtained with an intraoral scanner, and there are various research models and measurement methods. Depending on the research subject, it can be divided into clinical research[8–12] for actual patients and in vitro studies[13–16] conducted in models separately produced for research. Clinical studies have the advantage of being able to evaluate the conditions of an actual clinical setting, but it is difficult to control the variables and increase the number of clinical cases indefinitely. The number of clinical studies is not large because there is a limit to being able to evaluate the desired variables. On the other hand, many in vitro studies that evaluate the basic performance of the intraoral scanner by controlling variables have been reported[17]. The research model also includes a partial or complete arch of natural teeth[18–22] and a fully edentulous jaw with all teeth lost[23], or the case where the dental implant is installed and spaced apart at a certain interval[24–27], or a form in which the majority of the teeth remain and only a part of a tooth is missing[16,28]. However, studies on the distortion of the virtual impression body made by a handheld intraoral scanner have been limited to the qualitative evaluation of deviations through a color map created by superimposing it with reference data and expressed as one numerical value per data. It is difficult to accurately measure the 3D distortion of the complete arch because most studies only examine the localized portion of the dental arch with a nondirectional distance deviation.

In this study, the distortion of the dental arch during optical impression with an intraoral scanner is investigated by using a standard model with a coordinate system. The aim of this study is to provide information on a method for evaluating the accuracy performance of the intraoral scanners which exhibit various characteristics by the difference in optical hardware and processing software.

PROTOCOL:

1. Master specimen preparation

1.1. Model preparation

1.1.1. Remove the artificial teeth (left and right canines, second premolar, and the second molar) on the mandibular complete-arch model with only 1/5 of the cervical portion left.

1.2. CAD design

1.2.1. Acquire the data of the master specimen with a reference scanner.

1.2.2. Design the cylinders (with a top diameter of 2 mm and a cylinder height of 7 mm) on top of the trimmed six teeth with the reverse engineering software.

1.2.3. Add three reference spheres (3.5 mm in diameter) posterior to the left second molar for the purpose of defining the reference 3D coordinate system from the reverse engineering software.

1.2.4. Locate one sphere on the distal side of the distal and buccal side of the cylinder on the left second molar so that the coordinates of all the cylinders have positive values.

1.2.5. Design the left second molar cylinder so that it is inclined 30° medially and the right second molar cylinder so that it is tilted 30° distally. Set the other cylinders at right angles from the model.

1.3. Metal 3D printing

1.3.1. Manufacture a phantom model with CoCr alloy by a metal 3D printer to serve as a patient's dentition (**Figure 1**).

2. Reference data acquisition and software analysis

2.1. Scan the phantom with the testing intraoral scanner.

2.1.1. Obtain the reference image by scanning the metal phantom model with the industrial-level model scanner.

2.2. Establish a coordinate system by extracting points from reference spheres.

2.2.1. Load the reference image to the reverse engineering analysis software to calculate the reference coordinates of each cylinder position.

2.2.2. Extract the sphere by selecting the **Ref. geometry | Create | Sphere | Pick boundary points** command and picking the four points on the surface of the reference sphere that are furthest apart from each other (**Supplemental Figure 1** and **Supplemental Figure 2**).

2.2.3. Calculate the center of three reference spheres.

2.2.4. Use the **Ref. geometry** | **Create** | **Plane** | **Pick points** command to connect the centers of three spheres and create a plane (**Supplemental Figure 3**).

2.2.5. Set the formed plane as **XY plane**.

2.2.6. Select the **Ref. geometry** | **Create** | **Plane** | **Offset plane** command to create a tangent plane above the *xy* plane (**Supplemental Figure 4**).

2.2.7. Create points where the tangent plane and two lingual spheres meet by choosing the **Ref. geometry** | **Create** | **Point** | **Project on ref. plane** command (**Supplemental Figure 5**).

2.2.8. Generate a plane between the points created and the center of the two lingual spheres by using the **Ref. geometry** | **Create** | **Plane** | **Pick points** command (**Supplemental Figure 6**).

2.2.9. Measure the distance from this plane to the center of the buccal sphere with the **Inspection** | **Dimension** | **Linear** command (**Supplemental Figure 7**).

2.2.10. Create a parallel plane that passes through the midpoint of the buccal sphere with the **Geometry** | **Create** | **Plane** | **Offset Plane** command (**Supplemental Figure 8**).

2.2.11. Set the formed plane as **YZ plane** (**Supplemental Figure 9**).

2.3. Set the *x*, *y*, and *z* axes.

2.3.1. Set the center of the buccal sphere as the 'origin' of the coordinate system.

2.3.2. Set a line parallel to the line connecting the center points of the remaining two spheres while traveling in the forward and backward direction of the model through the origin as the **Y-axis**.

2.3.3. Set the line on the *xy* plane that passes the origin and is perpendicular to the *y* axis as the **X-axis**.

2.3.4. Use the **Ref. geometry** | **Create** | **Coordinate** | **Pick origin & X, Y direction** command to create a new coordinate system with the buccal sphere center as the origin (**Supplemental Figure 10**).

2.3.5. Set the line perpendicular to the *xy* plane and passing through the origin as the **Z-axis** (**Supplemental Figure 11**).

2.4. Transfer this detail from the scan coordinate system to the newly established coordinate system.

2.4.1. Use the **Ref. geometry | Bind to shell** command to fix the geometries created during this process on top of the scan data (**Supplemental Figure 12**).

2.4.2. Execute the **Ref. geometry | Transform | Coordinate | Align coordinate** command to transit from the basic coordinate system to the newly created coordinate system (**Supplemental Figure 13**).

2.4.3. In this way, assign a coordinate system to the metal master specimen with reference to the three reference spheres (**Supplemental Figure 14**).

2.5. Extract the measurement points from the cylinders at the main area.

2.5.1. Extract the *x*, *y*, and *z* coordinates for the upper circle centers of six cylinders to be analyzed for the distortion of the specified regions by the reverse engineering process.

2.5.2. For this, use the **Ref. geometry | Create | Cylinder | Pick boundary points** command and specify at least 10 points on the top border of the cylinder and designate the same amount of points on the ellipse that meets the tooth at the bottom of the cylinder (**Supplemental Figure 15**, **Supplemental Figure 16**, and **Supplemental Figure 17**).

2.5.3. Obtain the extracted coordinates of the cylinder top center. Evaluate the 3D deformation at each position by comparing it with the coordinate values of the same cylinder of the digital impression acquired by the intraoral scanner to be evaluated.

REPRESENTATIVE RESULTS:

The coordinates of each cylinder calculated from the originally designed CAD data and the reference scan image of the 3D-printed metal master specimen scanned by the industrial-level model scanner are shown in **Table 1**. The difference between the two showed a value of lower than 50 µm, but the *z* coordinate value of the right second molar cylinder from the 3D-printed master specimen was low. Although the metal phantom was produced from a high-end industrial 3D printer, a small difference in the height of one cylinder was found. While the design was done with CAD software, the metal phantom was used as a reference which was scanned with the various testing intraoral scanners, and the difference was negligible. If another evaluator fabricates a new phantom from the same shared data and executes the same process, the phantom should be scanned again with an industrial-level reference scanner to obtain reference coordinates and then proceed with the subsequent process. **Table 2** shows the coordinates of the master specimen which was scanned five times with an industrial scanner. Evaluating from the standard deviation, the average deviation was 45 µm, showing a large deviation in the *y* coordinate value of the right second molar cylinder. It could be concluded that the precision of the reference scanner was good enough for extracting the reference coordinates of point zero and six cylinders.

The evaluation of the reproducibility of the reference scanner was conducted through overlap comparison among five datasets of the metal master specimen scanned with the reference scanner. A total of 10 pairs were aligned and evaluated. The deviation of each pair resulted in reproducibility of 0.011 ± 0.002 mm (**Table 3**). The reproducibility of the reference scanner was calculated differently, and it was concluded that the results from both methods were reliable and the latter could be omitted.

FIGURE AND TABLE LEGENDS:

Figure 1: Design and manufacturing process of a phantom model for the distortion evaluation. (**A**) Originally designed CAD data. (**B**) 3D-printed master specimen made of CoCr alloy.

Supplemental Figure 1: Extract sphere picking points.

Supplemental Figure 2: Picking points on the surface of the reference sphere.

Supplemental Figure 3: Creation of the XY plane by picking the center of three spheres.

Supplemental Figure 4: Creation of the offset plane, half a diameter of the sphere above the XY plane.

Supplemental Figure 5: Creation of the points where the offset plane and two lingual spheres meet.

Supplemental Figure 6: Creation of the plane that passes both centers of the lingual spheres by picking four points.

Supplemental Figure 7: Measurement of the distance from this plane to the center of the buccal sphere.

Supplemental Figure 8: Creation of the parallel plane that passes through the center of the buccal sphere.

Supplemental Figure 9: Setting of the formed plane as YZ plane.

Supplemental Figure 10: Creation of a new coordinate system with the center of the buccal sphere as origin.

Supplemental Figure 11: Setting of the line perpendicular to the XY plane and passing through the buccal sphere center as the Z-axis.

Supplemental Figure 12: Fixing of the created geometries to the scan data.

Supplemental Figure 13: Transfer of the basic coordinate system to the newly created coordinate system.

Figure 14: Checking whether the origin and coordinate system are correctly moved to the one extracted from the scan data.

Supplemental Figure 15: Using the Pick boundary points **command to extract the cylinder.**

Supplemental Figure 16: Picking sufficient points on the top circle and bottom ellipse around the cylinder.

Supplemental Figure 17: Checking whether the extracted cylinder was reverse engineered correctly.

Table 1: Differences in cylinders' coordinates between CAD data and the 3D-printed metal master specimen. Unit: mm.

Table 2: Cylinders' coordinates of reference datasets acquired from the 3D-printed metal master specimen. Unit: m.

Table 3: Precision of the dataset acquired from the reference scanner. Unit: µm.

DISCUSSION:

Among the studies evaluating the accuracy of the intraoral scanner by evaluating the resultant digital impression body, the most common method is to superimpose the digital impression data on the reference image and calculate the shell-to-shell deviation[12–15,20,23]. However, this method is limited to calculating the deviation value from the paired data or evaluating the distribution qualitatively through the color map. In a study which measured the deviation of the local site by selecting points to be analyzed on the color map, the deviation in the x, y, and z direction was not considered[29]. In addition, these methods have limitations in that they should be analyzed after overlapping with reference data. Alignment can vary from one data point to another, and the results vary depending on the sorting criteria. In clinical trials involving patients, it is difficult to apply these methods because it is not possible to scan the complete dental arch through the mouth with an industrial scanner located outside the oral cavity.

