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Original Article

Modal analysis of the maxillary dentition in cleft lip and palate patients before and after bone grafting

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The aim of this study was to analyze the vibratory characteristics in the maxillary dentition of 4 cleft lip and palate (CLP) patients before and after bone grafting.

First, the central incisor on the noncleft side was impacted with an impact hammer, and the responses were received using an acceleration sensor from the teeth between the upper first molars on both sides. The transfer functions were then obtained from each measurement point using a fast Fourier transform analyzer. Finally, a computer analysis and simulation were performed based on the measured transfer functions to obtain the natural frequency, modal shape, decay rate (DR) and maximum displacement (MDP).

Before bone grafting, distinct phase differences between the major and minor dental arches (MDA and mDA) were observed in the modal shapes. After surgery, however, both the MDA and mDA vibrated in phase. These results were identical in all subjects. The MDPs of the central incisors conspicuously decreased after bone grafting in 3 subjects. From the standpoint of vibratory characteristics, this study indicated that bone grafting had a favorable effect on prosthodontic treatment using a fixed prosthesis across the cleft in CLP patients.

Key words: modal analysis, cleft lip and palate, bone grafting, modal shape, maximum displacement

Introduction

For cleft lip and palate (CLP) patients, bone grafting to the cleft has become a well-accepted treatment modality[1]. This surgery produces the formation of a bony bridge, eliminates oronasal fistulas[2-4] and prevents relapse after orthodontic treatment[5], all of which simplify the prosthodontic treatment of CLP patients[6].

Modal analysis is one method of revealing the dynamic characteristics of a structure by investigating how each component vibrates at its own natural frequency[7]. The vibratory characteristics of a structure depend on many factors, including its shape, mass and stiffness. Recently Du et al.[8] have revealed differences in vibratory characteristics of the maxillary dental arches between normal and CLP subjects by direct

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application of modal analysis to the living body. It is thought that the formation of a bony bridge across the cleft area would change the dynamic characteristics of the maxillary dentition; however, to date, there have been no studies focusing on the effects of bone grafting on the vibratory properties of the maxillary dentition. The purpose of this study was to analyze the vibratory characteristics of maxillary dental arches in CLP patients before and after bone grafting *in vivo* from the standpoint of the natural frequency, modal shape, decay rate (DR) and maximum displacement (MDP).

Materials and methods

1. Test subjects

Two male and two female patients with unilateral CLP ranging from 18 to 25 years of age (mean age: 21.8) were selected for this study. They were referred for prosthodontic treatment to the Maxillofacial Prosthetics Clinic, University Hospital, Faculty of Dentistry, Tokyo Medical and Dental University. All patients had finished orthodontic treatment and had sound dentition and clinically healthy periodontal tissue. However, based on a team conference consisting of the surgeon, orthodontist and prosthodontist, iliac crest bone grafting to the maxillary defect area was arranged to be performed prior to the prosthodontic treatment. Figure 1 shows the palatal views of maxillary dental arches after bone grafting in all patients. All subjects had given their informed consent to this study.

2. Measurement system and measurement points

Figure 2 is a diagram of the system used in this study. An impact hammer (Dytran 5800-SL, Dytran Instruments Inc., Chatsworth, CA, USA) was used to tap the central incisor on the noncleft side, and a single-axis acceleration sensor (NP-3210, ONO SOKKI Co., Tokyo, Japan) which was 5.84 mm in diameter and 3.96 mm in thickness, was used to receive the response only in the buccolingual direction from each measurement point. The excitation signal from the hammer and the response signal from the sensor were entered into a fast Fourier transform (FFT) analyzer (CF-6400, ONO SOKKI Co., Tokyo, Japan) to calculate the transfer function at each measurement point. All transfer functions were downloaded to a personal computer Vectra VE (Hewlett-Packard Co., Grenoble Cedex, France) and modal shapes were computed using the Vibrant GEN modal analysis software (Marubeni Solutions Co., Tokyo, Japan). To obtain the modal shapes of the maxillary dental arch,

