INTRODUCTION

The processing technology of crowns by CAD/CAM yields numerous advantages such as improved efficiency in prosthesis manufacturing, shorter time, and quality control\(^1\text{-}^2\). Recent advances in cutting tools and technology enable high-speed milling; this allows the completion of milling a single crown within 10 to 30 min. The machining time is primarily determined by the tool path, which in turn is governed by cutting parameters; these include the step-over distance, feed rate, spindle speed, and depth of the cut. For instance, in order to finish milling quickly, the step-over distance must be protracted, feed rate must be increased, spindle speed should be high, and the cut should be deeper.

These cutting parameters also determine product quality\(^3\text{-}^5\). Surface roughness is one of the most widely used index for determining the product quality and in most cases, it is a technical requirement for mechanical products\(^6\). The surface roughness after milling operation has been estimated using several approaches such as statistical, analytical, mathematical, neuro fuzzy, and neural network modelling. However, the exact process causing a change in the surface roughness of the CAD/CAM crown by varying the cutting conditions is still unknown\(^6\text{-}^8\).

The flexural strength of CAD/CAM crowns is important for durability in oral cavities. Flexural strength of composite resin materials are significantly influenced by several factors; these include degree of conversion, polymerization mode, filler content, and microstructure\(^9\). It has been reported that the grinding damage caused by a diamond disk results in micro cracks of the workpiece surface and a degradation in flexural strength and fracture toughness\(^10\text{-}^11\). Furthermore, rough surface of brittle materials can also lead to a diminution of the biaxial strength\(^12\). Although the CAM milling procedure significantly increases the surface roughness of CAD/CAM materials including ceramics and composite materials\(^13\), there is insufficient information about the effect of the cutting conditions on the flexural strength and surface roughness after milling.

In this study, to clarify the effect of milling conditions on the surface roughnesses and flexural strength of the CAD/CAM composite resin materials, we prepared rectangular composite resin samples with numerous surface morphologies by milling in varying step-over amounts. The rectangular specimens were milled from CAD/CAM blocks with step-over amount 0.01, 0.02, 0.05, 0.1, and 0.2 mm; further, a three-point bending test was conducted to reveal the flexural strength. The surface morphology after milling was assessed by a 3D laser microscope. The surface roughness significantly decreased by reducing the step-over amount. Although there was significant association between the surface roughness and flexural strength by the Pearson correlation, the 95% confidence intervals of the flexural strength were between the mirror-polished and sand-blasted groups. These results suggest that a precise step-over amount enables us to obtain a smooth surface. Furthermore, the flexural strength of the rough surface milled by a large step-over amount caused no damage to the composite resin for CAD/CAM crown.

**Keywords:** CAD/CAM, Composite resin block, Step-over amount, Surface roughness, Mechanical strength

MATERIALS AND METHODS

**Specimen preparation**

The data for sample preparation (Fig. 1) and the milling path was obtained using the CAD (CoCreate OneSpace Modeling ×64 edition (15.50.7.0), CoCreate Software, Sindelfingen, Germany) and CAM software (hyper DENT CLASSIC (v8.1.2), Follow-me! Technology, Munich, Germany), respectively. Further, the impact of the step-over distance during milling process on the morphologies and flexural strength of the resin blocks was evaluated; this was achieved by fixing the milling path so that the step over amount was as shown in Table 1. The resin...
blocks for CAD/CAM (EP; ESTELITE P BLOCK A3-LT, Tokuyama Dental, Tokyo, Japan) were milled using a dry milling machine (MD-350, CANON ELECTRONICS, Tokyo, Japan) and by diamond coating 2-flute long neck end mills [(DF2XLBFRO050N120, diameter 1.0 mm) and (DF2XLBFRO100N160, diameter 2.0 mm), Mitsubishi Materials, Tokyo, Japan] at a constant stage feed rate (1,500 mm/min) and spindle speed (25,000 rpm). When cutting each sample, a new ball-end mill was used and then the milling was performed; this was aimed at obtaining the same deterioration conditions that were associated with the processing. Subsequently, the blocks were sectioned with a low-speed diamond saw (Isomet, Buehler, Lake Bluff, USA) (Fig 1) and all specimens were polished with #1000 and #2000-grit silicon-carbide paper (NIHON KENSHI, Hiroshima, Japan) except for the milling surface. In this study, positive and negative