In this study, a master specimen made of metal, which is less affected by temperature and humidity, was proposed. The coordinate system for the specific 3D-printed metal specimen was set and the six cylinders' position coordinates were calculated in advance. In this way, regardless of the intraoral scanner, an individual coordinate system was formed from each digital impression through the reference spheres of the scan data so that the analysis could be performed with the scanned data only, without the reference image superimposition. The reference image obtained with the high-precision industrial reference scanner was used only to acquire the coordinate values of the six cylinders when the metal master specimen was first produced. The comparative evaluation between the reference and intraoral scan data was done just by simple arithmetic calculation through coordinate values. In addition, since the deviations in the *x*, *y*, and *z* directions of the cylinder coordinates were expressed as positive and negative values, 3D positional changes were shown for each region. Therefore, the method used in this study is suitable for evaluating the data distortion of the handheld device, the oral scanner. Since the deviation of the cylinder coordinates in the *x*, *y*, and *z* direction was displayed with positive and negative values, a 3D position change of each location becomes obvious. Therefore, the method used in this study is suitable for evaluating the distortion of digital impression data acquired with the handheld intraoral scanner.

Most of the coordinate values of each cylinder calculated from the original CAD data and the reference image of the metal master specimen showed values of less than 50 µm. This is related to the performance peculiar to metal 3D printers. Since the master specimen after 3D printing is used as a new reference rather than using standard CAD data, the limitations of these 3D printers do not need to be considered. The change in the master specimen was large at the *z* coordinate of the right second molar. It was because the cylinder was tilted distally and the length of the cylinder exposed above the tooth was short, which was disadvantageous for the reverse engineering process. Also, the cylinder's upper circle of this tooth was inclined to the *xy* plane of the 3D printer when metal printing was performed in this study. It seems that the characteristics of the 3D printer, in which *xy* accuracy and *z* accuracy are expressed separately, were also reflected. In future research, designing and using all cylinders without tilting can be a good alternative.

If there is a cost problem in fabricating a master specimen with a metal 3D printer, it can be made of gypsum or resin. As the new coordinate system was set and the coordinates of the six cylinders were calculated after specimen fabrication, the dimensional change that could be caused by the expansion and contraction of the material during the manufacturing process does not affect the final result. However, when using such a specimen for a long period of time, there may be a slight volume change due to moisture and temperature, and there is a possibility that it will be deformed due to breakage or abrasion. Therefore, a calibration procedure is required to periodically calculate the cylinder coordinate value with a reference scanner. In addition, instead of using an industrial reference scanner, the coordinate measuring machine (CMM) may be used to measure the reference coordinates of the master specimen. In this case, it is recommended to carry out a superimposing investigation with reference data for the purpose of evaluating the complicated tooth surface in addition to the deviation inspection through the coordinates of cylinders.

The limitations of this method are that the time required for reverse engineering analysis becomes longer when the number of digital impressions to be evaluated increases. However, recently introduced 3D image analysis software enables inspection automation through a macro function. Since the global shape of the master specimen is the same, it is possible to shorten the analysis time by automating the coordinate system setting and the cylinder coordinate calculation of the acquired digital impression.

By measuring the degree of distortion in each part of the complete-arch digital impression as a numerical value, it can be used to find and improve the inherent problems of the intraoral scanner to be evaluated for its performance. Since the intraoral scanner is a complicated optical device consisting of a projection lamp, a lens, a lens barrel, a camera, etc., hardware consideration factors are large. Also, a software algorithm that enables stitching together the acquired 3D data in real-time at more than 30 frames per second is also important[19]. It is possible to evaluate and improve the performance of the intraoral scanner by understanding the relationship between the recurrence pattern of the metal master specimen and the consideration factors of intraoral scanners. The scanning strategy determined by the direction and sequence of acquiring images is also an important element for acquiring digital impressions[30]. This method can be used to establish a strategy that minimizes deformation.

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DISCLOSURES:
The authors have nothing to disclose.

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Figure 1

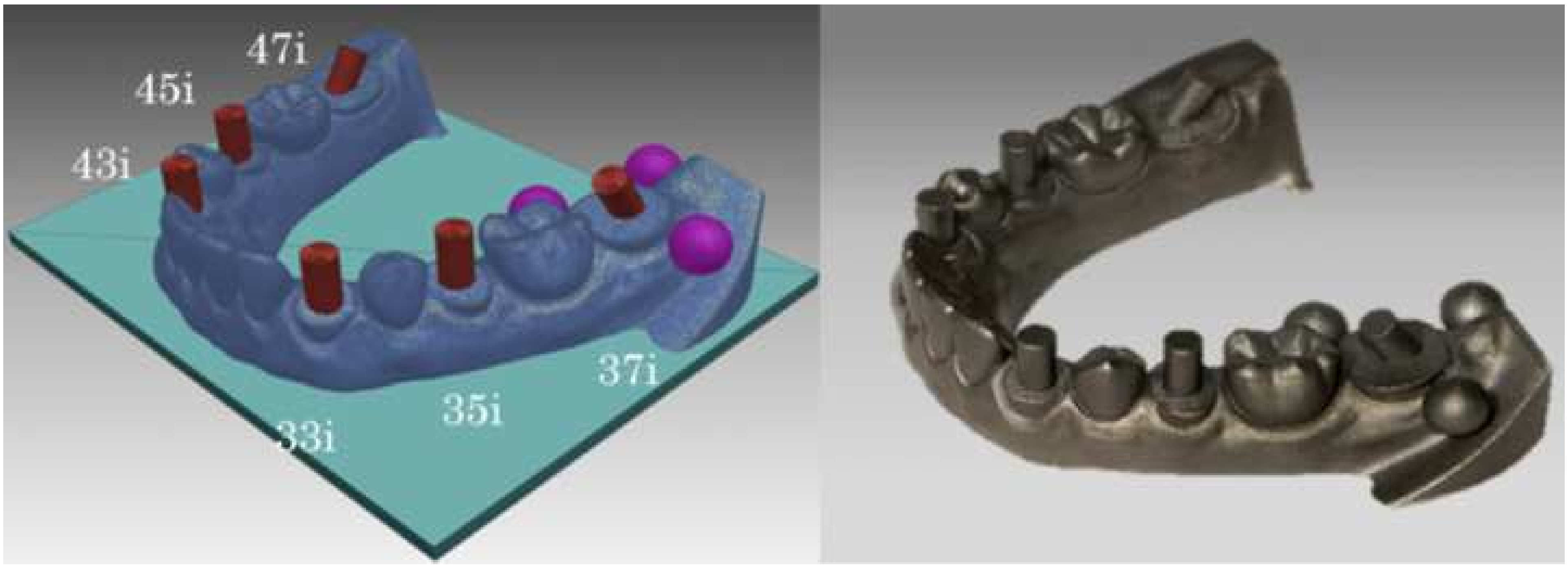

Table 1:

		CAD data	3D printed metal master specimen	Difference
37i	x	7.897	7.875	0.022
	y	6.418	6.373	0.045
	z	7.312	7.265	0.047
35i	x	8.481	8.427	0.054
	y	26.045	25.99	0.055
	z	7.846	7.846	0
33i	x	11.889	11.85	0.04
	y	40.16	40.106	0.054
	z	8.346	8.409	-0.063
43i	x	37.246	37.196	0.051
	y	45.738	45.686	0.052
	z	9.445	9.5	-0.055
45i	x	47.21	47.178	0.032
	y	35.115	35.081	0.034
	z	8.707	8.708	-0.001
47i	x	56.397	56.386	0.011
	y	13.038	13.041	-0.002
	z	7.558	7.451	0.107

Table 2

		Ref. 1	Ref. 2	Ref. 3	Ref. 4	Ref. 5	Mean ± SD
37i	x	7.856	7.874	7.871	7.89	7.885	7.875 ± 0.013
	y	6.406	6.375	6.358	6.356	6.368	6.373 ± 0.020
	z	7.259	7.274	7.269	7.265	7.258	7.265 ± 0.007
35i	x	8.435	8.379	8.393	8.471	8.46	8.427 ± 0.040
	y	26.032	25.98	25.996	25.962	25.979	25.990 ± 0.026
	z	7.838	7.883	7.837	7.858	7.816	7.846 ± 0.025
33i	x	11.839	11.779	11.794	11.925	11.91	11.850 ± 0.066
	y	40.129	40.085	40.112	40.097	40.106	40.106 ± 0.017
	z	8.372	8.485	8.391	8.414	8.381	8.409 ± 0.046
43i	x	37.177	37.115	37.155	37.269	37.262	37.196 ± 0.068
	y	45.711	45.723	45.725	45.622	45.65	45.686 ± 0.047
	z	9.437	9.568	9.541	9.498	9.457	9.500 ± 0.055
45i	x	47.15	47.123	47.142	47.246	47.23	47.178 ± 0.056
	y	35.109	35.148	35.135	34.988	35.025	35.081 ± 0.071
	z	8.609	8.785	8.728	8.738	8.681	8.708 ± 0.067
47i	x	56.369	56.373	56.371	56.409	56.407	56.386 ± 0.020
	y	13.085	13.122	13.114	12.923	12.959	13.041 ± 0.093
	z	7.349	7.445	7.457	7.527	7.478	7.451 ± 0.065

Table 3

Precision	1	2	3	4	5	6	7	8
erence scal	8.3	12.4	9.5	13.2	11.7	8	12.1	10.7

9	10	Mean ± SD
12.1	11.8	11.0 ± 1.8

Name of Material/ Equipment	Company	Catalog Number	Comments/Description
EOS CobaltChrome SP2	Electro Oprical Systems	H051601	Powder type metal alloy for 3D printing
Geomagic Verify	3D Systems	2015.2.0	3D inspection software
Prosthetic Restoration Jaw Model	Nissin Dental Products Inc.		Mandibular complete-arch model
Rapidform	Inus technology	RF90600-10004-010000	Reverse engineering software
stereoSCAN R8	AICON 3D Systems GmbH		Industrial-level model scanner

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Department: **Prosthodontics**

Institution: **Yonsei University College of Dentistry**

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Authors' response to the reviewers' comments

Re: **Manuscript # JoVE59261**

We would like to extend our appreciation for taking the time and effort necessary to provide such insightful guidance. We have revised our paper and explained in response to the reviewers' comments. We have exerted our best efforts to be completely responsive. We hope that these improve the paper such that the editor and the reviewers now deem it worthy of publication in **The Journal of Visualized Experiments**.