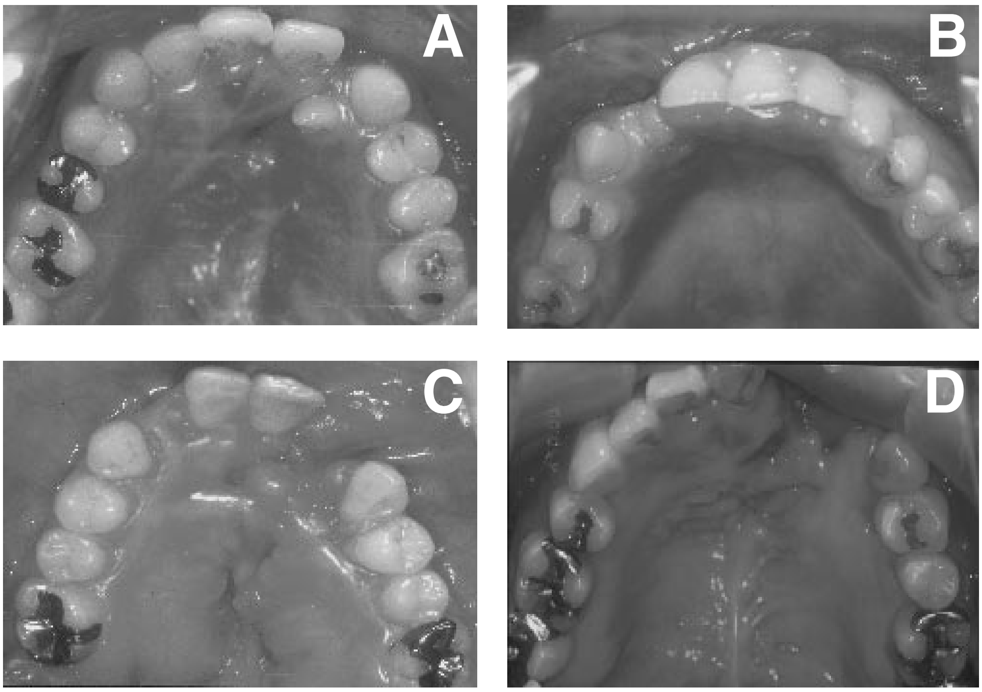

Fig. 1. The palatal views of the maxillary dental arch after bone grafting of each subject

the coordinate value of each measurement point must be input to the Vibrant GEN software before actual measurement. In this study, three coordinate axes were defined as shown in Fig. 3 and the measurement points were established on the buccal surfaces of the teeth between the upper first molars on both sides. The upper jaw impression was then taken to obtain a cast. The coordinate value of each measurement point on the cast was measured using SURFLACER, non-contact, high-speed 3-D Shape Measurement System (UNISN Inc., Osaka, Japan). The 3-D data were computed on an Indigo[2] workstation (Silicon Graphics Inc., Mountain View, CA, USA) using SURFACER, 3-D surface data management-convert-analysis software (Imageware Inc., Ann Arbor, MI, USA). To define the response direction of each measurement point, the value of angles formed by the X-axis and perpendicular lines tangential to the maxillary dental arch at each given measurement point must be entered into the Vibrant GEN software. These angles were geometrically calculated from the projection of measurement points onto the X-Y plane by using the cast (Fig. 4).

