Evaluation of the measurement precision and accuracy in the dental CAD/CAM system

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The purpose of this study is to investigate the precision and trueness of the occlusal contact record obtained with a dental CAD/CAM device (ARCTICA). Sandblasted spherical steel balls with diameters of 10–20 mm were measured using ARCTICA and a three-dimensional measurement device (FN503). The radius of each steel ball was calculated from the measured value and the difference between the measured and nominal values was obtained. Upper/lower dental arch casts were measured and processed for occlusal contact image creation using both devices. The graphical images of the occlusal contacts at the intercuspal position obtained from both systems and an occlusal analysis device (BE-1) were compared with the occlusal contact area. Excellent correlation was observed between the measurement results of ARCTICA and FN503 (p<0.001, R²: 0.99). The occlusal contact areas were 186.0 mm² (ARCTICA), 192.8 mm² (FN503), and 196.1 mm² (BE-1). This study showed that ARCTICA is capable of conducting highly accurate measurements and generating a graphical image of occlusal contacts with good reliability.

Keywords: CAD/CAM, Measurement accuracy, Reproducibility, Digitization of occlusal contact, Lateral border movement

INTRODUCTION

Computer-aided design and computer-aided manufacturing (CAD/CAM) systems¹ have experienced rapid development and have been applied to the fabrication of dental prostheses². Therefore, numerous dental clinical researches on using CAD/CAM systems have been reported³-¹¹. A few of these studies showed that the marginal fitness of crowns fabricated with a CAD/CAM system is high, and that there are almost no differences between the designed and observed values¹²,¹³. These results have led to increased clinical applications of CAD/CAM systems in recent years.

The crowns fabricated with CAD/CAM systems or conventional method require the use of the appropriate stomatognathic system in addition to accurate fit and functionality. Our research group has been working on determining the appropriate shape of the occlusal surface for jaw movements by developing a jaw tracking machine with a commercialized ultra-high accuracy three-dimensional measurement device owned¹⁴-²⁰. However, measurement of the occlusal surface is time-consuming and the procedure to combine the jaw movement data and three-dimensional occlusal data is complex. Therefore, an alternative device which can perform measurements quickly and easily is required. Generally, almost all commercial dental CAD devices can scan the dental arch or teeth on a stone model within a very short time using a laser sensor⁴. ARCTICA (ARCTICA⁶ Auto Scan, KaVo Dental, Biberach, Germany) is a commercial dental CAD/CAM system capable of importing jaw movement data from a six degrees-of-freedom jaw movement tracking device (ARCUS Digma 2, KaVo Dental; ARCUS Digma). Consequently, the transfer of data between these two devices was established through a unit in the prostheses manufacturing system. With this system, it is possible to analyze occlusal contact during static and dynamic jaw movements. However, to the best of the authors’ knowledge, its accuracy in analyzing the occlusion of the dental arch has not been sufficiently demonstrated. If the accuracy of this system in analyzing occlusal contact for every possible jaw movement is sufficiently verified, then it has the potential of being considered as an accurate virtual articulator.

To evaluate the precision and accuracy of the occlusal contact record of ARCTICA, two experimental methods were developed for this study. Note that the objective of this study is to determine the precision of ARCTICA and the visual coincidence of occlusal contact using other ultra-high accuracy scanning devices. Moreover, the study seeks to examine the effectiveness of these devices in analyzing occlusal contacts at the intercuspal and other positions during lateral border movements.

MATERIALS AND METHODS

An ultra-high accuracy three-dimensional measurement device (FN503, Mitutoyo, Kanagawa, Japan, maximum
error: 12.22 μm, mean error: 0.67 μm, standard deviation: less than 0.86 μm; FN503) that had already been reported with accuracy in the dental field, was used as a benchmark device, and measuring data by FN503 was used as master data.

Experiment 1
Spherical steel balls (rolling bearing balls, Amatsuji Steel Ball Mfg., Osaka, Japan) with diameters of 10–20 mm at 1 mm increments were prepared. Five balls were prepared for each diameter size. Each steel ball was processed by sandblasting using 40 μm of aluminum oxide and 0.4 MPa air pressure blown from a distance of 40 mm until the surface of the ball had no luster. The five balls of each size were set on a stone model (Fig. 1-1). Moreover, 11 sandblasted 10 mm diameter steel balls were set on a stone model resembling a dentition (Fig. 1-2).

