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A new mandibular deformation index predicts amount of bone deformation in edentulous patients treated with an implant-supported fixed prosthesis

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Abstract

Purpose: The present study was performed to examine the mandibular deformation during mouth opening in edentulous patients, treated with an implant-supported fixed prosthesis using strain gauges, and identify factors affecting deformation.

Methods: Twenty patients with a fully edentulous mandible who received either 4 or ≥6 implants were included. The distal-most implants were placed mesial to the mental foramen (premolar region) in patients with 4 implants and distal to the mental foramen (molar region) in patients with ≥6 implants. Mandibular deformation during mouth opening was measured using strain gauges in two directions: anteroposterior direction and lateral direction between the distal-most implants on the left and right sides (arch width). The mandibular anatomy was evaluated using computed tomography.

Results: Arch width reduction between the left and right implants during mouth opening ranged from 47.38 to 512.80 µm; the range of deformation was 0.12 to 15.14 µm in the anteroposterior direction. Furthermore, a significant positive correlation was noted between arch width reduction in the premolar region and the ratio between the symphyseal bone height and width ($P = 0.0003$, $r = 0.72$).

Conclusion: The reduction in arch width was higher in the molar region than in the premolar region during mouth opening. Moreover, the reduction could be high in the mandibular symphyseal bone because of its greater height and lesser width. The ratio between the symphyseal bone height and width is defined as the mandibular deformation index (MDI) and is used to predict the rate of mandibular bone deformation.

Keywords: Mandibular deformation, Fully edentulous, Dental implant, Symphyseal bone, Arch width

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1. Introduction

Dental implants are widely and successfully used in the treatment of missing dentition. Several implant treatment protocols have been developed for patients with an edentulous mandible because it is difficult to achieve sufficient patient satisfaction with conventional dentures.

When using full-arch implant-fixed prostheses in edentulous patients, installing four to six implants anterior to the mental foramina and delivering a superstructure using bilateral distal cantilevers are common techniques associated with excellent longevity and clinical efficacy[1]. Another technique is the All-on-4® treatment concept (Nobel Biocare, Kloten, Switzerland), in which four axial and tilted implants are placed between the mental foramina[2]. In contrast, two implants are often added distal to the foramina, in addition to the placement of anterior implants between the mental foramina to decrease the cantilever. However, the criteria for the number and arrangement of implants in edentulous patients are unclear.

Implant placement for supported prosthesis treatment has been performed in several studies, as described in a systematic review published in 2017[3]. The implant survival rate in the All-on-4® treatment was evaluated in several studies with different follow-up durations[4–6]. These studies revealed a mandibular implant survival rate of 98.0% after 5 years of follow-up and 94.8% after 10 years of follow-up. Other studies revealed a 100% implant survival rate in edentulous mandibles after 3 to 4 years of follow-up[7–9]. Furthermore, certain studies evaluated implant survival rates in patients with ≥4 implants and implant-supported fixed prostheses in edentulous mandibles. These studies showed that the implant survival rate was 98.4% to 100% after 5 years and 95.9% after 1 to 6 years of follow-up[10–12]. After 10 years of follow-up, the implant survival rate ranged from 93.9% to 98.0%[10,11,13]. Furthermore, the survival

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Table 1. Patient characteristics

Sex	Women	Men
	6	14
Age (y)	71.4 ± 9.5	
Number of cases	4 implants: n=13	≥6 implants: n=7
Implant and manufacturer	Noble Biocare (Mk III or Speedy Groovy) with a regular platform	

rate of a full-arch prosthesis supported with implants was 97.0% after 1 to 6 years[14], 95.5% to 98.6% after 5 years[11,12], and 97.3% after 10 years[11].

Although full-arch implant-supported fixed prostheses have a high implant survival rate, complications associated with these prostheses have been reported. Biological complications include soft tissue recession, peri-implantitis, marginal bone loss, and mucositis. Additionally, implant failure rates of 88.0%[15] and 81.3%[16] were reported after 5 years of follow-up. Furthermore, 47.7% of patients developed mechanical complications such as screw fracture and/or loosening, veneer fracture, and framework fracture after 5 years of follow-up[16]. A systematic review of complications associated with implant-supported fixed complete denture prostheses indicated that the cumulative rate of a complication-free prosthesis after 5 and 10 years was 29.3% and 8.6%, respectively[17]. The presence of bruxism, absence of a nightguard[18], and mandibular deformation were considered risk factors for mechanical complications[19–21].