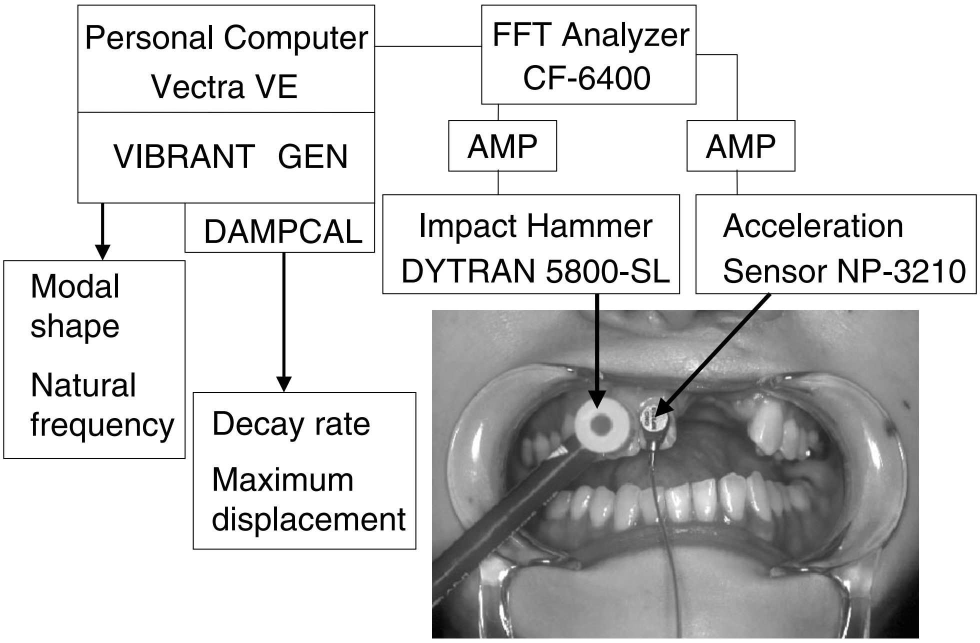

Fig. 2. Measurement system diagram

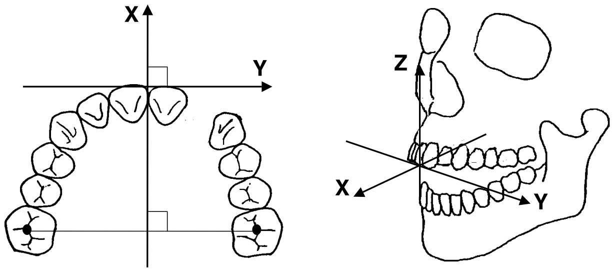

Fig. 3. The defined coordinate axes

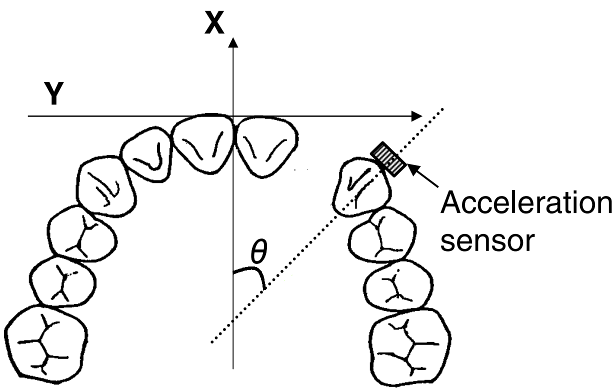

Fig. 4. The response direction was represented by the angle θ which was geometrically calculated from the projection of the measurement points onto the X-Y plane.

3. Measurement procedure

The vibratory measurements were all performed, at almost the same time, in a laboratory where the temperature and humidity were 25 °C and 70% respectively.

For each subject, the first measurement was performed within 5 days before bone grafting. Each subject sat in a dental chair and put their head on the headrest so that the Frankfurt planes were parallel to the floor. The retractor of angle of the mouth was inserted, and the subject was instructed not to contact the upper teeth with the lower teeth. The sensor was placed, to the best of our ability, on the buccal surface of the measurement tooth with utility wax so that the base plane of the sensor was parallel to the Z-axis as well as parallel to the line tangent to the maxillary dental arch, being consistent with the defined response direction at each given measurement point. In this study, the frequency range was set from 0 to 2000 Hz and the compliance (displacement/force) was used as the transfer function. The central incisor on the noncleft side was tapped ten times for each measurement point in the direction parallel to the X-axis, while the sensor was moved through all measurement points one by one. The transfer function of each measurement point was obtained by the FFT analyzer from the summed average of the 10 separate measurements. Then all transfer functions were transferred to the Vibrant GEN modal analysis software, and the curve-fitted transfer function was calculated by means of the curve-fitting function, with the error convergence rate kept to more than 99.95%. The natural frequency was then obtained and the modal shapes in the buccolingual direction computed.

