INTRODUCTION

Several new ceramic materials and techniques have been developed in recent decades to improve the strength and fracture toughness of dental prostheses. Zirconia has excellent strength and fracture toughness among dental ceramics. It has recently become widely used in clinical applications as a framework material for all-ceramic crowns, fixed partial dentures (dental bridges) and abutments of dental implants. However, the hardness of zirconia, and hence the difficulty of milling the substructure, is determined by the degree of sintering of the zirconia blocks. Milling of the zirconia substructure using computer-aided design (CAD)/computer-aided manufacturing (CAM) currently uses a semi-sintered zirconia material. The semi-sintered block has a chalky-like consistency, making it easily machinable in the milling unit. After milling, the substructure is sintered to full density. The advantage of the milled substructure is the excellent dimensional accuracy and fit achieved by milling the actual size of the substructure from the block; however, post-milling sintering of the zirconia substructure results in linear shrinkage of 15–30% (approximately 20%) and a subsequent increase in density. The increased milling efficiency with the softer semi-sintered block is offset by a potentially poorer fit resulting from sintering shrinkage of approximately 20%, the scanning process, compensatory software design, and milling. Apart from affecting the mechanical properties and esthetics, marginal discrepancies can affect the long-term clinical success of all-ceramic fixed prostheses. Poor marginal adaptation increases plaque retention and changes the distribution of the microflora, which can induce the onset of periodontal disease. In the present study, therefore, we developed a five-axis laser milling system for a zirconia prosthesis to keep the excellent dimensional accuracy of the advantage of the milled substructure without long sintering time and evaluated the accuracy of complete zirconia crowns milled by three- and five-axis laser milling systems, compared with crowns fully sintered by heating milled semi-sintered crowns; i.e., crowns produced using the conventional method.

MATERIALS AND METHODS

Materials

The materials used were fully sintered zirconia blocks (i.e., fully sintered blocks obtained by heating milled semi-sintered zirconia blocks; Aadv Zirconia Disk ST, Lot no. 1608241, GC, Tokyo, Japan) and semi-sintered zirconia blocks (Fig. 1), which shrink 19.808% by volume with full sintering according to the manufacturer's information.

Development of laser milling machines for the direct milling of fully sintered zirconia blocks

We first developed a three-axis laser milling machine for a zirconia prosthesis. This laser milling machine was a fiber semiconductor laser (Nd:YVO₄ laser; wavelength of 1,064 nm) with average output of 20 W (AC power supply; 100 V, 50 Hz), pulse energy of 1 mJ/pulse, M2...
value of 1.3, and resolution of 40 μm. The laser processing speed for zirconia milling was 500 mm/min. The known weakness of three-axis milling relates to the milling of specimens in the longitudinal direction of the prosthesis. Indeed, a brief test revealed this weakness. We therefore developed and constructed a five-axis milling machine that can create a zirconia prosthesis suitable for clinical use. Specifications of the five-axis milling machine were basically the same as those of the three-axis milling machine except for the number of axes and the movement of the machines.
CAM of semi-sintered zirconia crowns

Ten specimens in three sizes for each heating schedule were prepared by milling from semi-sintered zirconia blocks with a CAD/CAM machine (GM-1000, GC, Fig. 1). Three-dimensional CAD software (Power SHAPE2015, Delcam, Birmingham, UK) was used to design the specimens and CAM software (DentMILL2011, Delcam) was used to mill the specimens. Fully sintered crowns were fabricated from semi-sintered milling crowns following a heating schedule (to 1,000°C for 2 h and to 1,450°C for 4.5 h) or by rapid heating (to 1,450°C for 1 h, Fig. 1). The thickness of the cement layer of each specimen under the condition of a fully sintered zirconia crown was set as 0 μm.

Surface observations made using a scanning electron microscope

The surface geometry of the semi-sintered zirconia specimens and fully sintered zirconia crowns (sintered under rapid or normal heating) was observed under a scanning electron microscope (JSM-6365F, JEOL, Tokyo, Japan) at a magnification of ×10,000 and an accelerating voltage of 5.0 kV.

Mechanical properties of zirconia crowns

1. Vickers hardness test

The surface microhardness was determined in a Vickers hardness test using a microhardness device (MVK-H2, Akashi, Tokyo, Japan), which was calibrated following the manufacturer’s instructions. The Vickers hardness number was measured by applying a 100-g force to each specimen for 15 s.

