Application of modal analysis to human subjects: comparison of healthy subjects and cleft lip and palate subjects

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To evaluate the vibrational characteristics of the maxillary arch, modal analysis was applied to human subjects. Twelve healthy human subjects and 2 cleft lip and palate (CLP) subjects with surgical failure in their cleft area were chosen for this study. The main measurement system was composed of an impact hammer, acceleration sensor, CF-6400 FFT Analyzer, PC-9821Xn personal computer, and Vibrant PC modal analysis software. The measurement points were established on 12 teeth between the upper first molars on both sides of the mouth in healthy subjects, and on 10 teeth in CLP subjects. In all subjects, one distinct resonance peak was observed in each transfer function at each measurement point. All of the transfer functions of a given subject strongly resembled each other in terms of shape. The amplitude and modal shapes of the maxillary arches of all the subjects were obtained by using a curve-fitting function in the software. In the healthy subjects, the maxillary arch expanded outward and shrank inward on vibration with no node after an impact. In the CLP subjects, the phase lag between the large and small segment was distinctly observed after an impact. In this study, the applicability of modal analysis for human subjects was demonstrated.

Key words: Vibration, Modal shape of maxillary arch, Resonance frequency, Phase lag, Cleft lip and palate

Introduction

Contact between teeth during mastication or occlusion causes them to vibrate; this vibration is transmitted to the jaw bone and other teeth with some modifications. Many studies evaluating the vibration characteristics of teeth have been performed to know the functional situation of teeth and other oral structures under functional loading. After static loading, the mobility of teeth was studied\textsuperscript{1-3}; and after dynamic loading, the resonance frequencies of teeth were calculated\textsuperscript{4-12}. Also modal analysis has been used to evaluate the vibration characteristics of extracted teeth, a human dry skull, and a mandible after receiving an impact\textsuperscript{13-18}. Modal analysis has made it possible to visualize modal shapes on the computer display, but it was applied to only a few teeth or half of a skull or mandible. Recently, Hasegawa\textsuperscript{19} applied modal analysis to a whole human dry mandible and evaluated the effect of different forms of mouthguards on modal shape and damping ratio after an impact. Furthermore, Ou et al.\textsuperscript{20} applied modal analysis to a human upper dry skull to analyze the changes in decay rate of vibration due to mouthguards following an impact. However, the results of these studies cannot be applied to the human body directly. Therefore,
consideration should be given to choose a human body as a subject. To date, there have been no studies that apply modal analysis to human subjects.

The purpose of this study is to demonstrate the applicability of modal analysis for human subjects to evaluate the vibration of the maxillary arch after an impact. Furthermore, we attempted to compare the amplitude of vibration at each measurement point and modal shapes of maxillary arches between healthy subjects and subjects with cleft lip and palate (CLP) to clarify the vibrational differences between healthy subjects and CLP subjects.

Materials and methods

I. Test subjects

Twelve healthy human subjects (7 males and 5 females) and 2 subjects with left unilateral cleft lip and palate (CLP) were selected for this study. The healthy subjects who had no malocclusion ranged in age from 24 to 28 years (mean, 25.9 years). The CLP subjects were 22 and 20 years old, and had completed their orthodontic treatment, but they did not undergo bone grafting to their cleft area (Table 1, Fig. 1–4). All subjects had given informed consent before participating in this study.

II. Measurement system and measurement points

An impact hammer (Dytran 5800-SL, Dytran Instruments Inc.) was used to tap the right central incisor of

<table>
<thead>
<tr>
<th>Subject</th>
<th>Sex</th>
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<th>Type of cleft</th>
<th>Missing teeth</th>
<th>Site of cleft</th>
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<td>22</td>
<td>L-CLP</td>
<td></td>
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</tr>
<tr>
<td>B</td>
<td>Male</td>
<td>20</td>
<td>L-CLP</td>
<td>2-2</td>
<td>1-3</td>
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</tbody>
</table>

* cleft

Fig 1. Intraoral palatal view of subject “A”. Surgical failure exists at the cleft area.