Three or six months after bone grafting, when the patients were referred to our clinic again for prosthodontic treatment by the surgical team, the second measurement was carried out in the same manner as the first one.

4. Transient response simulation experiment

Transient response simulation in Vibrant GEN was applied after curve-fitting to produce the transient response wave. Both the central incisors were impacted at 5 kgf (= 49 N) in the direction of the X-axis at the same time (Fig. 5). The software was configured so that the direction of the transient response waves was aligned with the X- or Y-axis. In this study, the directions were assigned to the X-axis for the anterior teeth and the Y-axis for the posterior teeth. To evaluate the waves, the DRs and MDPs were calculated using DAMPCAL software (Marubeni Solutions Co., Tokyo, Japan). For the DR, the wave peaks were carefully selected and plotted on the computer display. As the result of this procedure, the DR (σ) was denoted in the equation shown in Fig. 6. The plotting was repeated

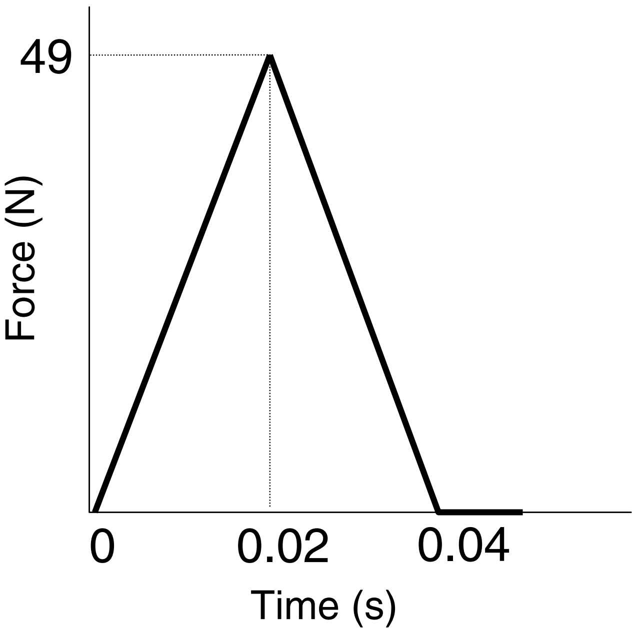

Fig. 5. The defined force for the transient response simulation

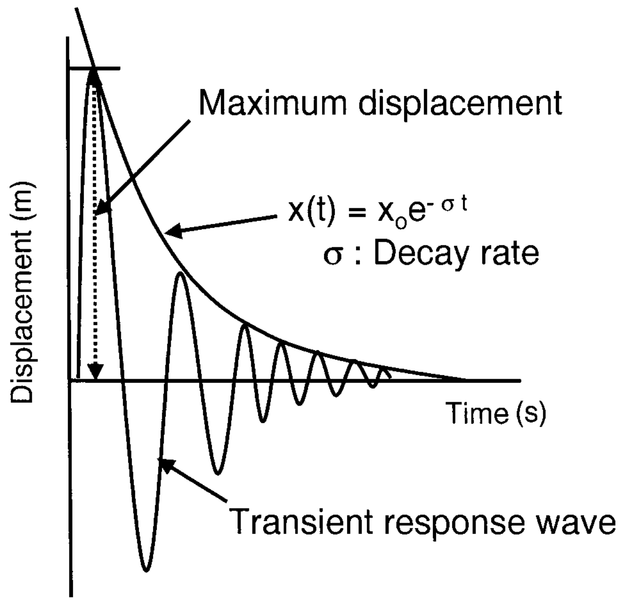

Fig. 6. Transient response diagram

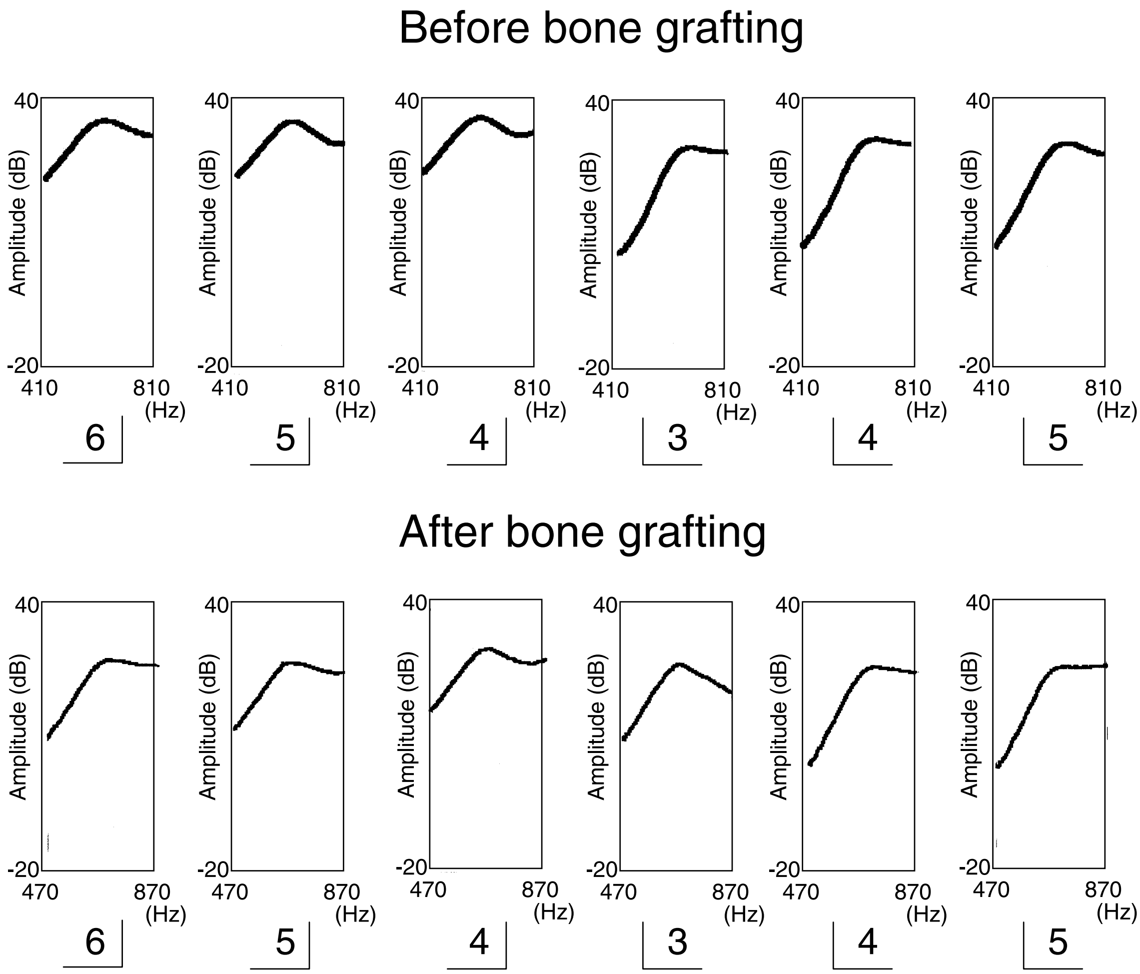

Fig. 7. Curve-fitted transfer functions before and after bone grafting at 6 different measurement teeth in subject A. One distinct resonance peak was showed in every function.

eight times to avoid the measurement error, afterwards the mean decay rate of the point was obtained. The DR before and after bone grafting in each subject were assessed as the average value for the dentition using Student's t-test ($p < 0.05$). The MDP value was automatically obtained from the transient response wave by the DAMPCAL software. Differences in the MDP between before and after bone grafting in each subject were assessed for each measurement point.