2. Lightness

We used a colorimeter (CR-100, Minolta, Tokyo, Japan) to measure the lightness ($L^*$) of zirconia crowns. The colorimeter was calibrated with a standard white porcelain plate, an accessory of the instrument, and $L^*$ was measured for the crown-shaped samples.

Accuracy of zirconia crowns

1. Marginal gap

An in vitro study was undertaken to compare the vertical marginal accuracy of CAD/CAM zirconia crowns. Crowns were prepared in two sizes (i.e., there were six specimens for each group) with a lingual thickness of 0.5 or 1.5 mm, buccal thickness of 0.5 mm and occlusal thickness of 0.5 mm (i.e., the dimensions of complete crowns, Fig. 1). The internal dimensions of the crown specimens were set the same as for the metal die abutment tooth, which meant that the cement layer was set as 0 μm. Zirconia crowns were seated on metal dies made of stainless steel (SUS303, Japan MECC, Tokyo, Japan), and the accuracy of fit was evaluated by measuring the gap between the base line on the die and the margins of the specimen at four specific sites using a measuring microscope (STM6, Olympus, Tokyo, Japan) with accuracy of 1 μm (Figs. 1 and 2).

2. Roundness of the marginal shape at the base

Three-dimensional data of the fully sintered zirconia crowns were obtained using a three-dimensional digital scanner (VIVID 9i, Konica Minolta, Tokyo, Japan), and three-dimensional images were constructed using three-dimensional CAD software (SolidWorks 2012, Dassault Systèmes SolidWorks, Vélizy-Villacoublay, France) to analyze the round shape at the base of the crowns (Fig. 1). A reference plane including three points on the base of the crown was set. The origin was set at the center of gravity (G) of a triangle consisting of these three points on the base of the crown on the reference plane.

The X-axis was defined as the line passing through point G parallel to the medial–distal line of the crown containing the points of the buccal (0.5 mm thick) and lingual (0.5, 1.0, and 1.5 mm thick) borders. The Y-axis was set as the orthogonal axis of the X-axis including point G. The coordinates ($x_i, y_i$) of 20 points on the internal surface of the base (internal margin) of the crown on the XY plane (the reference plane) were obtained to estimate the roundness and roundness error.
of the marginal shape of the crown.

Roundness was estimated employing the least-squares circle method, which uses a circle that separates the roundness profile of an object by separating the sum of the total area into equal amounts inside and outside:

\[ f = \sum [(x - x_i)^2 + (y - y_i)^2 - R^2]^2 + \sum [(x - x_i)^2 + (y - y_i)^2 - r^2], \]

where \( R \) is the radius of the least-squares circumscribed circle and \( r \) is the radius of the least-squares inscribed circle. A perfect circle has a diameter of 8.0 mm and roundness of 0.00.

Internal shape of zirconia crowns
Specimens were embedded with acrylic resin by a mounting machine (PNEUMET II, Buehler, Lake Bluff, IL, USA) to measure the internal height and corner shape of zirconia crowns. After the embedding of crowns, specimens were cut at the center of occlusal surfaces in the vertical direction with a diamond disc saw (Isomet low-speed saw model no. 11-1280-170 with Buehler wafering blades; Buehler). Cross sections of crowns were observed, and the internal height and internal corner shape of crowns were quantified by computer analysis (AR–UMMF software, Artray, Tokyo, Japan) of the length (mm) and area (mm²) of images obtained by a stereoscopic microscope (SMZ800, Nikon, Tokyo, Japan) and charge-coupled device camera (ARTCAM–130MI, Artray) and put into a Windows-operating computer (Alienware15, Dell, Round Rock, TX, USA, Fig. 1).

Experimental conditions, data, and statistical analysis
All experiments were performed in a laboratory maintained at a temperature of 23.0±1.3°C. Data were recorded in each experiment, and six data out of a total of eight were used by removing the maximum and minimum data. These six data were calculated and represented as the mean±standard deviation. The data were analyzed using the Tukey’s test to determine which of the differences were statistically significant.

RESULTS
Three- and five-axis laser milling machines for a zirconia prosthesis
Figure 3 shows the appearance of the developed three- and five-axis laser milling systems and a schematic representation of the movement for three- and five-axis laser irradiation. In the case of the three-axis laser milling system, irradiation of the zirconia block shifted through three-axis motion of the block stage (Fig. 3A). In the case of the five-axis laser milling system, the zirconia block was fixed on a rotating stage and three-axis motion of the stage was combined with rotation of the specimen and rotation of the laser converging optical unit (Fig. 3B).
Surface observation using a scanning electron microscope
Scanning electron micrographs of the surface of zirconia specimens are shown in Fig. 4. Zirconia particles were observed on the surface of the semi-sintered block but were largely absent from the surfaces of conventional CAD/CAM zirconia crowns. The irradiation trace of the laser beam was observed on the surfaces of fully sintered zirconia crowns milled by the three- and five-axis milling machines but not on the surfaces of conventional crowns. No clear difference was found between the surface properties of fully sintered zirconia crowns milled by the three- and five-axis laser milling machines.