EDITORIAL COMMENTS

1. COMMENT: The editor has formatted the manuscript to match the journal's style. Please retain the same.

RESPONSE: Thank you for reformatting the manuscript. The authors revised the manuscript while keeping style according to your recommendation.

2. COMMENT: Please address all the specific comments marked in the manuscript.

RESPONSE: The authors answered to each comment marked in the manuscript.

3. COMMENT: Once done please highlight 2.75 pages of the protocol including headings and spacings that identifies the essential steps of the protocol for the video, i.e., the steps that should be visualized to tell the most cohesive story of the Protocol.

RESPONSE: We have highlighted the protocol including headings and spacings that presents the essential steps of the protocol. Thank you for pointing it out.

4. COMMENT: Please highlight 2.75 pages of the protocol which forms the most cohesive story and will be the part of the filming process.

RESPONSE: We have highlighted the protocol which forms the most cohesive story.

5. COMMENT: Please include an ethics statement before the numbered protocol steps, indicating that the protocol follows the guidelines of your institution's human/animal research ethics committee.

RESPONSE: We have removed the embedded figures from the manuscript. Also, we have uploaded all figures separately to the editorial managing system. The titles and descriptions of each figure was placed after the Representative Results section.

6. COMMENT: From whom?

RESPONSE: We have utilized the ideal shape of artificial resin teeth and copied it through CAD software for the production of the metal master model, which we named as the phantom. The sentence has been edited accordingly.

7. COMMENT: We cannot have commercial language in the manuscript. Please use generic term here and move this to the table of materials.

RESPONSE: This study introduces useful tools for evaluating trueness and precision of intraoral scanners recently used in the dental clinic. To do this, we modified the dental arch model of ideal form and conducted a CAD design, and made a master phantom by 3D printing with metal with less distortion to the surrounding environment. We can evaluate the accuracy performance of intraoral scanners, which were and will be introduced in the future to the dental area, objectively and reliably by assessing the scan data from this master phantom with the method proposed in this study. Of course, there is a high possibility of applying this method to humans, but in this study, we did not conduct experiments on humans or animals. Researchers do not need approval from the research ethics committee for the in-vitro study in Korea. Thank you for your understanding.

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RESPONSE: We have amended the manuscript and added several sentences to draw conclusions. Thank you very much as your comments help us a lot.

9. COMMENT: What do you conclude from this data?

RESPONSE: The authors added conclusions at the end of each paragraph.

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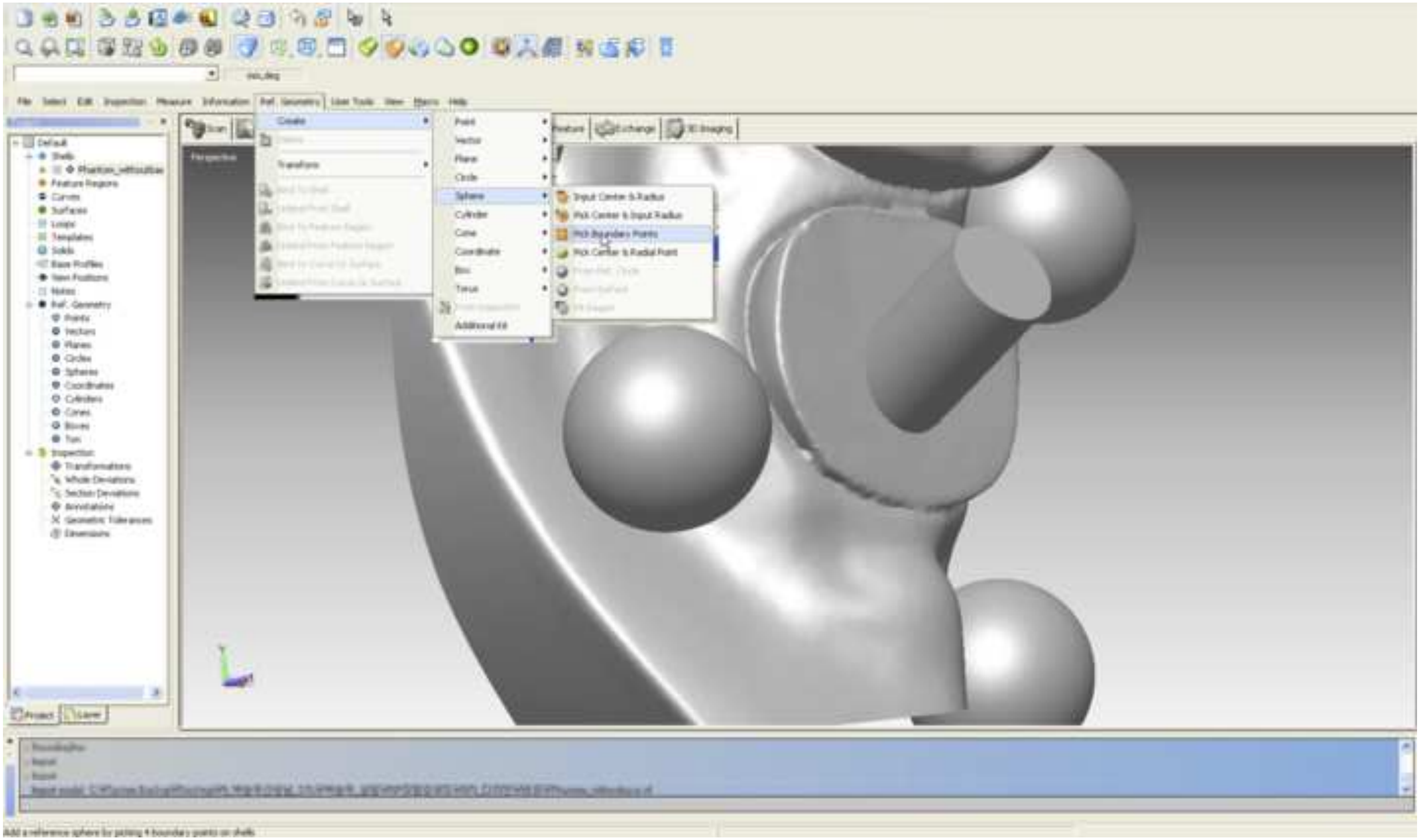

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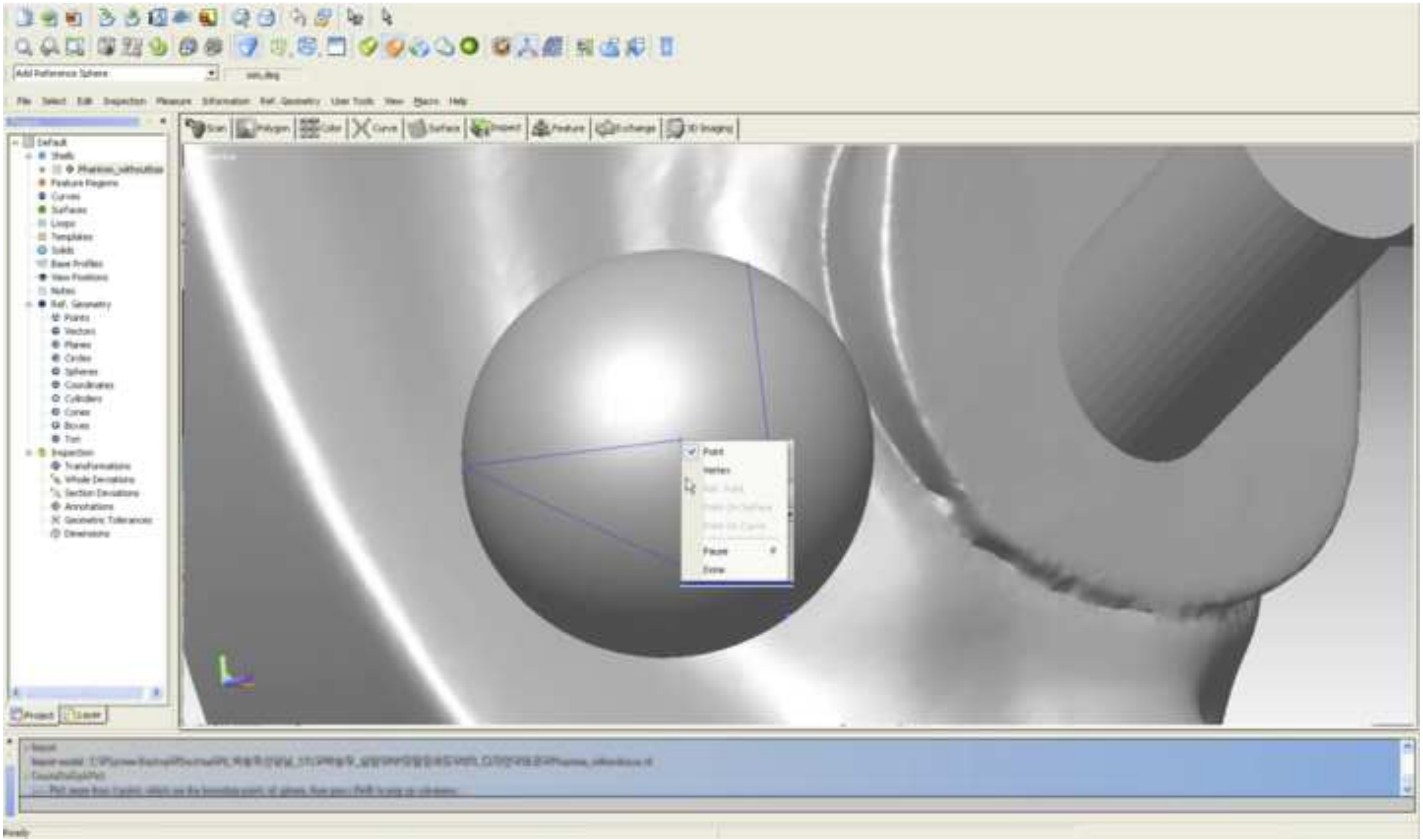