In this arrangement, the steel balls were measured using ARCTICA and FN503. Their measurement times were recorded as well. On the measured surfaces, 100 points were arbitrarily selected and the radius of each steel ball was calculated 1,000 times using the least squares method. Based on these calculations, the mean value and standard deviation was determined from respective measurement data with ARCTICA and FN503 for each size ball that from 10 to 20 mm. The distance between the centers of the steel balls, which were 11 sandblasted 10 mm diameter steel balls arranged on a stone model to resemble a dentition, were also calculated (Fig. 2). Then, the radiiuses obtained ARCTICA and FN503 were evaluated by regression analysis and F-test for each ball size. The distances obtained ARCTICA and FN503 were also evaluated the same method. The correlation coefficient that indicates strong correlation was set at r>0.7. Statistical significance was set at p<0.05 using EZR (Jichi Medical University Saitama Medical Center, Saitama, Japan).

Experiment 2
The theoretical values of the spherical balls were compared with the measured values to evaluate the accuracy of positioning of the upper and lower jaw measured by ARCTICA. Three sandblasted spherical steel ball with 10 mm diameter was set on the stone model as in Experiment 1. The occlusal plane table (setup support) for mounting the stone model of the upper jaw (Mat. No. 1. 001.9452, KaVo Dental) was attached to the articulator after sandblasting the surface. The stone model of the upper jaw on which the steel ball was set was attached to the articulator using setup support according to the method specified by KaVo (Fig. 3).
Fig. 4 Schematic diagram of surface area and cross-sectional area of comparison target between theoretical value and measured value.

The stone model and setup support were measured by ARCTICA. This measurement process was carried out 10 times. The coordinate data of the steel ball within 300 μm from the contact point between the steel ball and setup support was extracted. The radius was calculated using coordinate data of the obtained steel ball surface as in Experiment 1. The average of the difference between the z-coordinate values of point group data constituting the cross-section and the z-coordinate values of the contact point was calculated (height; μm). The surface area and cross-sectional area were calculated as measured values using the calculated radius and height. The difference in rate of change between measured and theoretical values of the surface area and cross-sectional area within 300 μm above the lowest point of the spherical ball was calculated with reference to previous reports (Fig. 4).

Experiment 3
A 47-year old male subject, with no reported problems about his masticatory system or TMD pain, was recruited for this study. Informed consent was obtained, and approval of the study was granted by the ethics board of Tokushima University.

Using ARCUS Digma, the jaw position and movements at the intercuspal position and during lateral border movements were measured. Simultaneously, the bite records of the subject at the intercuspal position and during each lateral border movement were taken using checking-fit materials (BLUE SILICONE, GC, Tokyo, Japan: BS)\(^{20}\). These were subsequently scanned by an occlusal analysis device (BITEEYE BE-1, GC: BE-1). At any jaw position, image of the occlusal contact was generated and its corresponding area calculated. A report on the reliability of BS and BE-1 was also generated\(^{27}\).

Precise impressions of the upper and lower dental arches of the subject were taken using an individual tray and silicone rubber impression material (Imprint™ II, 3M, St. Paul, MN, USA). Moreover, high-strength dental stone (NEWFUJIROCK, GC) was used to produce the dental cast (Fig. 5).

The upper and lower dental casts were individually measured by ARCTICA. Then, at a position during lateral border movement, the measured data on jaw movements was synchronized with those of the upper and lower dental casts, and superimposed using the imaging software in ARCTICA.

1. Evaluation of occlusal contacts at the intercuspal position
After ARCTICA scanned the upper and lower dental casts, the same casts were similarly measured using FN503. Then, the data were superimposed according to a previous report\(^{10}\). Occlusal contact points were assessed within 200 μm of the vertical distance between the upper and lower occlusal surfaces\(^{10}\), and their images were shown on the screen. At the intercuspal position, visual and quantitative comparisons between the images and areas of occlusal contacts generated by ARCTICA, FN503, and BE-1 using a commercial software (Leios2, EGSolutions, Bologna, Italy: leios2) were conducted. The measurement times of ARCTICA and FN503 were also recorded.