Mandibular deformation is defined as a change in the shape of the mandible and has been reported in numerous studies. Four patterns of mandibular deformation were classified by Hylander in 1984[22]: symphyseal bending associated with medial convergence, dorsoventral shear, corporal rotation, and anteroposterior shear. Contraction of the lateral pterygoid muscles pulls the mandibular condyles medially[20,22–26] and causes mandibular deformation during mouth opening. Gates and Nicholls[26] evaluated the mandibular width change in several mandibular positions and concluded that the maximum opening, protrusion, and biting forces cause the arch width of the mandible to decrease. Similarly, several studies[23,24,27–30] have shown that mandibular deformation during mouth opening in dentate subjects causes the mandibular arch to decrease. Because of the effect of the periodontal ligaments in dentate patients, data from patients with osseointegrated implants are required to measure the actual bone deformation in these patients; however, these data have been rarely reported. The purpose of this study was to measure mandibular deformation values in different directions with different implant positions and identify factors related to mandibular deformation.

2. Materials and Methods

2.1. Study population

This study involved 20 patients with a fully edentulous mandible (6 women and 14 men; mean age, 71.4 ± 9.5 years; age range, 50–86 years) who required either 4 or ≥6 implants (Brånemark System® Mk III or NobelSpeedy® Groovy with a regular platform; Nobel Biocare) (**Table 1**). In patients with four implants (n = 13), the distal-most implants were placed mesial to the mental foramen (premolar region). In patients with ≥6 implants (n = 7), the distal-most implants were placed distal to the mental foramen (molar region). After placement of the final prosthesis, all patients regularly underwent maintenance visits, and none developed implant-related complications. In addition, this study included patients with a normal range of maximum mouth opening who could control their mandibular movements without signs of a temporomandibular disorder. The exclusion criteria were systemic diseases affecting the quality and quantity of the mandibular bone, head and neck radiotherapy, or previous mandibular bone grafting. All patients agreed to the study protocol, which was approved by the Ethics Committee of Kyushu Dental University (approval number: 19-57).

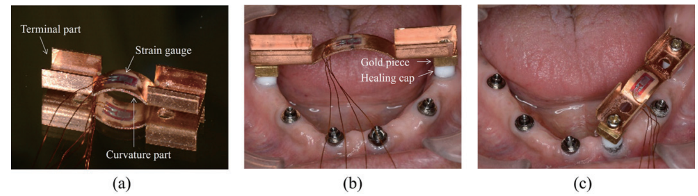


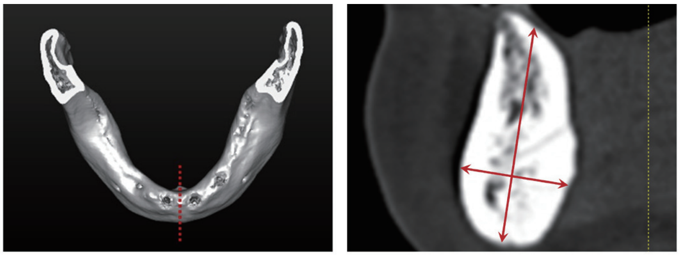
Fig. 1. Measurement tools. (a) The spring plate design (straight terminal parts and curvature in the middle) is shown, with strain gauges attached to the top and bottom. (b) The strain gauges are connected from the left to right implants to measure the change in arch width (lateral direction). The gold piece is connected to the healing cap to support the spring plate. (c) The strain gauges are connected to the anteroposterior implants for anteroposterior measurements.

2.2. Preparation of measurement tools

We designed a tool to measure mandibular deformation values. First, we measured the distance between implants in a stone model using an electronic digital caliper to select the proper length of the spring plate (Tokyo Measuring Instruments Laboratory; Tokyo, Japan), which ranged from 30 to 60 mm. Next, we created two holes evenly spaced from the center on both sides to connect the spring plate with the dental implants in the patient's mouth. The spring plate design had straight terminal parts and a curvature in the middle (**Fig. 1a**). The purpose of this design was to avoid bending of the spring plate. The terminal part with the raised edge increased the strength of the plate. Two strain gauges (FLA-2-11; Tokyo Measuring Instruments Laboratory) were attached to the spring plate at the top and bottom at the middle position of the curve of the spring plate (**Fig. 1a**) with cyanoacrylate adhesive (CN Adhesive; Tokyo Measuring Instruments Laboratory). A strain gauge was attached on both sides to confirm the direction of the force. Finally, a chloroprene rubber coating (Hamatite A-862-B; Yokohama Rubber Company, Tokyo, Japan) was applied for moisture prevention.