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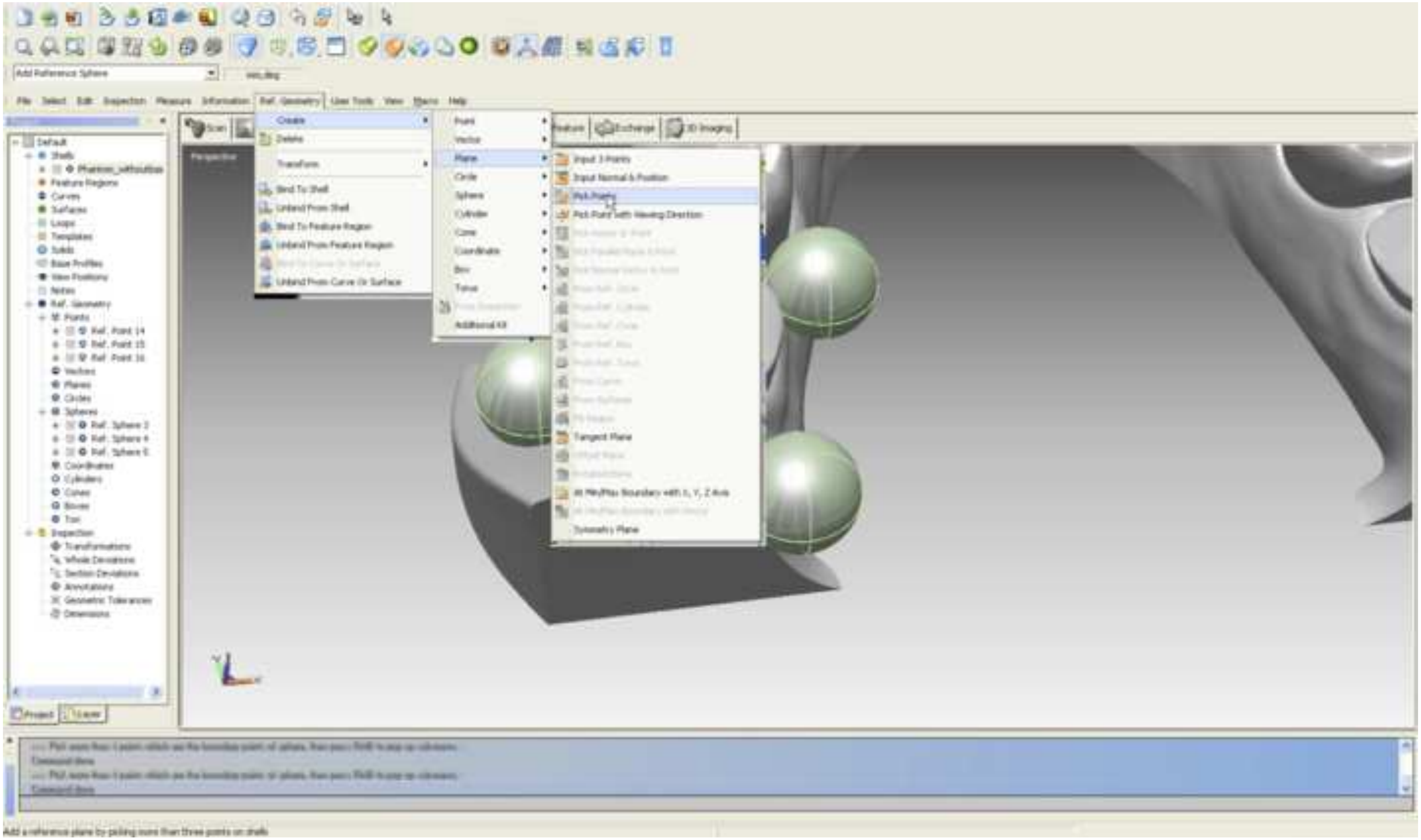

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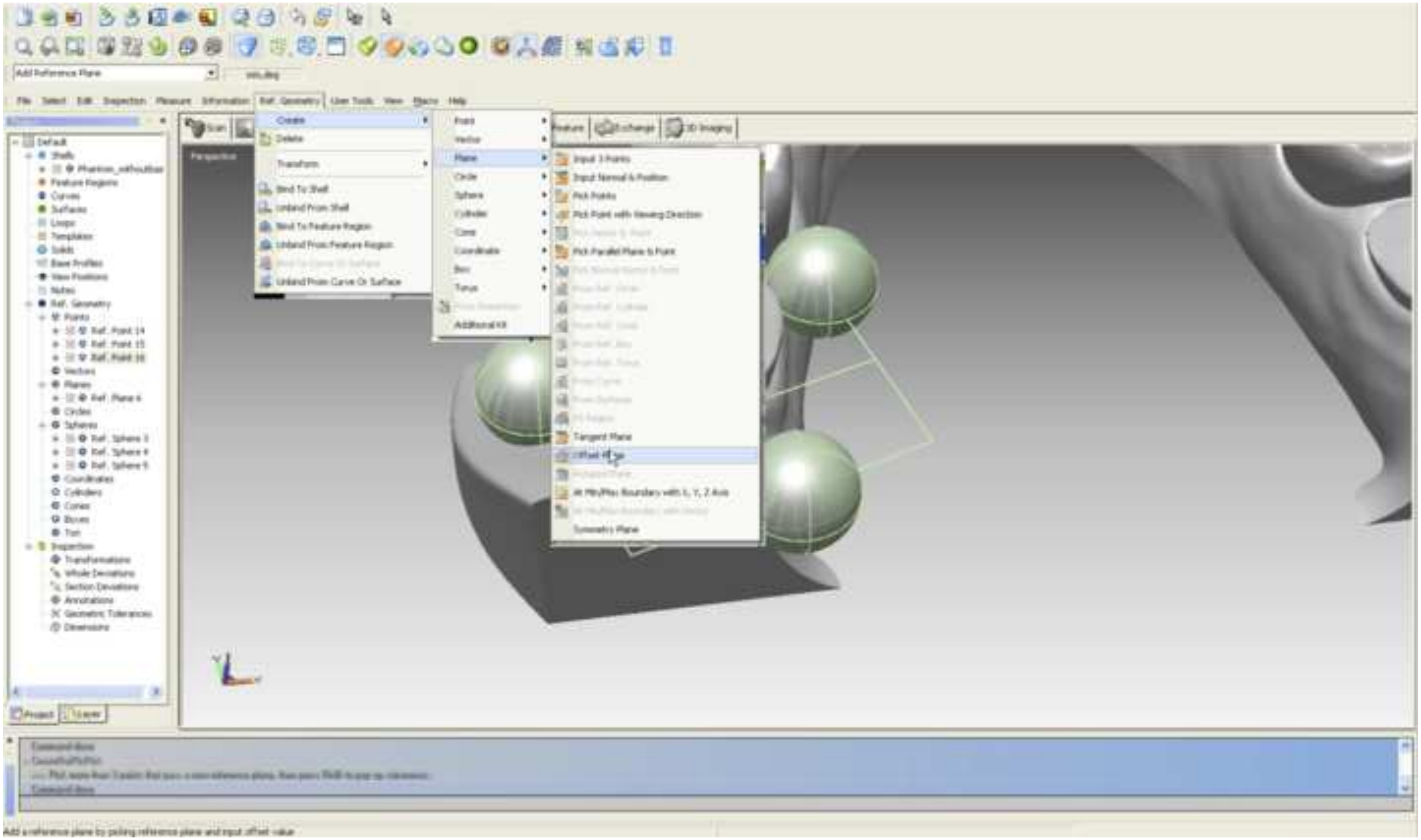

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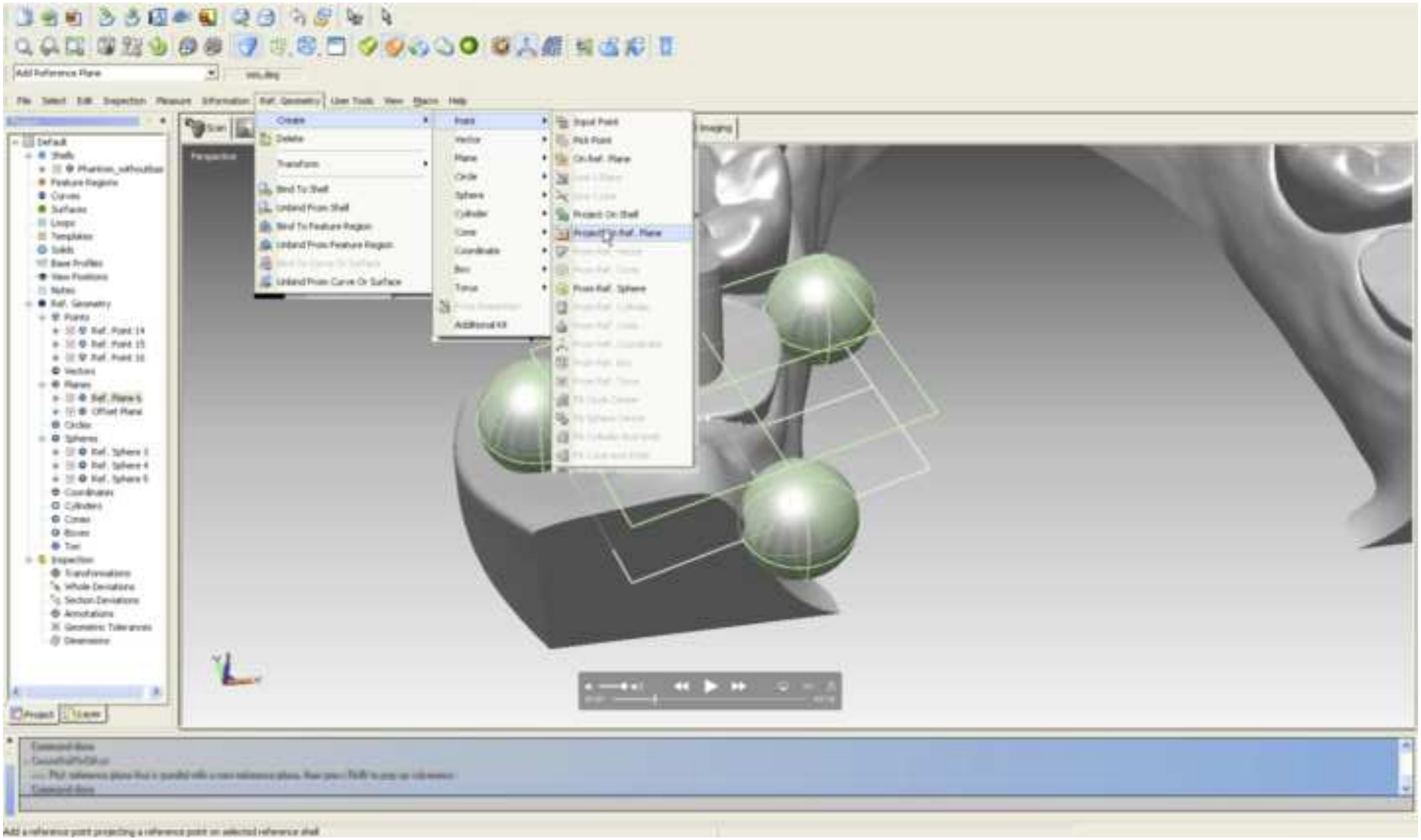