Mechanical properties of zirconia crowns
The Vickers hardness test revealed that the hardness values of zirconia specimens in laser milled and conventional specimens were almost the same (three-axis, 1518.6–1545.6 Hv1.0; five-axis, 1523.9–1530.4 Hv1.0; conventional, 1530.0–1546.0 Hv1.0), whereas the hardness of the chalk-like semi-sintered specimens was extremely low (69.4–72.3 Hv1.0, Fig. 5A).

The lightness value ($L^*$) was highest for chalk-like semi-sintered specimens (100.1–100.6) followed by laser milled and conventional specimens, with values being similar (three-axis, 84.1–84.3; five-axis, 84.3–84.4; conventional, 83.4–83.8, Fig. 5B).

Accuracy of the marginal fit
The accuracy of the marginal fit was estimated from the

Fig. 4 Scanning electron micrographs of zirconia specimens (with the white bar indicating 1 or 50 µm).

Fig. 5 Mechanical properties of zirconia crowns.
A. Hardness, B. Lightness
n=6 for each experimental condition. *p<0.05, **p<0.01. Data were analyzed in the Tukey’s test to determine which differences were statistically significant.
marginal gap, which is the distance between the base line of the metal die and the margin of the crown (Fig. 2). The order of the marginal gap of crowns by creating method was three-axis milling>conventional>five-axis milling system. The order of crown by lingual thickness was 1.5 mm>0.5 mm in the conventional group, and almost the same for the direct milling system (Fig. 6).

**Roundness of the internal marginal shape**

Distortion of the internal marginal shape at the base of zirconia crowns is shown as a superimposition over a perfect circle with a diameter of 8 mm (Fig. 7). The diameter of crowns in all groups was 8.0 mm (Table 1). However, the buccal side (0.5 mm thickness) of the conventional crown with lingual thickness of 1.5 mm was constricted on the inward side, which was not reflected by the diameter but by the roundness (Fig. 7 and Table 1). Crowns with lingual thicknesses of 0.5 and 1.5 mm directly milled from fully-sintered zirconia blocks with three- and five-axis laser milling machines were almost perfect circles (Fig. 7 and Table 1).

The distortion of marginal shapes of crowns was reflected by the roundness (Table 1). The values of roundness of marginal shapes of laser-milled crowns having the two lingual thicknesses were almost the same, while conventional crowns had larger values (order of roundness by lingual thickness, 1.5 mm>0.5 mm, Table 1).

**Internal shape of zirconia crowns**

Observation of the internal corner shape of zirconia crowns was performed.

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Table 1  Roundness of the internal marginal shape of the base of fully-sintered crowns

| Method      | Conventional | Direct milling |
|-------------|--------------|---------------|
|             |              | Three-axis    | Five-axis    |
| Thickness   | Buccal       | 0.5           | 0.5          | 0.5 | 0.5 |
| (mm)        | Lingual      | 0.5           | 1.5          | 0.5 | 1.5 |
| Diameter (mm)|            | 8.0           | 8.0          | 8.0 | 8.0 |
|             |              | (0.03)        | (0.03)       | (0.02) | (0.01) |
| Roundness   |              | 0.06          | 0.10         | 0.03 | 0.02 |
|             |              | (0.020)       | (0.023)      | (0.010) | (0.007) |

n=6 for each experimental condition. *p<0.05, **p<0.01. Data were analyzed in the Tukey’s test to determine which differences were statistically significant.
crows reveals the corner roundness of crowns milled by the three-axis milling machine and produced conventionally, while the crowns milled by the five-axis milling machine had a sharp corner edge (Table 2). The internal gap of zirconia crowns in three-axis milling groups had large variance, and there was thus no statistical significance between three-axis and conventional groups. Meanwhile, the internal gap in the five-axis group was almost zero (Table 2).