At the maintenance visit, we removed the upper and lower superstructures and subsequently screwed the healing cap (Nobel Biocare) on the targeted implant in the patient's mouth. We then connected gold pieces (Tokyo Measuring Instruments Laboratory) to the healing cap with cyanoacrylate solution (Aron Alpha A "Sankyo;" Daiichi Sankyo, Tokyo, Japan) (**Fig. 1b**). The gold pieces served to create a screw hole for connecting the spring plate to the healing caps. Finally, the prepared spring plate was screwed onto the gold pieces.

The strain gauges were connected to a personal computer program (DSCLog24; Mantracourt Electronics, Exeter, Devon, United Kingdom) to graph the changes that occurred when the patients moved their jaws from the resting position to the maximum mouth opening. We confirmed that the patients painlessly opened their



(a) (b)

(c) Mandibular Deformation Index (MDI) = symphyseal bone height/width

Fig. 2. Mandibular anatomy analysis. (a) Position of the cross-sectional region for measuring various mandibular anatomies in the symphyseal region using Simplant® software (Dentsply Sirona, Charlotte, NC, USA). (b) Image of the symphyseal bone height measurement line perpendicular to the width measurement line. (c) Formula for calculation of the mandibular deformation index (MDI). The MDI was defined as the ratio between the symphyseal bone height and width.

mouths as wide as possible and to a maximum interincisal distance of at least 30 mm. We next calculated the amount of mandibular arch reduction in micrometers.

2.3. Measurement position

We measured the mandibular deformation in two directions: laterally, between the most distal implants on the left and right sides (arch width), and anterior to the most distal implant position (anteroposterior direction). In patients with four implants (n = 13), the distal-most implants were placed in the premolar region, and in patients with ≥6 implants (n = 7), these were placed in the molar region. We referred to the group of data from the distal-most implant as "Dataset I" (n = 20).

In patients with ≥6 implants, implants were placed in both the molar and premolar regions. All 20 patients had implants placed in the premolar region; therefore, only data from premolar implants were analyzed as "Dataset II" (n = 20) to exclude the implant position as a factor affecting the measurement.

2.4. Mandibular anatomy analysis

Data for various mandibular anatomies were collected from computed tomography (CT) images to identify the factors affecting deformation. X-ray CT images of all patients were acquired to plan the implant treatment. CT images were acquired using the following devices: XVision and Activion 16 (Toshiba Corporation, Tokyo, Japan), Somatom (Siemens Healthineers, Erlangen, Germany), and Brilliance 64 (Philips, Amsterdam, Netherlands). Mandibular anatomy, including the buccal and lingual cortical bone thickness at the symphysis and the symphyseal bone width and height, were measured in cross-sectional images of the symphyseal area using the Simplant® software (Dentsply Sirona, Charlotte, NC, USA) (**Fig. 2a**). We first measured the height from the highest bone position and then measured the width perpendicular to the height measurement line (**Fig. 2b**). We next calculated the ratio between the symphyseal bone height and width (**Fig. 2c**).

2.5. Statistical analysis

In Dataset I, the Mann–Whitney *U* test was used to compare the deformation values divided by the direction of the deformation measurement. In Dataset II, Spearman's rank correlation was used for correlation analysis between the mandibular anatomy factors and arch width reduction values. P-values of <0.01 were considered significant in both analyses.

3. Results

All 20 patients underwent mandibular deformation measurements from resting to the maximum mouth opening in two directions (Dataset I); these data are summarized in **Table 2**. The mean arch width reduction value between the left and right implants during mouth opening was 165.16 μm (range, 47.38–512.80 μm). The mean deformation value in the anteroposterior direction was 3.36 μm (range, 0.12–15.14 μm). These directional data are compared in **Figure 3**. The degree of deformation was significantly greater in the lateral than in the anteroposterior direction (P < 0.01).

We divided the data into two groups according to the position of the distal-most implant (molar or premolar) and compared the measurements. The mean arch width reduction value was 100.07 μm (range, 47.38–174.40 μm) in the premolar region and 286.05 μm (range, 125.61–512.80 μm) in the molar region (**Fig. 4a**). In the anteroposterior direction, the mean arch width reduction value was 1.57 μm (range, 0.12–3.93 μm) in the premolar region and 6.672 μm (range, 0.74–15.14 μm) in the molar region (**Fig. 4b**). The degrees of deformation were significantly greater in the molar region than in the premolar region in both directions (P < 0.01).