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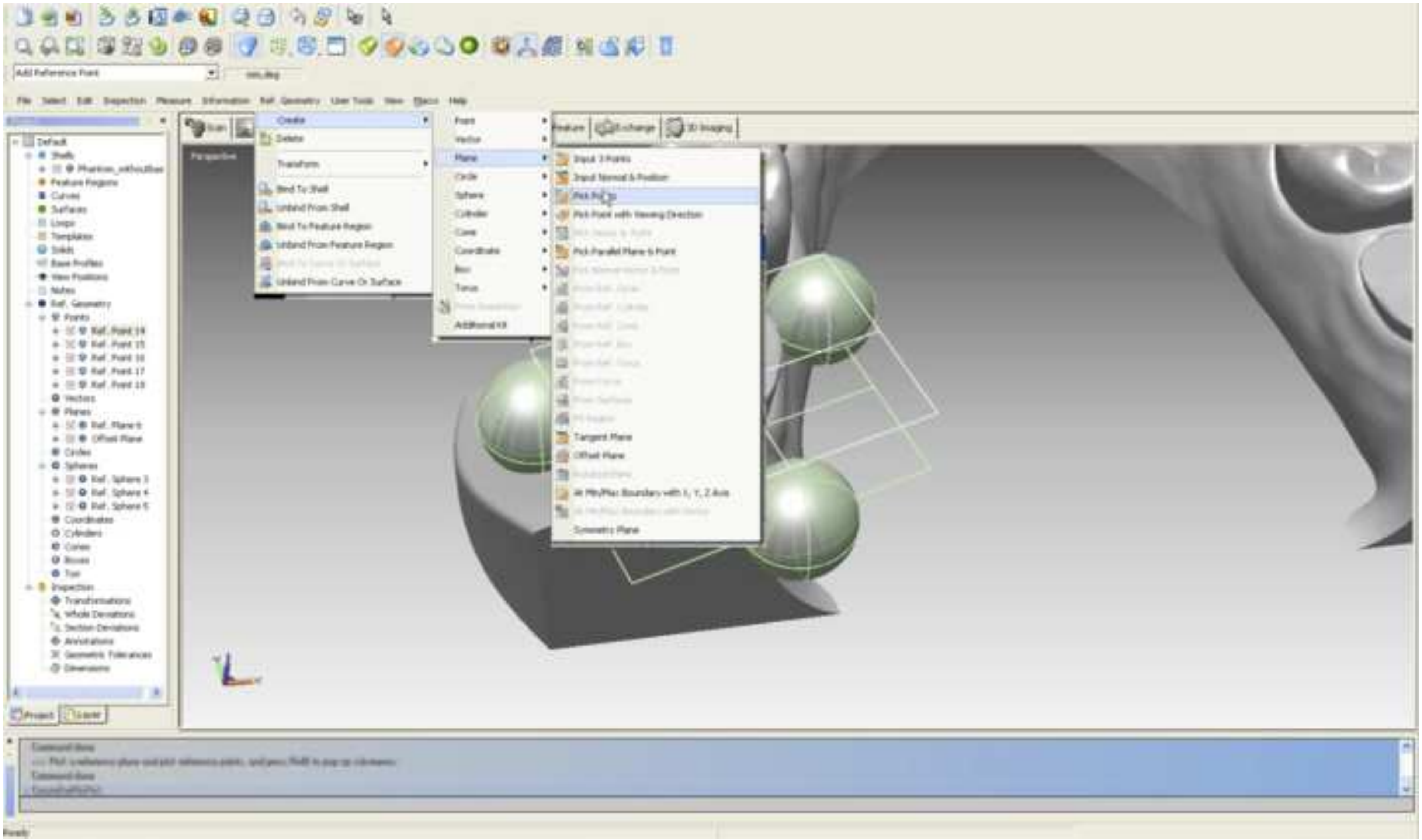

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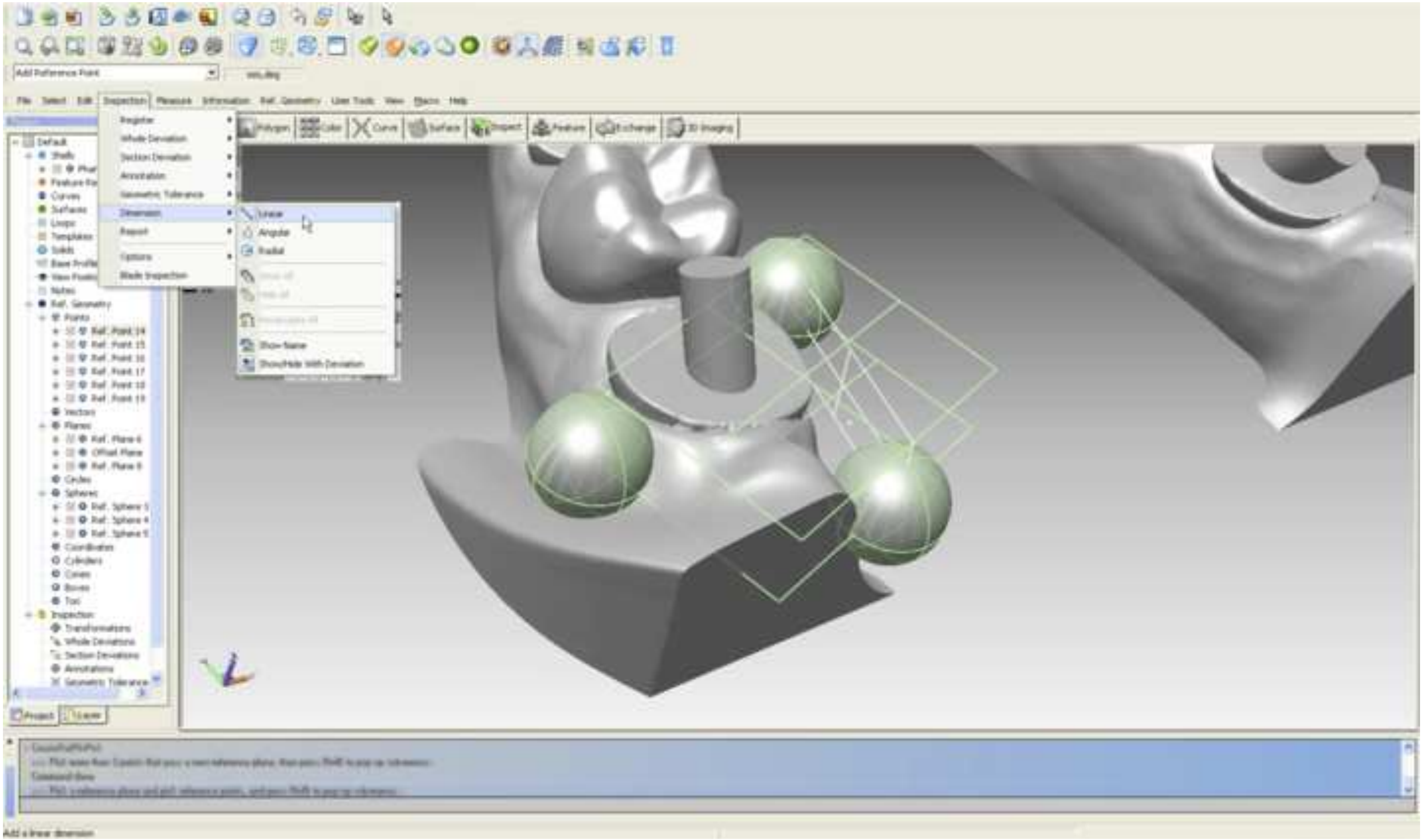

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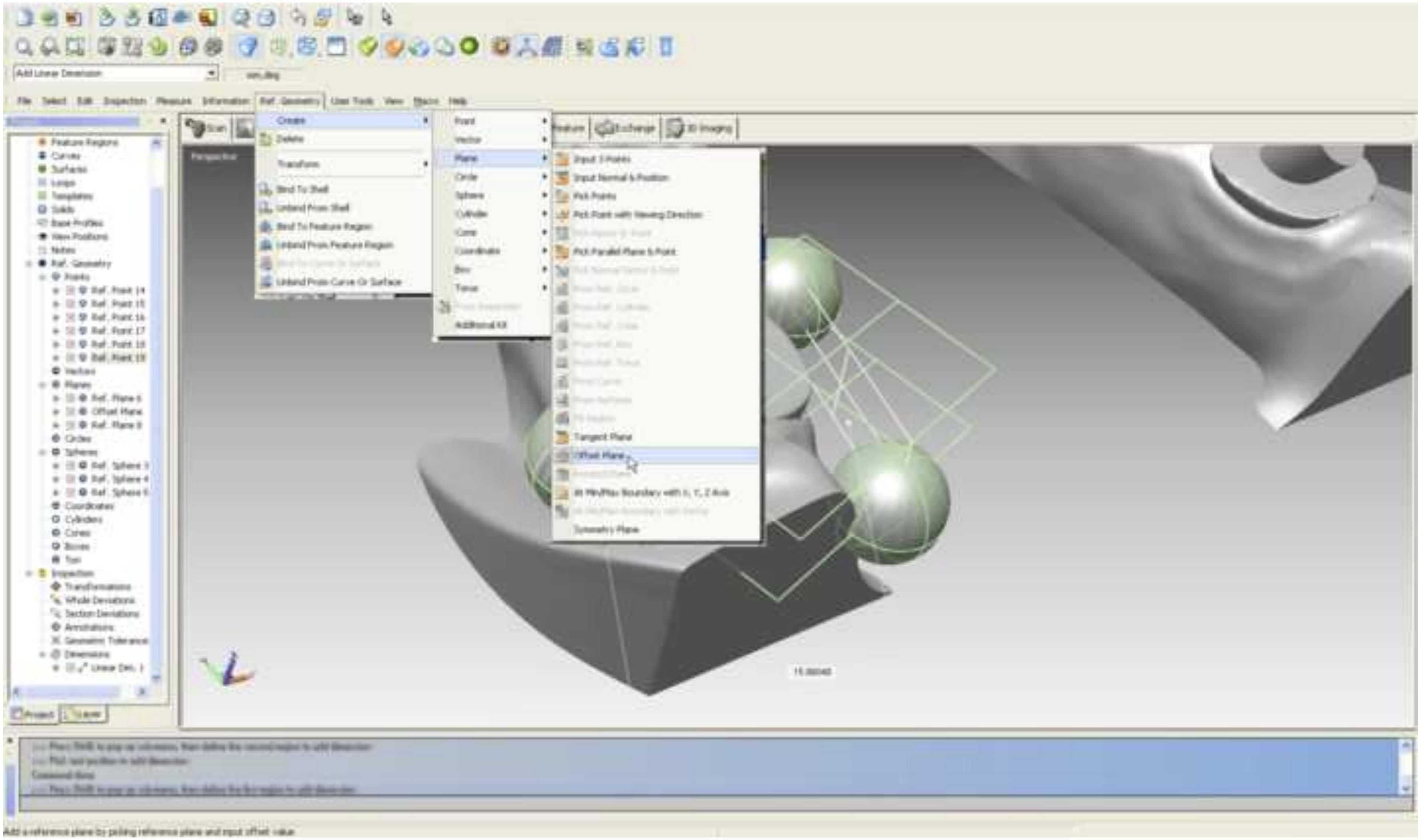