Results

Table 1 shows the natural frequency and curve-fitting frequency range of each subject. In subject A, to maintain a high error convergence rate, the frequency range for curve-fitting was set from 420 to 820 Hz before bone grafting and 470 to 870Hz after surgery. As a result, one distinct resonance peak was observed at 609.3 Hz before surgery and at 653.3 Hz after surgery (Fig. 7). In other subjects, one distinct resonance peak was observed before and after bone grafting, as in subject A. The modal shapes at the natural frequency of the maxillary dental arch in subject A before bone grafting at 6 time points of regular intervals during one period of vibration are shown in Fig. 8 and after bone grafting in Fig. 9. Before surgery, the MDA and mDA located inside the static maxillary dental arch moved outward at part Ⅰ. At part Ⅱ, both the MDA and mDA still moved outward, but the MDA was already located outside the arch. At part Ⅲ, the mDA still moved outward, but the MDA moved inward. A phase difference was distinctly observed at this part. At parts Ⅳ and Ⅴ, both the MDA and mDA moved inward, but the MDA moved faster. Finally, at part Ⅵ, the mDA still moved inward, whereas the MDA moved outward. A

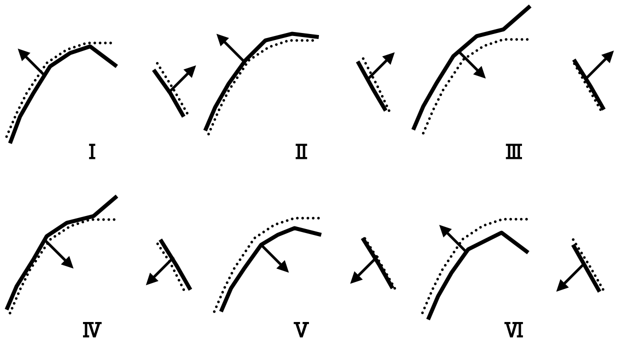

Fig. 8. Modal shapes before bone grafting of the maxillary dental arch in subject A. The dotted lines, solid lines and arrows in this Figure respectively represent the static dental arch, the vibrating dental arch and the direction of vibration.

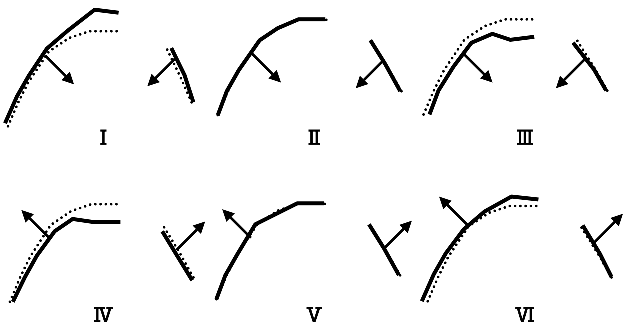

Fig. 9. Modal shapes after bone grafting of the maxillary dental arch in subject A. The symbols represented are the same as in Fig. 8.

phase difference was also observed at this part, as at part III. Through all the parts, the central incisor adjacent to the cleft showed the most conspicuous vibration. However, after bone grafting, there were no phase differences between the MDA and mDA at any of the parts. These changes in modal shapes before and after bone grafting were analogous in all subjects.

The mean ± SD of the DR of all subjects before and after bone grafting are shown in Table 2. The DR after bone grafting decreased significantly in subjects A and C, but in subjects B and D, it was significantly higher after surgery.