2. Evaluation of occlusal contacts at a position during lateral border movement
At a position during right and left lateral border movements, visual and quantitative comparisons between the images and the areas of occlusal contacts generated by ARCTICA and BE-1\(^{27}\) (with the use of Leios2) were conducted.

The procedures of Experiment 1, Experiment 2, and Experiment 3 are shown in flowcharts, respectively (Fig. 6).
RESULTS

Experiment 1

The difference between the calculated averages of the radiiuses and their true values were within 6 μm using ARCTICA and FN503; whereas, the calculated distances between the center coordinates of the steel balls were within approximately 11 μm, as listed in Tables 1 and 2, respectively. The correlation coefficient of the radiiuses of the steel balls showed excellent correlation between ARCTICA and FN503 ($p<0.001$, $R^2: 0.99$). The F-test showed no significant difference ($F (109, 109)=0.999$, $p>0.05$). Moreover, the correlation coefficient of the distance between the centers of the steel balls showed very high correlation between ARCTICA and FN503 ($p<0.001$, $R^2: 0.99$). The F-test showed no significant difference ($F (59, 59)=1.004$, $p>0.05$). The measurement time of ARCTICA was approximately 10 min (including system startup and storage times), whereas that of FN503 was approximately 10 h.

Experiment 2

The theoretical and average measured values of the surface area are 9.42 and 9.19 mm$^2$, respectively. The maximum and minimum difference between the measured and theoretical values are 0.28 and 0.18 mm$^2$, respectively. The theoretical and average measured values of the cross-sectional area are 9.14 and 8.91 mm$^2$; and the maximum and minimum difference between the measured and theoretical values are 0.26 mm$^2$ (rate of change: 2.9%) and 0.15 mm$^2$ (rate of change: 2.3%) (Table 3), respectively.
Table 1  Difference between measurement values and true value of the radius of steel balls

| Diameter of steel ball | 10 mm | 11 mm | 12 mm | 13 mm | 14 mm | 15 mm | 16 mm | 17 mm | 18 mm | 19 mm | 20 mm |
|------------------------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|-------|
| ARCTICA                |       |       |       |       |       |       |       |       |       |       |       |
| Error (μm)             | 1.1   | 4.4   | 3.6   | 5.4   | 3.4   | 1.5   | 1.6   | 4     | 4.5   | 3.7   | 3.3   |
| S.D. (μm)              | 0.3   | 0.4   | 0.6   | 1.7   | 1.2   | 0.2   | 0.2   | 0.2   | 5.4   | 1     | 0.1   | 1     |
| FN503                  |       |       |       |       |       |       |       |       |       |       |       |
| Error (μm)             | 5.1   | 4.8   | 4.1   | 5.1   | 4.4   | 4.9   | 5.2   | 4.4   | 4     | 4.1   | 3.7   |
| S.D. (μm)              | 3     | 3     | 2.8   | 3.2   | 2.9   | 2.2   | 2.8   | 2.2   | 2.4   | 2.1   | 2.4   |

Upper: True value—Measurement value (μm), Lower : S.D.

Table 2  Distance between center coordinates of steel balls

| Distance 1 | Distance 2 | Distance 3 | Distance 4 | Distance 5 | Distance 6 |
|------------|------------|------------|------------|------------|------------|
| ARCTICA    |            |            |            |            |            |
| Distance (μm) | 10,000.1  | 10,070.7   | 10,922.4   | 10,339.9   | 11,220.5   |
| S.D. (μm)   | 0.6        | 0.5        | 0.6        | 1.1        | 0.9        |
| FN503       |            |            |            |            |            |
| Distance (μm) | 10,002.2  | 10,070.8   | 10,929.1   | 10,348.3   | 11,230.3   |
| S.D. (μm)   | 0.5        | 0.7        | 0.2        | 0.3        | 0.3        |
| Difference (FN503-ARCTICA) (μm) | 2.1 | 0.1 | 6.7 | 8.4 | 9.8 |