**DISCUSSION**

Compared with conventional methods, the major advantages of CAD/CAM prostheses are 1) the omission of the troublesome processes of waxing, embedding, and casting; 2) the minimal chance of errors occurring and excellent dimensional accuracy; and 3) the short manufacturing time\(^a\)\(^b\)\(^c\). These advantages can be observed for CAD/CAM prostheses made of resin and metal but not for ceramic prostheses. Fully sintered zirconia, as well as alumina ceramics, have extremely high hardness (approximately 580–1,900 Hv) and it is thus difficult to mill a prosthesis from a fully-sintered ceramic block. Therefore, CAD/CAM ceramic prostheses usually take the form of a fully sintered prosthesis milled from a semi-sintered ceramic block by a CAM machine\(^5\). In the process of fully sintering a semi-sintered ceramic prosthesis, linear shrinkage of 15–30% (normally about 20%) is observed\(^4\)\(^5\). At present, CAD/CAM ceramic prostheses are designed by CAD to be 20% larger. These larger chalk-like semi-sintered prostheses are then milled by the CAM machine, and fully sintered for clinical use. To overcome this unpredictable and irregular shrinkage with long-time full sintering, direct milling of the prosthesis from a ceramic block has been trialed using a laser; however, this technique has not been put to practical use\(^13\). In laser milling, it is difficult to mill the crown in the height direction, and laser milling is therefore an unsuitable method for creating a prosthesis that covers an abutment. We therefore developed a five-axis milling machine for a zirconia prosthesis and suggest that a five-axis milling machine produces CAD/CAM ceramic prostheses that have an excellent fit to the abutment tooth with precise dimensions and shape, in comparison with three-axis milling and using the conventional method.

Zirconia ceramics are used for prostheses requiring excellent esthetics together with mechanical strength, such as veneered crowns, all-ceramic crowns, and the framework of fixed partial dentures\(^1\)\(^-\)\(^3\). The hardness and color of dental ceramics are known to be affected by heating\(^14\). In the process of laser milling a zirconia block, surfaces reach high temperatures\(^2\)\(^3\)\(^-\)\(^6\). Compared with conventional CAD/CAM crowns fully sintered by heating milled semi-sintered crowns, the hardness and lightness values of crowns directly milled from fully sintered zirconia blocks by the three- and five-axis laser milling systems developed in this study were almost the same, indicating that there are no hardness or color issues when directly milling CAM crowns (Fig. 5). This finding suggests that directly milled zirconia may be suitable not only for the framework of an esthetic prosthesis (e.g., the abutment of a dental implant or the frame of a fixed partial denture) but also for a prosthesis that can be directly viewed in the oral cavity. Scanning electron microscopic observation of particles on the zirconia crown surfaces revealed a clear difference between conventional and laser-milling crowns, and no clear difference between three-axis and five-axis laser-milled specimens. However, a marked difference in the surface conditions was observed between fully sintered zirconia blocks and laser-milled specimens, which could result in the fusion of zirconia particles of blocks at the high temperature of laser irradiation (Fig. 4).

The ISO standard of dimensional accuracy for CAM-milled crowns provides only an estimation of the marginal gap between the metal die and a specimen\(^17\). This method is simple and useful in cases that the shrinkage of the crown in the manufacturing process is uniform. However, such shrinkage is never uniform in practice and varies according to the part of the crown, because of different thicknesses and complicated shapes. The marginal gap

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**Table 2 Internal shapes of zirconia crowns**

| Method         | Conventional | Direct milling |          |          |
|----------------|--------------|----------------|----------|----------|
|                |              | Three-axis     | Five-axis|
| Thickness (mm) |              |                |          |          |
| Buccal         | 0.5          | 0.5            | 0.5      | 0.5      |
| Lingual        | 0.5          | 1.5            | 0.5      | 1.5      |
| Internal gap (mm) |            |                |          |          |
|                | (0.083)      | (0.023)        | (0.060)  | (0.031)  |
|                | (0.26)       | (0.27)         | (0.027)  | (0.06)   |
| Internal corner shape (×10\(^{-3}\) mm\(^2\)) |              |                |          |          |
|                | (4.93)       | (29.46)        | (10.39)  | (0.04)   |
|                | (19.5)       | (25.2)         | (1.5)    | (1.4)    |

\(n=6\) for each experimental condition. \(*p<0.05, \,**p<0.01.\) Data were analyzed in the Tukey’s test to determine which differences were statistically significant.
between the metal dies and specimens with different thicknesses of the buccal and lingual walls was greater than that for specimens with a uniform wall thickness in the conventional group, but not that for specimens in the laser-milling groups. In the conventional group, different thicknesses resulted in different shrinkages during the full sintering of a milled semi-sintered zirconia crown. This indicates the superiority of the laser milling systems in creating a zirconia prosthesis. We first developed a three-axis laser milling machine for a zirconia prosthesis. Specimens milled by a three-axis milling machine were briefly tested and did not exhibit enough accuracy for a prosthesis having a complicated shape. The three-axis laser-milling specimens shown in Fig. 6 also had large marginal gaps compared with the conventional group. More exact dimensional accuracy is needed for clinical use. We therefore developed and completed a five-axis milling machine for a zirconia prosthesis. Five-axis laser-milling specimens had almost zero values, demonstrating that the insufficient accuracy of three-axis laser milling had been overcome (Fig. 6).