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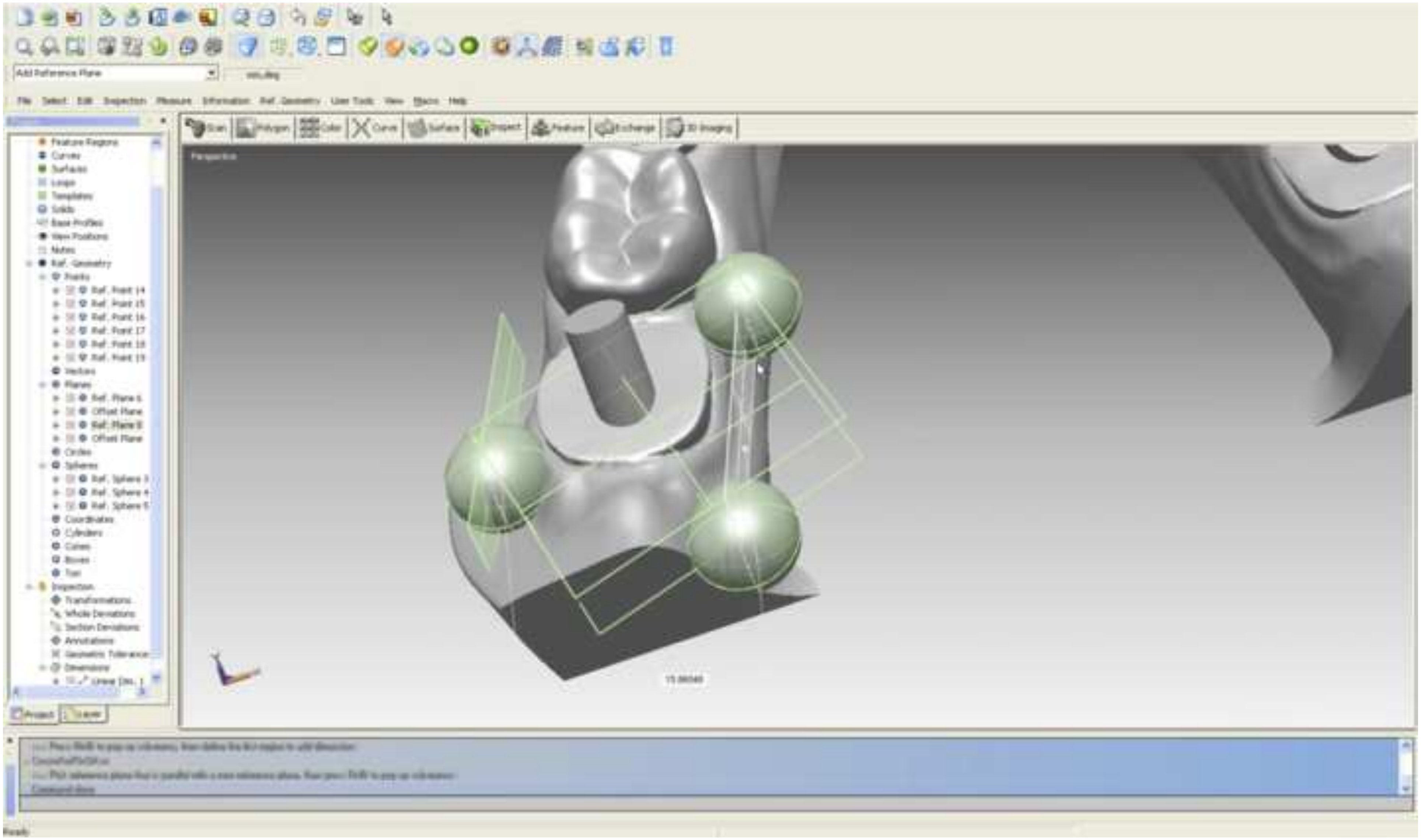

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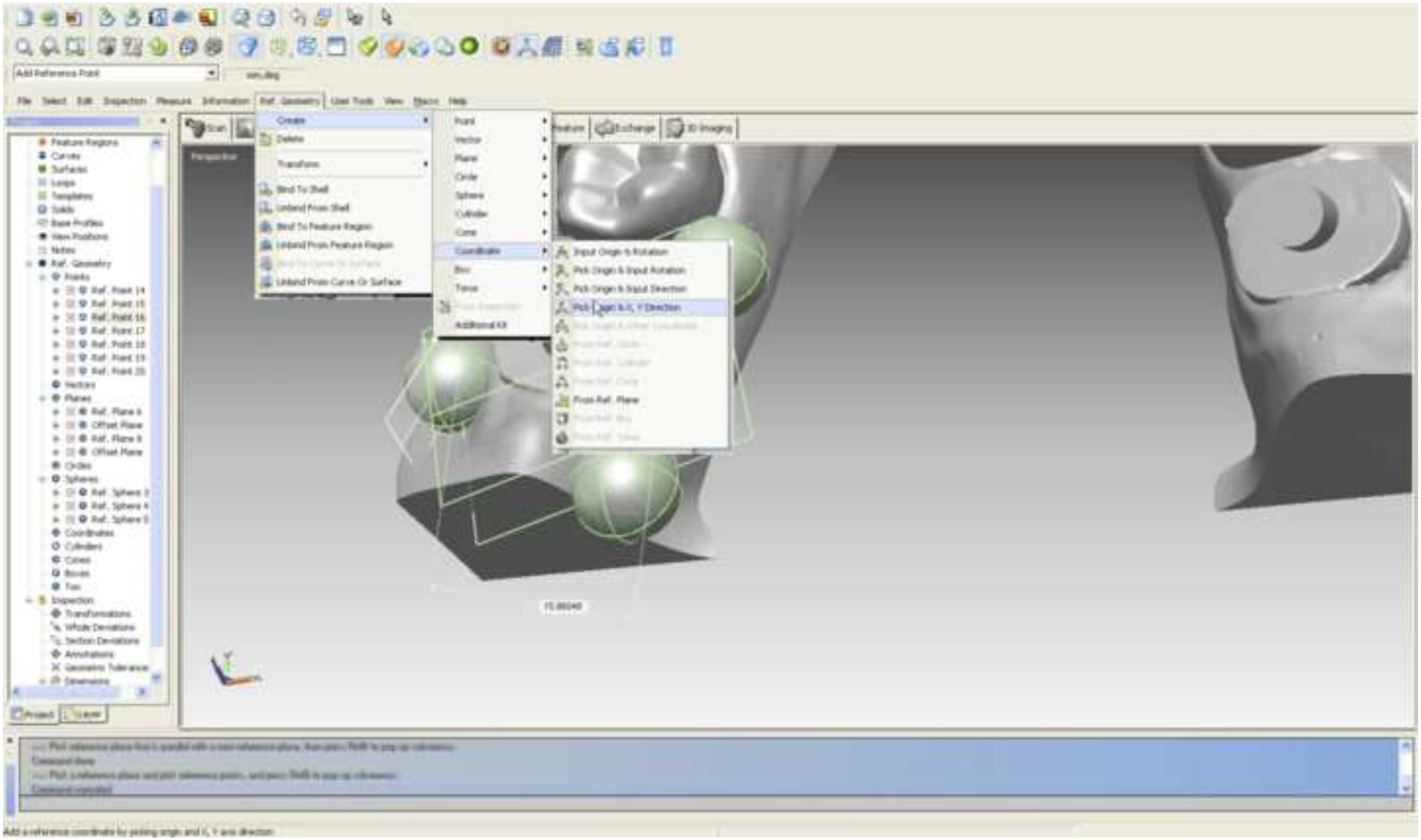