Using Dataset II, Spearman's rank correlation analysis was performed to evaluate the factors affecting the reduction in the arch width in the premolar region during the maximum mouth opening. The statistical analyses of all contributing factors, including correlation coefficients and P-values, are presented in **Table 3**. The buccal and lingual cortical bone thickness in the symphyseal region and the symphyseal bone height and width did not correlate with a reduction in the arch width. A significant positive correlation was noted only between a reduction in width separating the left and right implants in the premolar region and the ratio between the symphyseal bone height and width (P = 0.0003, r = 0.72). The scatter graph in **Figure 5** is a plot of the arch width reduction between the left and right implants in the premolar region and different ratios of symphyseal bone height and width.

4. Discussion

In this study, we investigated mandibular deformation in patients with osseointegrated implants. Several researchers have performed these measurements in dentate patients; however, their findings did not accurately represent mandibular deformation in edentate patients because natural teeth have periodontal ligaments that allow movement. Because implants involve functional ankylosis of the mandibular bone, which differs from the characteristics of the periodontal ligaments in natural teeth, it is possible to measure mandibular deformation more accurately in edentate patients. Although certain reports[31–33] evaluated the change in arch width by direct measurement in patients with implants, these measurements were only performed for implants placed in the interforaminal region, and no reports have addressed molar strain.

Table 2. Mandibular deformation values (µm) divided by different conditions (Dataset I)

	Divided by measurement direction		Divided by the most distal implant position			
	Lateral direction	Anteroposterior direction	Lateral direction		Anteroposterior direction	
			Premolar region	Molar region	Premolar region	Molar region
Mean	165.16	3.36	100.07	286.05	1.57	6.67
Minimum	47.38	0.12	47.38	125.61	0.12	0.74
Maximum	512.80	15.14	174.39	512.80	3.93	15.14
P-value	< 0.01		< 0.01		< 0.01	

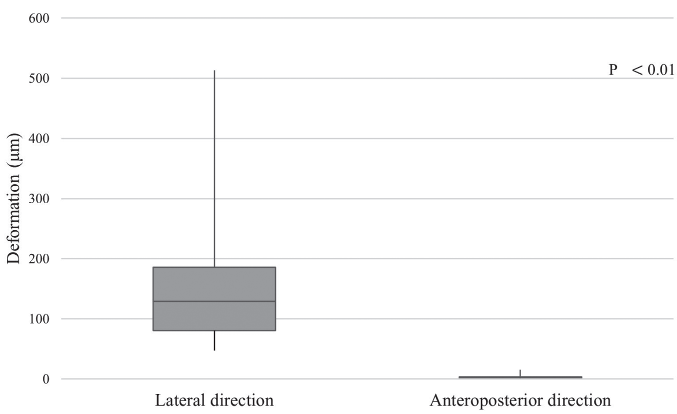


Fig. 3. Comparison of mandibular deformation value in 2 measurement directions (lateral and anteroposterior). The measurement in each direction was significantly different (n = 20, P < 0.01).

In this study, mandibular deformation during the maximum mouth opening reduced the mandibular arch width, similar to the results of previous studies[23–25,27–30,34,35]. The range of mandibular reduction in the present study was 47.38 to 512.80 µm, which conformed to the range of 12 to 1500 µm of deformation reported in other studies[23–25,27–30,34,35] in which deformation was measured in the molar region of dentate patients. Therefore, the mandibular deformation value is probably identical between dentate and edentulous patients. However, previous studies included indirect measurements of models of patients with natural teeth, and the properties of the periodontium could affect the precision of deformation values derived from natural teeth. In contrast, the range that we measured in the premolar region (47.83–100.07 µm) was higher than that in previous studies measuring mandibular deformation values in patients with implants in the premolar region. Al-Sukhun et al.[31] reported reduction values of 11.0 to 52.5 µm in an all-female cohort; therefore, the study had no sex diversity. Abdel-Latif et al.[33] reported lower values (1.4–41.3 µm) in six subjects, which was a small population. Furthermore, El-Sheikh et al.[32] reported deformation values of 14.7 to 42.2 µm; however, unlike in our study, they used a straight and flat spring plate design with no curvature. A straight and flat design cannot control the direction of force transfer to the strain gauge, and the obtained deformation values may be imprecise. Therefore, to obtain more precise data, we used a spring plate design that was more rigid in the terminal part with a raised edge and could better control the direction of force while avoiding plate bending.