Fig 2. Intraoral frontal view of subject “A”.

Fig 3. Intraoral palatal view of subject “B”. Surgical failure exists at the cleft area.

Fig 4. Intraoral frontal view of subject “B”.
each subject as the exciting force point; and an acceleration sensor (NP-3210, Ono Measuring Co.), which was 5.84 mm in diameter and 3.81 mm in thickness, was affixed to the measurement point with utility wax. The data from both the hammer and the sensor were entered into a CF-6400 FFT Analyzer to calculate the transfer function at each measurement point. All transfer functions were downloaded to a personal computer, PC-9821xN (NEC Corp.), and modal shapes were obtained through the Vibrant PC modal analysis software (Marubeni Solutions Co.) (Fig. 5).

In this study, the measurement points were established on 12 teeth between the upper first molars on both sides of the mouth in healthy subjects and on 10 teeth in CLP subjects.

In this system, the coordinate values of each measurement point in the defined coordinate system (Fig. 6) must be input into the Vibrant PC software before the actual measurements. Therefore, we took upper jaw impressions of each subject to form casts. The values of each measurement point for each cast were measured by using a coordinate measuring machine, Micro Code CX (Mitutoyo Co.).

To the best of our ability, the sensor was placed on the buccal surface of the measurement tooth so that the base plane of the sensor was parallel to the Z axis in the defined coordinate system, as well as parallel to the line tangent to the maxillary arch at each given measurement tooth. All angles formed by the X axis and lines that intersect the X axis while running perpendicular to the base planes of the sensors at each of the measurement teeth must be entered into the Vibrant PC software. These angles were geometrically calculated from the projection of measurement points onto the X-Y plane (Fig. 7).

III. Procedure of measurement

The subjects sat in a dental chair and put their heads on the head rest so that their Frankfort planes were parallel to the floor. As the exciting force point, the right central incisor was tapped five times at each measure-
Fig 8. The sensor was placed on the measurement point, and the right central incisor was tapped as the exciting force point.

ment point in the direction parallel to the X axis and X-Y plane, while the sensor was moved through all measurement points one by one (Fig. 8).

The measurement frequencies existed within a 0–2000 Hz range, and the compliance (deformation/force) was used as the transfer function.

The compound average was calculated for the 5 transfer function measurements taken at each measurement point. Then 12 transfer functions from the healthy subjects, and 10 from the CLP subjects were transferred to the Vibrant PC modal analysis software and the modal parameters were calculated by means of the curve-fitting function in that software\(^{21,22}\). These modal parameters enabled the visualization of subject modal shapes on the computer display\(^{21}\).

IV. Experimental design

The reproducibility in this study

One 28 year old healthy male subject was chosen to confirm the reproducibility in the measurement system of this study. The measurements were repeated 3 times on the same day, then these measurements were repeated again on two different days and at the same time as the day before. The mean, standard deviation and coefficient of variation of the resonance frequencies at each measurement point were calculated.

Measurements of 12 healthy subjects and 2 CLP subjects

Measurements were performed on 12 healthy subjects to demonstrate the applicability of modal analysis for human subjects. Twelve transfer functions from the FFT Analyzer were processed with the modal analysis software; amplitudes corresponding to each measurement point, and modal shapes were obtained through the curve-fitting function.

After the measurements were taken for the healthy subjects, the measurements of the 2 CLP subjects were attempted. The amplitudes and modal shapes were compared between healthy subjects and CLP subjects.

Results

I. The reproducibility in this study

One distinct resonance peak was observed in each transfer function. The mean of the resonance frequencies at each measurement point ranged from 535.1 Hz

<table>
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<td>572.0</td>
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<td>535.0</td>
<td>535.0</td>
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<td>555.0</td>
<td>557.0</td>
<td>565.0</td>
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<tr>
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<td>556.0</td>
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<td>555.0</td>
<td>555.0</td>
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<td>C.V.</td>
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to 565.9 Hz (Table 2). The coefficient of variation of 9 resonance frequencies at each measurement point ranged from 0.03% to 2.0%.