Table 3  Difference of average measured and theoretical values of the surface area and cross-sectional area within 300 μm

| Sample 1 | Sample 2 | Sample 3 | Sample 4 | Sample 5 | Sample 6 | Sample 7 | Sample 8 | Sample 9 | Sample 10 | Theoretical value (mm²) |
|----------|----------|----------|----------|----------|----------|----------|----------|----------|-----------|--------------------------|
| Measured value (mm²) | 8.89 | 8.9 | 8.99 | 8.92 | 8.93 | 8.93 | 8.9 | 8.89 | 8.88 | 8.89 | 9.14 |
| Difference (mm²) | -0.25 | -0.24 | -0.15 | -0.22 | -0.21 | -0.21 | -0.24 | -0.25 | -0.26 | -0.25 | 9.42 |
| Measured value (mm²) | 9.24 | 9.2 | 9.17 | 9.19 | 9.2 | 9.2 | 9.22 | 9.15 | 9.14 | 9.16 | 9.42 |
| Difference (mm²) | -0.18 | -0.22 | -0.25 | -0.23 | -0.22 | -0.22 | -0.2 | -0.27 | -0.28 | -0.26 | 9.42 |

Experiment 3-1
The graphical image of the occlusal contact area generated by ARCTICA is similar to those of FN503 (Fig. 7) and BE-1 (Fig. 8). Thus, it is considered that the measurement precision of ARCTICA is similar to that of FN503. In particular, the occlusal contact areas were 186.0, 192.8, and 196.1 mm² as measured by ARCTICA, FN503, and BE-1, respectively; these show that the devices yielded approximately the same experimental results.

Finally, the occlusal contact area measurement time of ARCTICA was approximately 20 min, whereas that of FN503 was approximately 40 h.

Experiment 3-2
The graphical image generated by ARCTICA is visually similar to the image produced by BE-1 at a position during the left or right lateral border movements.

Furthermore, at a position during left border movement, the areas of the occlusal contacts given by ARCTICA and BE-1 were 21.2 and 23.8 mm², respectively (Fig. 9-1); during right border movement, the areas were 27.9 and 28.5 mm², respectively (Fig. 9-2).

DISCUSSION

Study population
This study aims to clarify whether ARCTICA and ARCUS Digma can measure the dentition and occlusal contacts at any position during lateral border movements. It was necessary to clarify the accuracy and precision of these devices to address this question. With the development of digital technology in recent years, the fabrication of dental prosthesis using CAD/CAM system has been clinically applied. In this regard, accuracy was also exhibited by the peripheral devices.
of commercial CAD/CAM devices developed third-party suppliers\(^8,13,28\). However, the capabilities of other devices were not sufficient to yield the required estimates. The two important requirements for CAD/CAM systems are as follows. First, to measure with high accuracy natural tooth/teeth or their models set on a dental arch; second, to reproduce occlusal contacts at the intercuspal or other positions during lateral border movement as these are used to integrate the measured data on dental form and jaw movement.

To determine the required measurement accuracy to fabricate a dental crown, ARCTICA was compared with FN503, whose accuracy and precision was already confirmed and used with high-precision measuring instruments in the industry. According to previous reports that examined occlusal contact, occlusal adjustment, and periodontal ligament threshold, the required accuracy and precision is approximately 10 \(\mu m\)\(^{29}\). Based on the manufacturer’s specifications for FN503, the measurement and indicated accuracy for each axis were noted as \(4+4L/1,000\) and \(3+3L/1,000\ \mu m\) (L: arbitrary measurement length (mm)), respectively. Therefore, FN503 can be used as a benchmark in the accuracy testing of ARCTICA.