The additional direction in which we measured the deformation values was in the anteroposterior direction. The mean deformation value in the anteroposterior direction was 3.36 µm, which was significantly lower than that in the lateral direction between the distal-most implants on the left and right sides. Our results suggest that the mandible does not deform similarly in all directions; rather, it deforms more at the midline. However, although the deformation value in the anteroposterior direction was lower than that in the lateral direction, we cannot deny that the deformation is affected in both directions.

Implant-supported full-arch fixed prostheses are influenced by several conditions that affect the survival rate of both the implant and prosthesis, including the number of implants[36]. Previous studies have recommended four to eight implants for supported fixed prostheses[37]. Brånemark et al.[1] suggested that four implants were sufficient for supported fixed prostheses. This recommendation is similar to that of Heitz-Mayfield et al.[38], who preferred four implants in the mandible. Furthermore, Polido et al.[37] reported a lack of evidence to determine the optimal number and distribution of implants to support a complete arch-fixed prosthesis. Thus, other factors should be evaluated before determining the number of implants required to achieve a high success rate with implant-supported fixed prostheses. Naert et al.[39] and Quirynen et al.[40] advised caution in patients with parafunctional habits, including high occlusal force[36]. Naert et al.[39] recommended shorter cantilevers, optimal spreading of implants along the arch, maximal implant length, and a nightguard. Moreover, Kim et al.[36] concluded that a shorter cantilever length was more favorable for the success of mandibular fixed implant-supported prostheses. However, the criteria for placement of implants extending to the molar region to increase the number of implants in patients with implant-supported fixed prostheses are currently unclear.

In this study, the degree of deformation was greater in the molar region than in the premolar region. This suggests that when implants are placed in the molar region followed by a prosthodontic treatment, the effects of mandibular deformation increase in both directions. Fischman[25] and McCartney[41] recommended the use of a connecting framework for anterior implants only. The framework covers but does not attach to posterior implants, and posterior implants should be freestanding and associated with short prosthetic spans. Although mandibular implant treatment has a high success rate, the long-term clinical significance of jaw deformation remains unknown, and the possibility that these dimensional changes and resultant strains might be a source of failure cannot be excluded[33].

We examined the relationship between mandibular anatomy and deformation to identify the factors influencing mandibular deformation. We used Dataset II to exclude the implant position as a factor and found that the ratio between the symphyseal bone height and width was related to mandibular deformation (r = 0.72). To predict the rate of mandibular bone deformation, we defined the ratio between the symphyseal bone height and width as the mandibu-

Table 3. Correlation analysis between mandibular anatomy factors and arch width reduction values

	Rs	P-value
Implant-Implant Distance	0.190	0.423
Cortical bone thickness (buccal side)	-0.423	0.063
Cortical bone thickness (lingual side)	-0.302	0.195
Symphyseal bone width	-0.326	0.160
Symphyseal bone height	0.453	0.045
Ratio of symphyseal bone height/width	0.721	0.0003

Spearman's rank correlation was used for correlation analysis between the mandibular anatomy factors and arch width reduction values in the premolar region during maximum mouth opening (Dataset II).

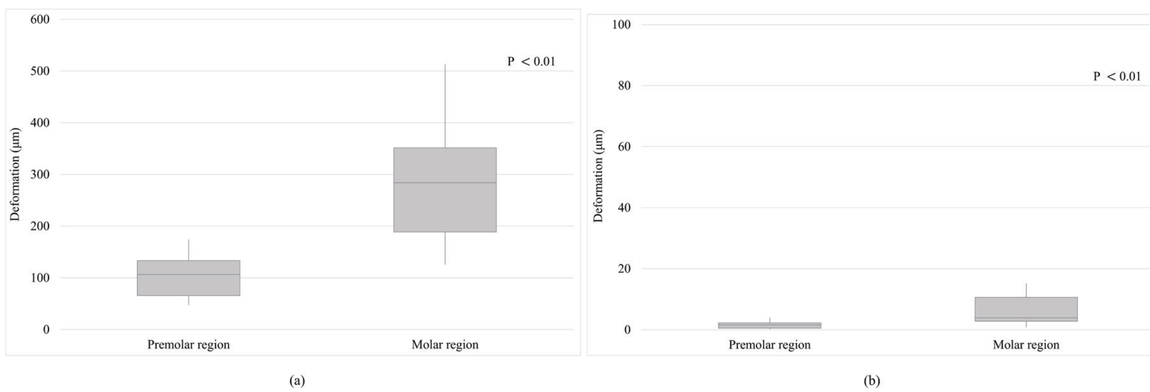


Fig. 4. Mandibular deformation values divided by the distal-most implant position. (a) Comparison of deformation values measured in the lateral direction. (b) Comparison of deformation values measured in the anteroposterior direction. Premolar region, n = 13; molar region, n = 7. The measurement in each direction was significantly different (P < 0.01).