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**Table 1** Milling condition of MD350 in this study (plate specimen)

| Group | Step over (mm) | XY feed rate (mm/min) | Spindle (rpm) |
|-------|---------------|----------------------|---------------|
| BP    | 0.2           |                      |               |
| SB    | 0.2           |                      |               |
| HQ 0.2|               |                      |               |
| HQ 0.1| 0.1           | 1,500                | 25,000        |
| HQ 0.05|              | 0.05                 |               |
| HQ 0.03|              | 0.03                 |               |
| HQ 0.01|              | 0.01                 |               |

**Table 2** Milling condition of MD350 in this study (crown specimen)

| Group | Step over (mm) | XY feed rate (mm/min) | Spindle (rpm) | Milling time |
|-------|---------------|----------------------|---------------|--------------|
| A     | 0.2           |                      |               | 9' 40"       |
| B     | 0.1           |                      |               | 10' 10"      |
| C     | 0.05          | 1,500                | 25,000        | 12' 20"      |
| D     | 0.03          |                      |               | 15' 55"      |
| E     | 0.01          |                      |               | 23' 00"      |
| F     | 0.005         |                      |               | 44' 20"      |

**Table 3** Protocol of the tool path in this study (crown specimen)

| Group | Step over distance (diameter of ball end mill in mm) |
|-------|-----------------------------------------------------|
| A     | 0.2 (2)→0.2 (1)                                      |
| B     | 0.2 (2)→0.1 (1)                                      |
| C     | 0.2 (2)→0.1 (1)→0.05 (1)                            |
| D     | 0.2 (2)→0.1 (1)→0.05 (1)→0.03 (1)                   |
| E     | 0.2 (2)→0.1 (1)→0.05 (1)→0.01 (1)                   |
| F     | 0.2 (2)→0.1 (1)→0.05 (1)→0.01 (1)→0.005 (1)         |
control were treated with sandblasting under a pressure of 0.2 MPa at a 10 cm distance for 10 s using 70 \( \mu \)m aluminum-oxide (Hi-alumina, Shofu, Kyoto, Japan) (SB); further, the positive and negative control were mirror polished using #1000 and #2000-grit silicon-carbide paper after milling (BP), respectively. SB groups indicate the control materials that are subjected to traditional treatment in recent dental practice. Subsequently, all specimens were ultrasonically cleaned in distilled water for 10 min and air dried. The width and thickness of each specimen were measured carefully with digital micrometers (MDC-25MX and BLM-25MX, Mitsutoyo, Tokyo, Japan) and it was ensured that the samples were not chipped. A total of 56 beam-shaped specimens were fabricated that were 4.0±0.05 mm wide, 1.2±0.05 mm thick, and 15.0±0.05 mm long (\( n=8 \) per group).

In addition, CAD/CAM composite resin crowns of a lower first premolar were designed using CAD software; further, these were milled to investigate the influence of the milling process on the surface roughness. Based on the CAD data, the milling path with various cutting conditions was set so that the step over amount, the stage feed rate and the spindle speed were as shown in Table 2. The protocol of the tool path was shown in Table 3. The resin blocks were milled using large ball end mill (2 mm for rough milling and small ball end mill (1 mm) for precious milling. A total of 36 crown specimens were fabricated (\( n=6 \) per group). When cutting each sample, a new ball-end mill was used; further, milling was performed so that the deterioration conditions were the same as that during processing. The prepared crowns were divided into three pieces with a diamond disk; these included the occlusal surface (Oc), buccolingual surface (BL), and mesiodistal surface (MD). Subsequently, all specimens were ultrasonically cleaned in distilled water for 10 min and air dried.

Surface analysis
Surface morphology was observed using a laser microscope (LEXT OLS4100, OLYMPUS, Tokyo, Japan) with an objective magnification of ×20. Based on images obtained from laser microscopy, the cusp span and arithmetical mean height (\( S_a, \mu m \)) of the milled surface of each disk shape specimen were measured. Further, arithmetical mean height (\( S_a, \mu m \)) of the inner surface (group A to F; Oc, BL and MD) of each crown specimen were measured.