II. Measurements of 12 healthy subjects

One distinct resonance peak was observed in each transfer function of all the healthy subjects, and the transfer functions of a given subject all strongly resembled each other in terms of shape. Figure 9 shows the transfer functions at 6 of the 12 measurement points of subject “d”. Curve-fitting could be performed for all the subjects. The resonance frequencies after the curve-fitting of each of the healthy subjects were between 546.7 Hz and 785.5 Hz (Table 3). Table 4 shows the amplitude at each measurement point. The amplitude was maximum at the right central incisor and tended to become smaller as the measurement point was set further back.

Figure 10 shows modal shapes of the maxillary arch at 6 different times during one period of vibration for subject “d”. From this animation, it was observed that the maxillary arch expanded outward and shrank inward on vibration with no node after an impact. The maxillary arch of other subjects vibrated with almost the same movement as subject “d”.

III. Measurement of CLP subjects

Each transfer function of both subjects had one distinct resonance peak and the transfer functions of a given subject all strongly resembled each other in terms of shape. Figure 11 shows the transfer functions at 6 of the 10 measurement points of subject “A”. The resonance frequencies after the curve-fitting of the CLP subjects were 614.7 Hz and 597.9 Hz, and these measurements were within the range of the healthy subjects (Table 5). The amplitude was maximum at the left central incisor and tended to become smaller as the measurement point was set further back in the large segment of both subjects (Table 6). The amplitudes in the small segment were much smaller than those in the large segment.
Table 4. The amplitude of vibration at measurement point of healthy subjects (10^-6 m/Kgf)

<table>
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</tbody>
</table>

Fig 10. Modal shapes at 6 different times for subject "d". The maxillary arch expanded outward and shrank inward on vibration with no node.

Figure 12 shows modal shapes of the maxillary arch at 6 different times during one period of vibration of subject “A”. Both segments expanded outward and shrank inward on vibration during one period. However, a difference between the movements of both segments was observed. From graph I to graph III, both segments moved inward, and the small segment was located at its innermost position in graph III. From graph III to graph IV, the large segment still continued to move inward. On the other hand, the small segment had already started to move outward at this stage. The phase lag at this time was observed distinctly between these two segments. Figure 13 shows modal shapes of the maxillary arch at 6 different times during one period of vibration of subject “B”. The maxillary arch of subject “B” vibrated with the same kind of movement as subject “A”, and the phase lag was distinctly observed between these two segments at the time between graph III and graph IV.

Discussion

In a recent study, Hasegawa applied modal
Fig 11. Transfer functions at 6 different measurement points of subject “A”. They strongly resembled each other in terms of shape.

**Table 5.** The resonance frequencies of CLP patients

<table>
<thead>
<tr>
<th>Subject</th>
<th>Frequencies (Hz)</th>
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<tbody>
<tr>
<td>A</td>
<td>614.7</td>
</tr>
<tr>
<td>B</td>
<td>597.9</td>
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</table>

analysis to the whole human dry mandible and obtained modal shapes of the whole mandible using the Vibrant PC computer software. It was the first study which applied modal analysis to a whole human dry mandible. After that, Ou et al.20 applied modal analysis using the same computer analyzing software to a human dry skull to investigate the effects of mouthguard designs and mouthguard material on vibration decay rate. In these two studies, the applicability of modal analysis for a human dry mandible or a human dry skull was demonstrated. But the results of these studies cannot be applied to the human body directly. Therefore, the application of modal analysis for human subjects should be considered. However, no study has applied modal analysis to a human subject directly, so the applicability of modal analysis for human subjects needs to be demonstrated.