lar deformation index (MDI), where MDI = symphyseal bone height/width. This result was consistent with the findings of Chen et al.[27] that the symphyseal bone width and area are related to mandibular deformation, as well as the finding by Hylander[22] that force from mandibular movement directly affects the symphyseal region. Thus, these factors can be used to diagnose and select an appropriate treatment plan for patients with factor-related high deformation.

One study showed that mandibular deformation caused micro-damage in the crestal region and poor osseointegration because of micromovements around the implants[20]. Additionally, Horiuchi et al.[42] reported that intermittent stress occurring around implants secondary to the mandibular flexure may cause chronic bone resorption. Fischman[25] reported that stresses transmitted to the bone by the implant during the function were greater than the bone's ability to repair the damage, resulting in bone loss in the crestal region. Therefore, reducing the effect of mandibular deformation may increase longevity and improve the outcomes of implants and prostheses. In addition, reducing unnecessary stresses and strains on the metal substructure and retaining screws may help increase the longevity of the prosthesis[43].

For full-mouth implant-supported fixed prostheses, Paez et al.[43] and Zarone et al.[44] stated that splitting a superstructure in the symphyseal region could achieve more natural biomechanical behavior of the mandible and minimize the adverse effects of mandibular deformation. However, it is difficult to adopt a split superstructure in all patients because the number of implants and costs are higher than in a one-piece superstructure. Our findings indicated

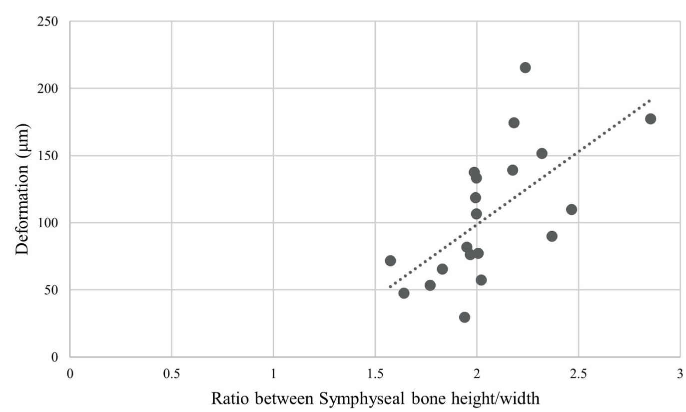


Fig. 5. Correlation between deformation values and mandibular anatomy. Scatter plot showing deformation values (arch width) in the premolar region with different ratios of symphyseal bone height and width.

that the mandibular symphyseal bone shape following MDI should be evaluated to assess the risk of mandibular deformation before deciding on the implant treatment plan and prosthodontic design. Prostheses in patients with ≥6 implants are more strongly affected by mandibular deformation than those in patients with 4 implants. Careful consideration is required for full-mouth implant-supported fixed prostheses and long-span prostheses, particularly in high-risk cases with severe mandibular deformation.

This study had two main limitations. First, the number of patients was less. After performing the post hoc analyses, we found that the statistical power for these experiments was higher than the adequate power level (0.8), suggesting that the results of our study are reliable and acceptable despite the small number of patients. However, further studies with larger numbers of patients are required to obtain more precise and accurate mandibular deformation values. Second, although there exist different types of mandibular deformations, we examined only two directions of change in this study. Other mandibular deformations, such as dorsoventral shear and corporal rotation, should also be evaluated in future studies.

5. Conclusion

Within the limitations of this research, our *in vivo* study of mandibular deformation values and the factors affecting mandibular deformation led to the following conclusions.

1. The arch width reduction between the left and right implants during mouth opening (measurement range, 47.3–512.8 μm) was greater than that during anteroposterior deformation (measurement range, 0.12–15.14 μm).
2. The degree of deformation was significantly greater in the molar region than in the premolar region in both the lateral and anteroposterior directions.
3. The ratio between the symphyseal bone height and symphyseal bone width (i.e., the MDI) was highly and positively correlated with the mandibular arch width reduction value.

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Conflicts of interest

ST, CM, TN, TM, TM, YK, and RH state that there are no conflicts of interest related to this study.

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