Three-point bending test
Flexural strength test specimens were determined using a three-point bending test that was in accordance with ISO 6872: 2015\(^{14}\). A three-point bending test with a support span of 12 mm at a crosshead speed of 1.0 mm/min was conducted using a universal testing machine (AUTOGRAPH AG-X, Shimadzu, Kyoto, Japan). The specimens were placed with the milled surface facing down. The flexural strength were calculated using a software (TRAPEZIUM X, Shimadzu) by using the following formula:

\[
\sigma = \frac{3Pl}{2wb^2}
\]

where \( P \) is the breaking load (N), \( l \) is the support span (mm), \( w \) is the width of each specimen (mm), \( b \) is the thickness of each specimen (mm).

Statistical analysis
The data were analyzed using the statistical software IBM SPSS Statistics, version 25 (SPSS, Chicago, IL, USA). Statistical analysis was performed by one-way ANOVA with Dunnett’s T3 pairwise comparison post hoc test (\( p<0.05 \)); this was aimed at detecting significant differences among all groups (BP, HQ0.01 to 0.2, SB) in the surface roughness and flexural strength. Subsequently, the 95% confidence intervals of each group about the flexural strength were compared. Additionally, the Pearson correlation was performed between the step-over amount and surface roughness; further, the correlation coefficient (r) value was calculated between the surface roughness and flexural strength.

RESULTS
Characterization of surface morphology
The representative images of the flexural strength test specimens observed with a laser microscope are shown in Fig. 2. The images were captured keeping in mind that the vertical direction was parallel to the cutting direction. It was observed that HQ0.01 to 0.2 had contact marks of burs due to milling. Further, the step-over amount was larger, and the contact mark was thicker. The data obtained by measuring the cusp span from the images (a) to (e) in Fig. 2 are shown in Fig. 3. The standard deviation of all groups were within 10%, which was implied to be comparable to the step over amount. In addition, the presence of contact marks of the abrasive paper in BP and the spread of uniform particles of aluminum-oxide in SB were observed. It was confirmed that the number of flaws in the specimens decreased as the step-over amount reduced.

Subsequently, the data of \( S_a \) was obtained as shown in Fig. 4. The minimum of the measured value was observed in BP and the maximum in SB. Further, on increasing the step-over amount, the value of \( S_a \) was found to be larger. The surface roughness results were found to be significantly different in each group.

Three-point bending strength
The three-point bending strength are shown in Fig. 4. The results were expressed as a percentage, which was based on the BP group of mirror-polished samples. The three-point bending strength of BP was 257.15±10.47 MPa. The maximum of the bending strength was observed in BP and the minimum in SB. No significant differences were found among each group except between BP and SB and BP and HQ0.03.

Relation between surface roughness and flexural strength
Pearson’s product-moment correlation coefficient was
Fig. 2 The laser microscope images of the milling surface at ×20 magnifications. 
(a) HQ0.2, (b) HQ0.1, (c) HQ0.05, (d) HQ0.03, (e) HQ0.01, (f) BP, (g) SB

Fig. 3 The correlation plot of mean cusp span vs. step over.

Fig. 4 Mean surface roughness (Sa) (white bar) and flexural strength ratio (dark bar). There are significant differences in surface roughness among all groups (p<0.05). The flexural strength (MPa) of BP is described as 100%. The horizontal line indicates a significant difference (p<0.05).
calculated from the results of the surface roughness and the flexural strength. The value of \( r \) between the step-over amount and the surface roughness was 0.965; from this result, a high positive correlation was recognized between the two. On the other hand, the value of \( r \) between the surface roughness and the flexural strength was −0.554; from this result, a negative correlation was recognized between the two.

The relationship between the surface roughness and the flexural strength is shown in Fig. 5. Comparing the 95% confidence intervals of each group namely, BP, HQ0.01 to 0.2, and SB, it was observed that SB showed higher values in the order as seen in the figure. In addition, all groups in HQ0.01 to 0.2 showed higher values than the 95% lower confidence limit of SB.