**Experiment 1**

The rolling bearings steel ball sphericity, which conform
to Japanese Industrial Standards (JIS: B 1501-2009) and ISO/TS16949, were similarly prepared as measurement objects. These balls are made of Grade 40 steel with the following properties—sphericity: 1 μm, diameter inequality: 1 μm, surface roughness: 0.08 μm, and dimension error in the diameter of rot: 2 μm. Each device measured multiple points on the surface of the balls, and the radiuses of the balls were calculated by solving simultaneous equations using the least-squares method. The differences between the calculated and true values of the radiuses were evaluated; and the distances between the centers of the balls, which were arranged in the form of a dental arch, were calculated by each device and evaluated. The results showed that in terms of measurement accuracy, both ARCTICA and FN503 had less than 6 μm error when compared with the true value of the radiuses. With regard to the center-to-center distances between the balls measured by ARCTICA and FN503, the maximum difference is approximately 11 μm. Therefore, ARCTICA has sufficient accuracy for the measurement of a dental model. Furthermore, because the measurement time of ARCTICA was significantly shorter than that of FN503, the usefulness of ARCTICA was confirmed as a system for clinical applications.

Experiment 2
Generally, the theoretical and measured values are compared for the accuracy testing of equipment and evaluation of products. We also performed this experiment according to previous reports. This experiment was performed with reference to JIS, which is the standard for industrial products in Japan (JIS: B 0405). The rates of change between the theoretical and measured values of the surface area and cross-sectional area within 300 μm from the contact point were both within 2.9%. The result of this experiment satisfied the standard for the highest accuracy grade of JIS B0405. Therefore, it was suggested that the occlusal contact area of the stone cast of the upper and lower jaw has high reproducibility.

Experiment 3
The images of the occlusal contacts at the intercuspal position generated by ARCTICA and FN503 were compared and estimated. However, for the occlusal contacts during lateral border movements at the same optional jaw position, it was difficult to compare the images created by ARCTICA and FN503. In addition, because dental occlusal silicon material was used for occlusal examination, and it was possible to simultaneously record using silicon material and ARCUS Digma at same jaw position, the impressions of occlusal contacts were visually compared with the image of occlusal contacts from ARCTICA at the same jaw position during lateral border movement. The resulting data showed that the image of occlusal contacts at the intercuspal position from ARCTICA was clearer than that from FN503. Moreover, with regard to the occlusal contact area, the results provided by ARCTICA, FN503, and BE-1 were quantitatively similar. The difference in results was primarily because of differences in the measurement interval of each device: The measurement interval of ARCTICA ranged from 10 to 30 μm, whereas that of FN503 was 100 μm. In addition, the image and area of occlusal contact at an optional position during lateral border movement from ARCTICA were visually and quantitatively similar to the impressions on dental occlusal silicone material. In the comparison of the occlusal contact areas between ARCTICA, FN 503, and BE-1, the maximum difference at the intercuspal position and lateral movement position was 10.1 and 6 mm² between ARCTICA and BE-1, respectively. These results suggest that the occlusal contact built by ARCTICA has high reliability and accurately represented the optional position at every jaw position. The fact that it was possible to analyze occlusal contacts during static and dynamic lateral border movements suggest the potential application of these CAD and jaw tracking devices as virtual articulators under clinical conditions in a future study.

Limitation
There are two limitations noted in this study. First, the measurement method and measurement interval differed between ARCTICA and FN503—ARCTICA is a noncontact laser scanning method, whereas FN503 is a contact-type using a touch probe. ARCTICA scanned the dental model by laser, whereas FN503 touched the model with a probe; the laser scanning method was able to acquire more data than the touching probe method. Therefore, the number of measurement points of ARCTICA is several times greater than that of FN503. If the number of measurement points between the two devices is the same, measurement with FN503 will take longer.

Second, the occlusal contact was not measured quantitatively at the optional position during every jaw movement such as masticatory movement, but it was visually and quantitatively evaluated at a position during lateral border movement in this study. Thus, our results suggest that occlusal contacts generated by ARCTICA satisfied the requirements of analysis.

CONCLUSIONS
The accuracy and measurement time of ARCTICA were evaluated in this study and yielded the following results:

1. The measurements provided by ARCTICA were accurate and precise, in contrast with those of previous three-dimensional devices.
2. The measurement time for the dental arch stone model using ARCTICA was much shorter than that of FN503.
3. ARCTICA is a suitable device for analyzing the occlusal contacts at optional positions during each jaw movement.
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