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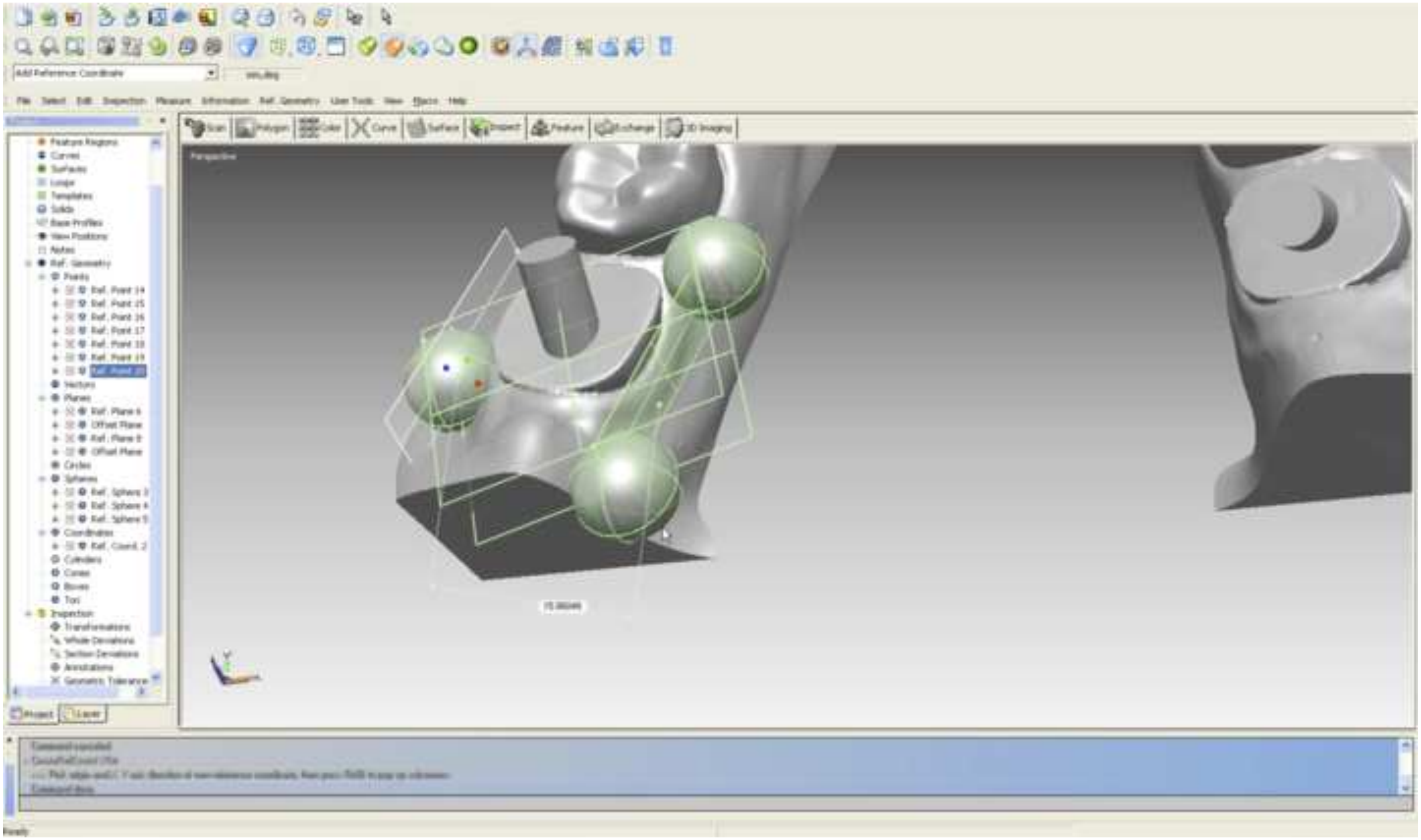

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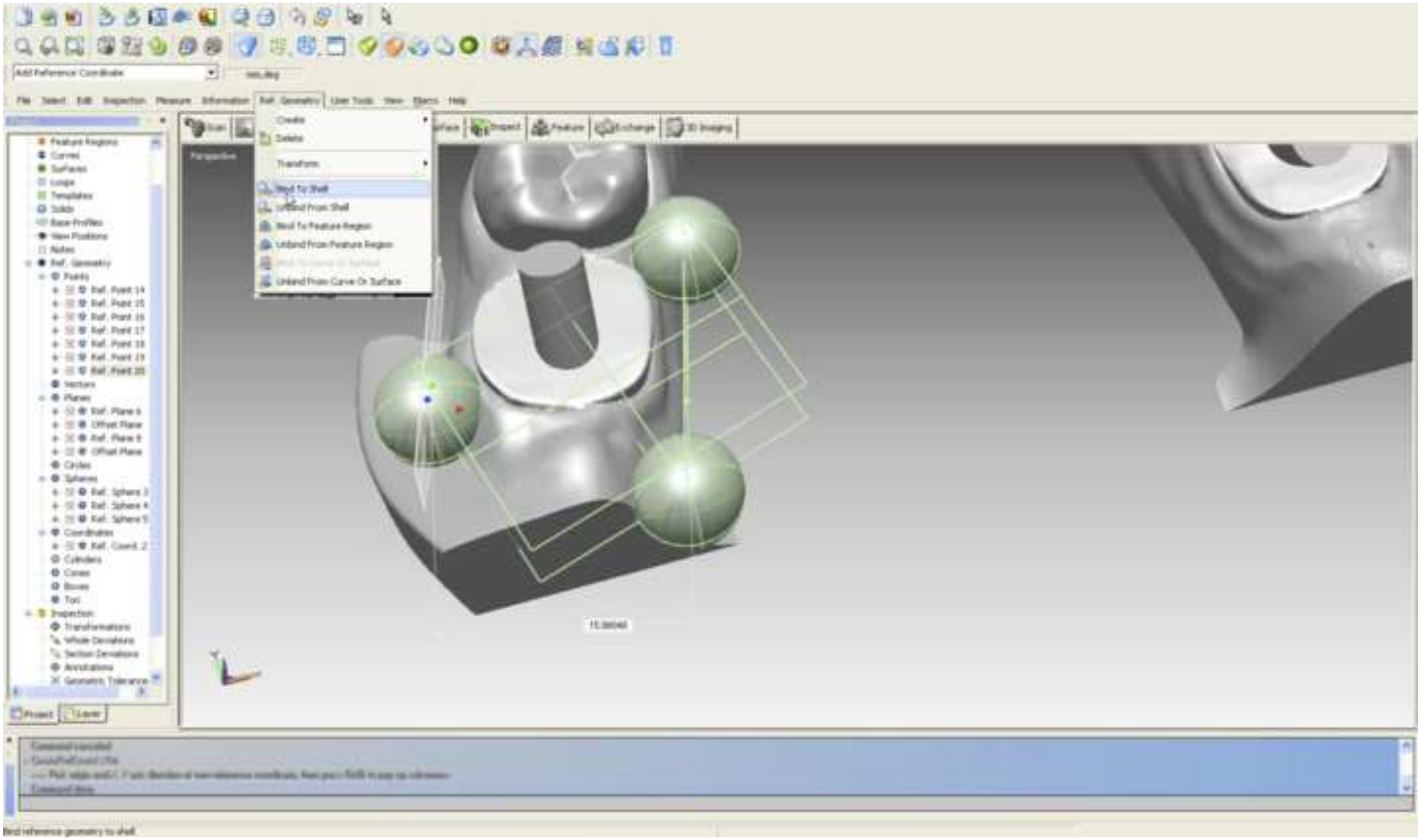

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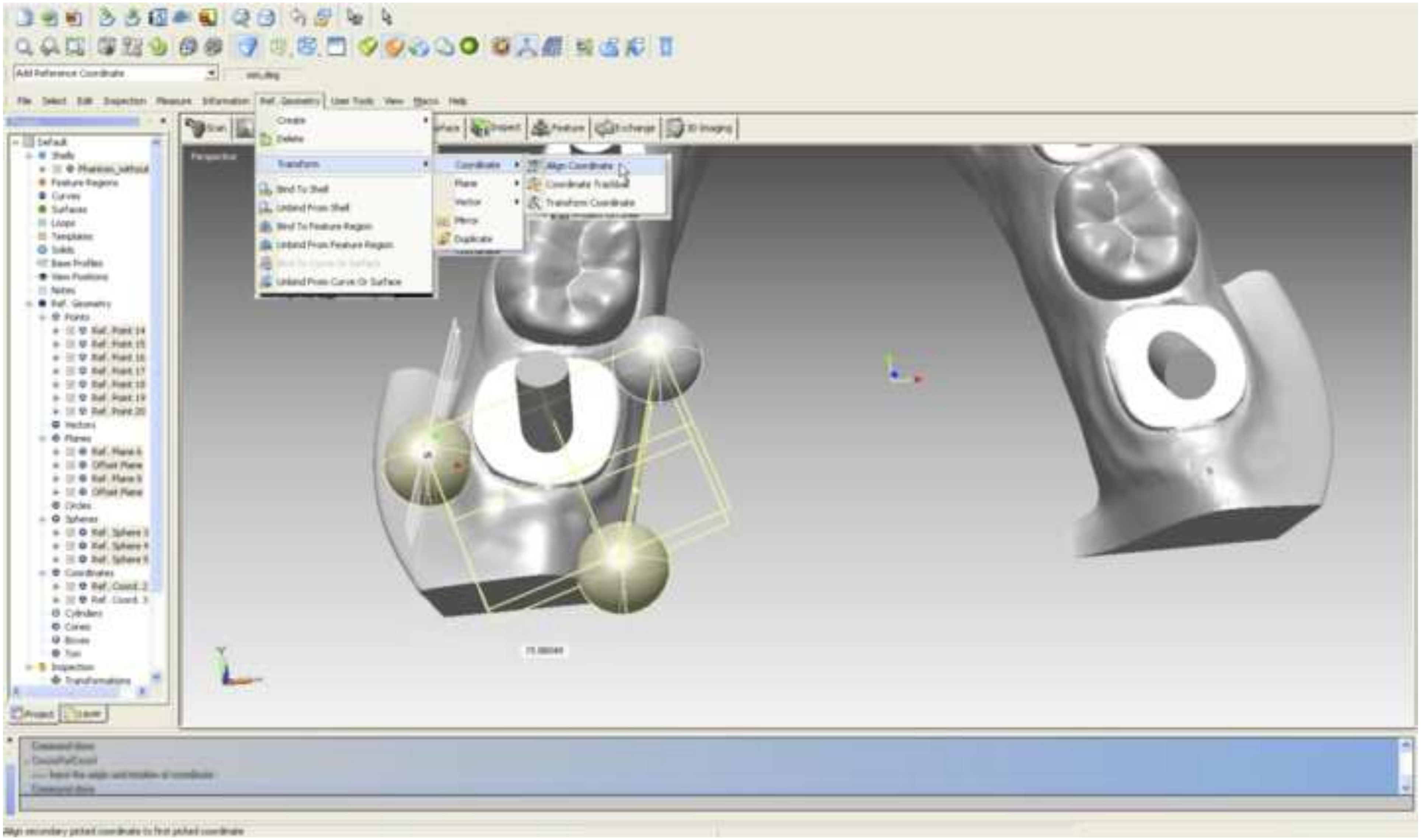