To clarify the cause of shrinkage and distortion of zirconia CAD/CAM crowns, we evaluated the dimensional accuracy of fully sintered zirconia specimens by estimating the marginal gap between the metal die and the specimen and calculating the deviation of the internal margin of the specimen from the theoretical internal margin, which is a perfect circle, and internal corner shape of specimens (Fig. 7, Tables 1 and 2). The results show that the marginal gaps could result in the combination of the distortion of marginal and internal shapes in the conventional group, and the distortion of the internal corner shape in the three-axis milled group. In the case of the three-axis milling system, the milling of crowns in the longitudinal direction might be insufficient, which would be a weakness of the system. These distortions were not observed in the five-axis milled group. Five-axis milling overcomes the weakness of three-axis milling and is thus superior in creating a zirconia prosthesis.

Results of the present study suggest that a five-axis laser-milling zirconia prosthesis can be used clinically without worrying about accuracy and the risk of unpredictable and irregular shrinkage resulting from varying thickness and the complex shape of a prosthesis during full sintering. Compared with the conventional method (e.g., full sintering after the milling of a prosthesis from semi-sintered zirconia blocks, a laser-milling system can produce a fully sintered prosthesis without sintering concerns of unpredictable and irregular shrinkage. Meanwhile, laser irradiation produces high temperatures at the surface of a prosthesis, and changes in the surface character (i.e., cracking and darkening) with Nd:YAG laser irradiation have been reported\(^{18}\). The present study employed Nd:YVO\(_4\) laser irradiation, which did not crack the zirconia surface. However, the darkening of zirconia specimens has been affected by oxygen vacancies\(^{16,17}\), with specimens returned to their original white color by oxidation with heating at 1,000°C for 5 min in air\(^{15,18}\). The mechanical characteristics of the laser-milling specimens were almost the same as those of conventional specimens, making the laser-milling specimens suitable for clinical use as esthetic prostheses. Increasing the number of axes of movement of the milling machine from three to five allows the creation of an extremely accurate prosthesis. In clinical use, the high accuracy of the milling machine is needed for basic performance. In the design of a CAD/CAM crown, the completed cement layer is usually set at 20 \(\mu\)m. The cement layer of CAD/CAM crowns produced employing the three approaches used in the present study was set as 0 \(\mu\)m, so as to determine the accuracy. Results obtained for the five-axis laser milling CAD/CAM crowns in the present study suggest the realization of more accurate zirconia CAD/CAM crowns with an accurate cement layer.

The post-milling sintering of the semi-sintered zirconia substructure using conventional CAD/CAM results in linear shrinkage of approximately 20% and a subsequent distortion in dimension. That is the reason why we developed a five-axis laser-milling system to keep the excellent dimensional accuracy of the advantage in the milled zirconia substructure without long sintering time. The results of the present study suggest the superiority of five-axis milling systems in creating a zirconia prosthesis with arbitrary complex shape and various thickness. Further study is needed to investigate laser-milling methods having five or more axes and more accurate, easier, and shorter operation and higher performance.

## CONCLUSION

Results of the present study show that zirconia crowns directly milled from fully sintered zirconia blocks by a five-axis laser-milling system, which we developed, had excellent dimensional and form accuracy, compared with three-axis laser-milling and conventional specimens produced by heating milled semi-sintered crowns. Crowns created by the conventional method with different buccal and lingual thicknesses had unpredictable and irregular shrinkage. Direct milling specimens had an extremely low distortion of shape and high dimensional accuracy; however, the disadvantage of three-axis laser milling was roundness of the internal corner of crowns. Five-axis milling overcame this weakness and realized excellent accuracy.

We conclude that five-axis milling systems perform well in creating a zirconia prosthesis with precise dimensions and shape all over the prosthesis, leading to excellent accuracy.

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## CONFLICTS OF INTEREST

The authors declare no potential conflicts of interest.
with respect to the authorship and/or publication of this article.

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