Table 3 shows the MDP of each tooth before and after bone grafting. In subject A, the MDPs of all teeth in the MDA decreased after surgery, especially in the left central incisor, which showed a drop from 278.7 to 79.8 μm. In subject B, only the MDP of the right central incisor showed a conspicuous decrease after surgery, from 61.3 to 4.3 μm. In subject C, only the MDPs of both central incisors conspicuously decreased after surgery, from 131.6 to 91.6 μm in the right, from 85.4 to 14.5 μm in the left. In subject D, there was no marked decrease after surgery.

Table 1. The curve-fitting frequency range and natural frequency of all subjects before and after bone grafting (Hz)

Subject		Curve-fitting frequency range	Natural frequency
A	Before	420 - 820	609.3
	After	470 - 870	653.3
B	Before	460 - 860	647.2
	After	460 - 860	643.7
C	Before	460 - 860	656.4
	After	435 - 835	610.3
D	Before	400 - 800	596.6
	After	350 - 850	571.4

Table 2. The mean ± SD of the DRs in all subjects before and after bone grafting ($\times 10^2$/s)

Subject	Before	After
A	4.71 ± 0.07	3.98 ± 0.07*
B	5.24 ± 0.05	5.41 ± 0.11*
C	7.15 ± 0.14	4.96 ± 0.08*
D	2.15 ± 0.03	4.83 ± 0.07*

* : p<0.05 Student's t-test

Discussion

Modal analysis is normally applied to rigid subjects in engineering fields. In the dental profession, this form of analysis has been similarly used for rigid subjects or subjects regarded as or assumed to be rigid. Inoue et al.[9] investigated the vibration effect of the metal framework design of maxillary partial dentures. Oki et al.[10] analyzed the vibratory characteristics of a metal obturator with a resin bulb, while Komin et al.[11] studied the effect of the soft lining material in the bulb on the vibratory properties of a metal obturator. Hanai[12] investigated the dynamic behavior of artificial abutment teeth with fixed splinting that simulated natural teeth. Hasegawa[13] evaluated the effects of different types of mouthguards on the modal shape and damping ratio of the human dry mandible. Ou et al.[14] studied the effects of mouthguard forms and materials on the vibration decay rate of the human dry skull.

Table 3. The MDP of each measurement point in all subjects before and after bone grafting (μm)

Subject	Measurement point	6⌋	5⌋	4⌋	3⌋	2⌋	1⌋	⌊1	⌊2	⌊3	⌊4	⌊5	⌊6
A	Before	95.6	96.7	103.2	77.2	158.2	165.2	278.7	*	5.2	16.4	5.5	
	After	19.1	17.9	20.4	15.5	30.7	98.6	79.8		12.1	11.8	12.2	
B	Before	6.7	5.9	7.8	5.0	*	61.3	38.4	14.3	5.7	4.4	6.3	7.9
	After	3.3	4.0	4.2	8.6		4.3	42.1	9.4	7.3	4.1	6.7	4.7
C	Before	10.0	20.3	3.4	2.5		131.6	85.4	*	23.9	38.7	30.8	18.6
	After	4.9	7.2	4.5	10.2		91.6	14.5		8.1	8.1	6.6	7.5
D	Before	27.1	24.5		18.3	31.8	26.1	42.3	*	7.5	9.0	9.4	9.4
	After	17.3	15.8		16.9	15.1	10.4	20.9		0.6	0.7	10.8	10.1

* Position of the cleft

Kurabayashi and Hojyo[15] investigated the effects of the attached gingiva on the modal shape and amplitude of maxillary dentition in cadavers.