### DISCUSSION

This study showed that reduction of the step over amount improved the milling accuracy of CAD/CAM crowns and that the flexural strength of the milled resin blocks were within the clinically acceptable range under any milling conditions. Because the traces of cusp show the accuracy of the movement of cutting tools\(^1\), we measured the mean cusp span by laser microscope images and compared them to the step over amount. The mean cusp span was in good agreement with the set step-over amount. The theoretical surface roughness (\( R_z \)) can be calculated from the step-over amount, which is the movement distance in the XY plane component of the ball end mill, using the following formula when the free form surface is milled with the ball-end milling cutter:  

\[
R_z = R - \sqrt{R^2 - \left( \frac{S_o}{2} \right)^2} = \frac{f_s^2}{8 \left( \frac{D_c}{2} + f_s x z \right)} \pi
\]

where \( R \) is the ball radius, \( S_o \) is the step over amount, \( f_s \) is the feed amount per blade, \( D_c \) is the end mill blade outer diameter, \( z \) is the number of blades. Therefore, the surface roughness of resin blocks for CAD/CAM is inferred to be proportional to the step over amount. The surface roughness obtained in this study was in good agreement with this tendency. A high positive correlation was found between the surface roughness and the step over amount from Pearson’s product-moment correlation coefficient. This result proves that the step over amount improves the surface roughness. However, the measured roughness was different from the theoretical roughness. This is because the surface roughness has been reported to be affected by not only milling conditions but also tool vibrations\(^2\).

The flexural strength of CAD/CAM ceramics materials has been reported to decrease with increase of surface roughness\(^3\), but few studies have been conducted on resin composite blocks. Therefore we evaluated the flexural strength of resin composite blocks milled in various setting conditions. Although a negative correlation was found between surface roughness and
flexural strength, there were no significant differences among the resin composite blocks. Therefore, we compared the 95% confidence intervals of the flexural strength of each group; this was achieved by referring the flexural strength of the sandblasted specimens and the polished specimens based on the clinical technique\textsuperscript{10-21}. The flexural strength in any of the milling groups is found to be the maximum in BP and the minimum in SB; this indicates that the flexural strength of all specimens in the milling group is within the clinically applicable range and the cutting method had an insignificant effect on the flexural strength.

Subsequently, we evaluated the surface roughness of the mandibular premolar crown model under various conditions to show the effect of step-over effect on the surface roughness in clinical situations. The surface roughness decreased as the step over amount decreased as in the case of the flexural specimens. However, it tended to differ depending on the position of the inner surface. The reason for this difference is supposed to be inferred from the contact zone between the ball end mill and the workpiece. While the occlusal surface is milled with the tip of the cutting burs, the buccolingual and mesiodistal surface are milled with the side. The inclination angle of cutting burs against the workpiece surface has been proved to affect the cutting force and cutter’s displacement, which directly affects the quality of the finished surface\textsuperscript{22,23}. Besides, owing to the increase of the contact area, the cutting force increases with an increase in the radius of curvature for sculptured surface machining, which results in the surface quality\textsuperscript{24}. Therefore, the surface roughness of the buccolingual surface, which is a complicated shape curved more than the mesiodistal surface, was a high value. Although the tendency of surface roughness was different between rectangular samples and premolar crowns, the surface roughness of crowns was within the range of the rectangular samples. These facts indicated that the strength of crowns milled in various conditions has suitable flexural strength.

From the above discussion it can be stated that a smooth surface was obtained by decreasing step-over distance; further, the time for polishing the crown surface by hand was shortened. However, it is necessary to select an optimal cutting condition to obtain a desired surface morphology because the processing time is significantly prolonged by reducing step-over distance. From the viewpoint of flexural strength, the milling conditions showed no significant effect on bending strength; this suggested that any conditions used in this study are acceptable.

CONCLUSIONS

Current advances of CAD/CAM technology introduce high-speed milling in dental fields and enable them to fabricate dental crowns in a short time. However, the effect of cutting conditions on the surface morphology and flexural strength of composite resin block is unclear. We elucidated the relationship between the surface roughness of composite resin for CAD/CAM crowns and step-over distance for the first time. The smooth surface was obtained by reducing step-over distance, although the processing time was prolonged. The flexural strength of milled-composite resin samples was clinically acceptable even within the roughest cutting conditions. However, the milling conditions that makes the surface rougher than sandblasted-surface (Sa; 1.06 μm) should be avoided because flexural strength may deteriorate.

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CONFLICT OF INTEREST

The authors have no conflict of interest to declare.

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