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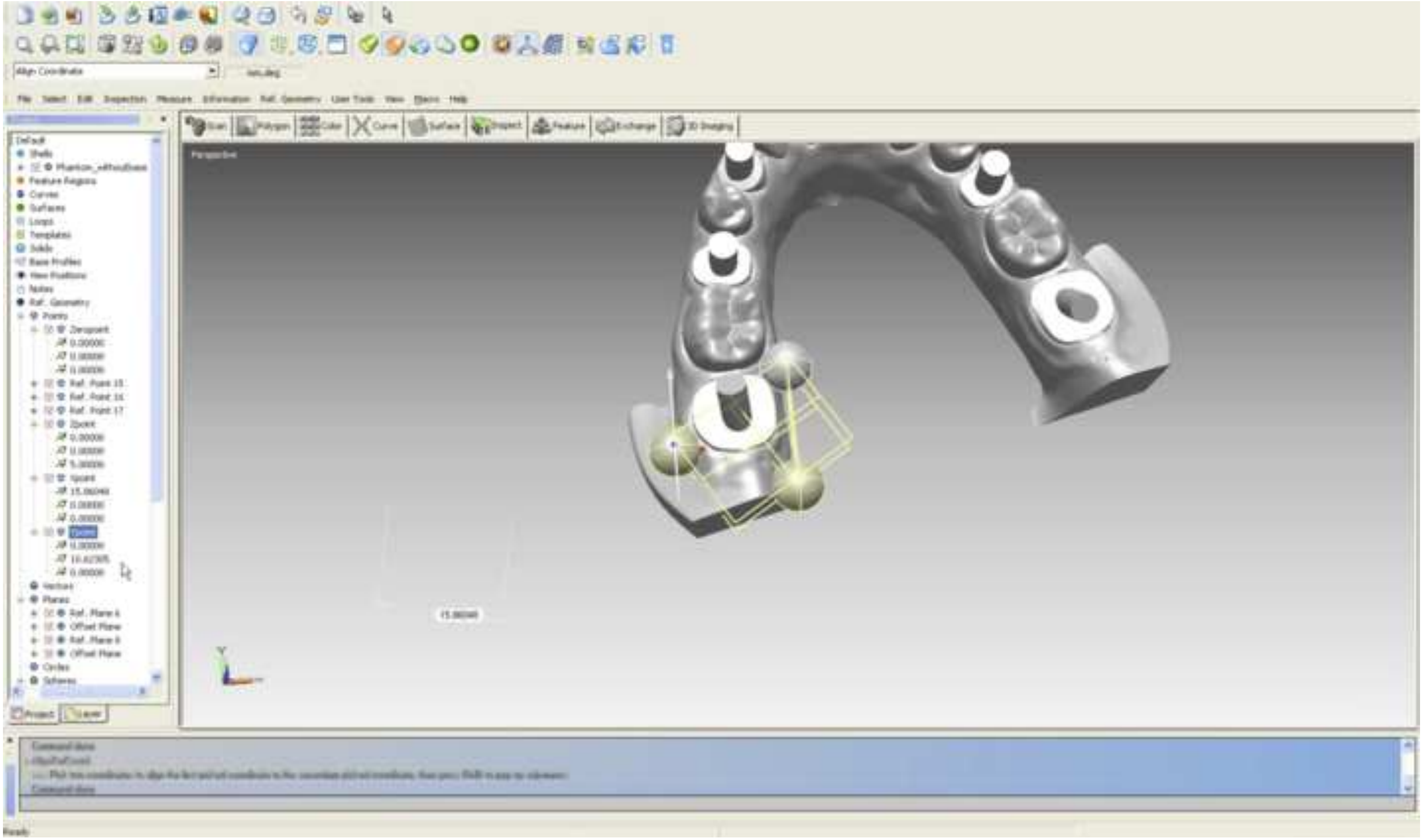

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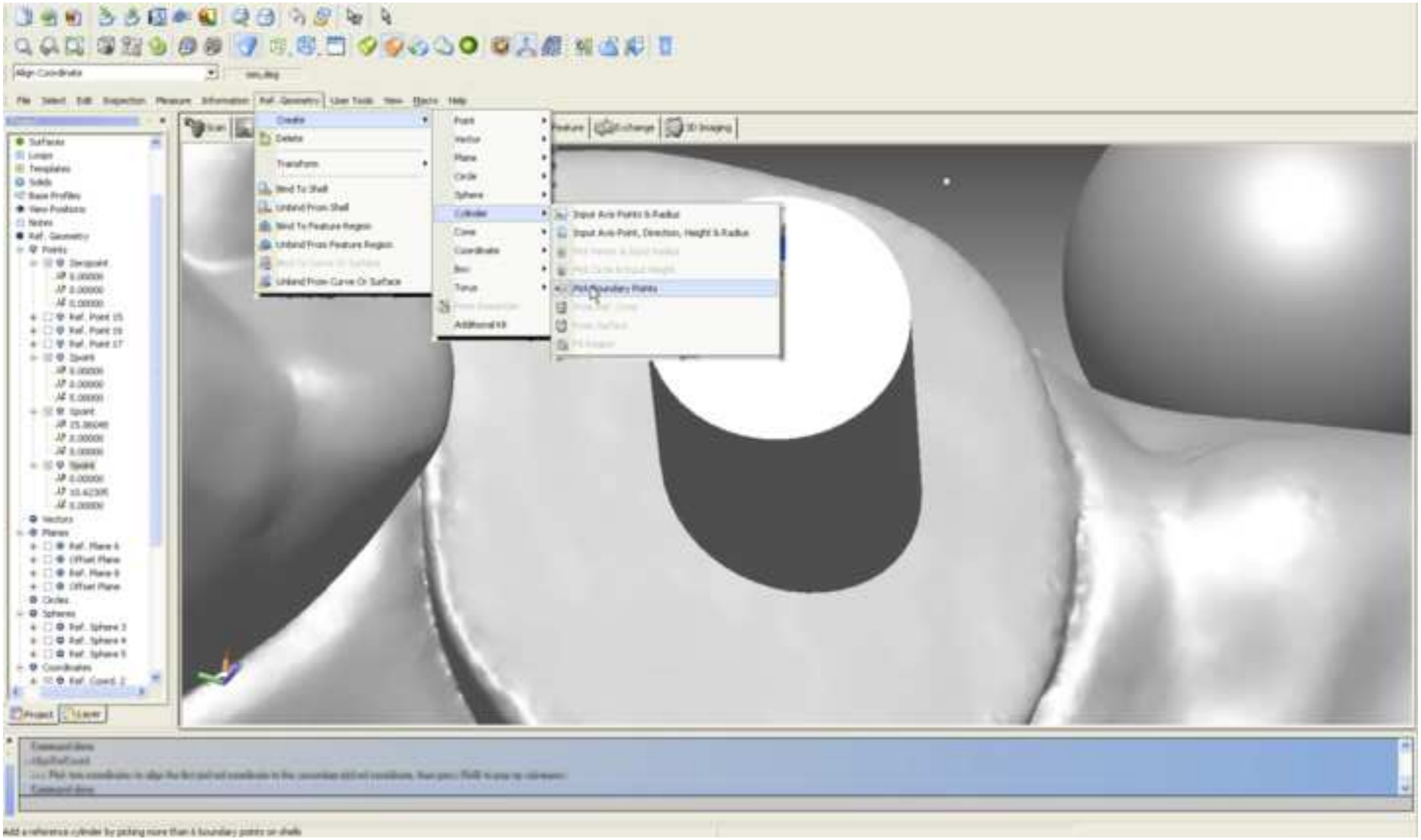

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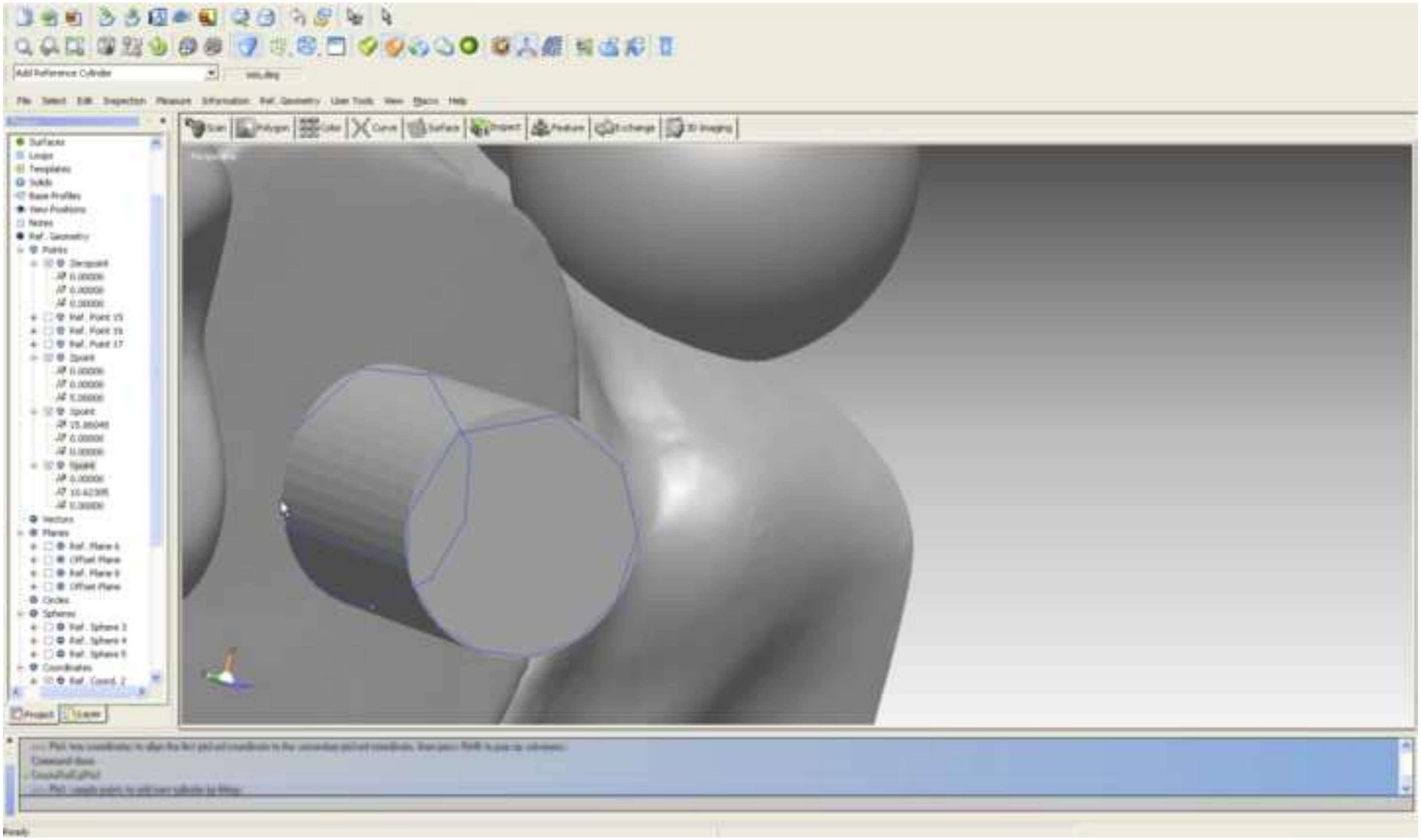

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