However, there are still many difficulties with the application of modal analysis directly to the living human body due to the highly damping effect of the soft tissue that covers the bone and surrounds the teeth. Recently Kitazaki and Griffin[16] applied modal analysis directly to the living human body. In their study, the modal shape of the vertebral column was demonstrated by vibrating a chair on which the subject was seated and attaching sensors to the surface of the back skin. Du et al.[8] directly analyzed the maxillary dentition of normal human and CLP subjects. Their study showed the high reproducibility of the resonance frequencies of each measurement point and the clear possibility of curve-fitting for measured transfer functions of all measurement points. The transfer function obtained had a blunt resonance peak which coincided with that of the vertebral column but not with that of the metal framework. The modal shapes of maxillary dentition in normal human and CLP subjects were also demonstrated. To evaluate the effects of bone grafting on the maxillary dentition of CLP patients, modal shape, DR and MDP were investigated in this study.

The setting of a curve-fitting range is a significant factor in deciding whether the curve-fitting function is performed at a high error convergence rate. In this study, several curve-fitting trials were carried out for each dentition, and setting the curve-fitting range close to 400Hz, including the resonance peak, turned out to be the most appropriate.

As before, there was one resonance peak on the curve-fitted transfer functions after bone grafting. Considering the increase in the number of resonance peaks means the structure would have many chances to vibrate intensely, the maxillary dentitions after bone grafting have never become to be easier to vibrate than before.

The natural frequency increased in subject A after bone grafting, while it decreased in other 3 subjects. The natural frequency, theoretically, decreases with the increase of mass but increases with the rise of stiffness. In subject A, stiffness might influence on the natural frequency more than mass.

The modal shapes observed after bone grafting indicated that the impact was transmitted to the mDA through the bony bridge. The phase differences were eliminated. In other words, the vibration of the maxillary dentition may have synchronized with that of the maxillary bone although it was strictly separated from the bone by the periodontal ligament.

In the transient response simulation of this study, the intensity, direction and location of the impact force can be applied arbitrarily. The maximum biting force of the central incisor adjacent to the cleft in the unilateral cleft lip and palate patients was from 2.04 to 10.32 kgf[17]; thus, in this study, the defined force for the simulation was set at 5 kgf as the horizontal component of the biting force on each central incisor.

The DR is the function that demonstrates how vibration declines with the elapse of time, and a high DR indicates that the subject stops vibrating quickly. The maxillary dentition should, ideally, stop vibrating quickly; however, the effect of bone grafting on the DR of the maxillary dentition was not identical among the 4 subjects. As the DR of a structure depends on many factors including its shape, mass and stiffness, the variation of the results among 4 subjects may depend on the different proportion of volume or mass of the grafted bone to the maxillary bone.

In the MDP, there was severe dispersion between the anterior and posterior teeth in each dentition; thus we evaluated the differences between before and after bone grafting by each tooth. The highest value for MDP was 278.7 μm at the left central incisor of subject A before bone grafting. It was higher than the physiological horizontal tooth movement under the function that was up to 200 μm[18]. Furthermore, the MDP of the first molar in the MDA of subject A was also higher than the displacement during mastication reported by Miura et al[19]. However, after surgery, the MDP of the left central incisor decreased to 79.8 μm, within the range of physiological movement. The first molar showed the same result. In other subjects, a conspicuous decrease in the MDP was seen in the central incisors but not in the posterior teeth. The difference of MDP among the 4 subjects may depend on the difference of the size or form of the maxillary dental arch, maxillary bone, grafted bone and so on.

The results of this study suggest that if a fixed prosthesis across the cleft is set on the maxillary dentition before bone grafting, strain will be applied to the prosthesis due to vibration, which might make it more likely for the luting cement to shatter.

The results of this study indicate that an adhesive or pinledge bridge can be used in CLP patients after bone grafting, which has been not recommended for patients who have not undergone bone grafting. It also indicates that modal analysis may be used as a criterion for deciding on what prosthodontic treatment modality should be selected. In addition, modal analysis may also be used as a criterion for estimating the maturity of the bony bridge by observing the phase difference between the MDA and mDA on the modal shapes by measuring periodically soon after bone grafting.

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