In the first experiment, each transfer function at different measurement points of the human subject had one distinct resonance peak, and all of the transfer functions of a given subject strongly resembled each other. Also the coefficient of variation of the resonance frequencies at each measurement point ranged from 0.03% to 2.0% of the average, which was considered to be quite small in the experiment using human subjects. From these results, an adequate reproducibility of this measurement system was demonstrated.

In the second experiment, the transfer functions at each measurement point of healthy human subjects were entered into a personal computer, and they were

**Table 6.** The amplitude of vibration at measurement point of CLP patients (10⁻⁶m/Kgf)

<table>
<thead>
<tr>
<th>Measurement point</th>
<th>6</th>
<th>5</th>
<th>4</th>
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<tr>
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</tbody>
</table>
Fig 12. Modal shapes at 6 different times for subject "A". Both segments expanded outward and shrank inward on vibration, but from graphs III to VI, a phase lag was observed between both segments.

Fig 13. Modal shapes at 6 different times for subject "B". Both segments expanded outward and shrank inward on vibration, but from graphs III to IV, a phase lag was observed between both segments.

adjusted with the curve-fitting function in the software. Based on the curve-fitting results, modal parameters (Modal mass (M), Modal damper (C) and Modal stiffness (K)) were calculated. Modal analysis could not be performed without these modal parameters. If any transfer function did not fit the curve-fitting results during the calculation, these parameters could not be obtained. In this study, all transfer functions fit the curve-fitting results well, although they varied within a range of approximately
30 Hz, and the modal shapes of each subject could be visualized (Fig. 14). From these results, it was demonstrated that curve-fitting could be performed on the transfer function from a human subject. Therefore, the applicability of modal analysis to the human subject was clarified.

In the healthy subjects, the amplitude was maximum at the right central incisor, the exciting force point. On the other hand, in the CLP subjects the amplitude was maximum at the left central incisor. Figure 15 shows the average amplitude percentage, (the amplitude of the right central incisor was designated as 100%), at each measurement point of the healthy subjects and the amplitude percentage of the CLP subjects. From this figure, it was observed that the amplitude percentage became smaller as the measurement point was set further back in the healthy subjects. It can be explained that the energy of an impact diffused backward in the healthy subjects. However, the amplitude percentage at the left central incisor of the CLP subjects was much larger than those recorded in the healthy subjects. The left central incisor of the CLP subjects was located at the free end of the large segment. This result corresponds to the fact that such
a location has a higher potential to move more easily than other locations in the segment. On the contrary, a very small amplitude percentage was observed at the canine in the small segment of the CLP subjects, which is also located at the free end of the small segment. It can be explained that the total impact could not be transmitted to the small segment, because there was no bone connection at the cleft area and the impact energy could be absorbed by the soft tissue around that area. Furthermore, an obvious phase lag between both segments was observed in the CLP subjects. It can be considered that the impact could not be transmitted directly through the alveolar bone to the small segment because of a defect in the area of the cleft, and, therefore, it took more time to reach the small segment.

Regarding the prosthodontic treatment for the CLP patients, fixed splinting across the cleft is an optimal solution to prevent a relapse after orthodontic and surgical treatment. Our study indicates that a stress or distortion generated by the phase lag may concentrate at the base of the cleft from where the maxillary jaw bone is split. Therefore, some appliance that connects both segments to protect the maxillary jaw bone should be considered. The fixed splinting of both segments is a desirable solution from the standpoint of protection and preventing relapse. Also, bone grafting to the cleft area is another solution. Further studies are needed to evaluate the effect of these treatments on vibration characteristics, and our method is considered to be very useful for that purpose.

Our method is applicable not only for CLP patients, but also for many other fields. In sports dentistry, the effect of mouthguards on protecting the teeth and jaw bone of a user by absorbing impact can be evaluated directly in a human subject. Also, in prosthodontics, the effects of denture design on the vibration characteristics of a human subject can be evaluated. This is the first trial to apply modal analysis to human subjects. Therefore, additional studies will be needed to make further progress in these methods.

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References


