Development of a new evaluation method for orthodontic forces generated in individual patients

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Numerous experimental studies have examined how much orthodontic force is needed to move teeth more smoothly; however, no reports have examined this clinically in individual, living subjects. We aimed to develop a method for quantifying the force exerted on individual teeth by an orthodontic wire to measure how loads placed on crowded teeth change dynamically over time. Accordingly, we fabricated a series of dental casts of patients undergoing orthodontic treatment (using optical impressions and a three-dimensional printer), fitted these models with nickel-titanium wire, and subjected them to bending load tests. During leveling, nickel-titanium wire is generally considered to exert a weak force due to its low elastic modulus, with a weak orthodontic force applied over a long period of time due to its superelasticity; however, we found that the actual energy exerted by nickel-titanium wire is also largely affected by other factors (e.g., amount of crowding).

Keywords: Bending load test, Leveling, Nickel-titanium wire, Optical impression, Orthodontic force

INTRODUCTION

During orthodontic treatment, teeth are moved by the force (stress) produced as a deformed wire tries to regain its original shape. Nickel-titanium (Ni-Ti) wire is commonly used for leveling, which is the first step in orthodontic treatment. The low elastic modulus and superelasticity of the Ni-Ti alloy are utilized to apply a constant, weak load on the teeth⁵. This physical load causes bone remodeling in the surrounding alveolar bone by changing the blood circulation in the periodontal membrane and promoting metabolic activity in various types of cells.

Tooth movement is caused by the resorption and formation of alveolar bone, and maintaining an appropriate level of force is essential to the success of orthodontic therapy⁶. During the orthodontic treatment process, periodontal tissues are remodeled in response to a variety of mechanical stresses (e.g., compressive and tensile forces). New blood vessels that form inside the periodontium as it undergoes remodeling serve many important roles, supplying hematopoietic stem cells, as well as nutrients and oxygen, to remodeled tissue via the bloodstream³⁵. Continued application of a compressive force enhances vascular endothelial growth factor production by periodontal ligament cells (PDLs) and angiogenic activity⁰; this “vascular activation” process via compressed PDLs is essential for periodontal tissue remodeling. However, excessive loading can impede the blood circulation in tissues, causing hyalinization.

These phenomena render it critical to determine the mechanical stresses (such as compression and expansion) on endothelial cells and ensure that the force is sufficient to stimulate cellular activity, but not so strong as to completely block the PDL vasculature.

Numerous studies have been published on the optimum orthodontic force needed to achieve smoother, painless tooth movement⁷. However, determining the optimum orthodontic force for individual patients in a clinical setting requires a more detailed qualitative assessment of the orthodontic force exerted on each dental arch and the relationship between this orthodontic force and the physiological characteristics of each patient (e.g., bone density and bone metabolism). Nevertheless, there are no published studies examining this topic in individual living subjects in an actual clinical setting, potentially because each case of malocclusion differs, and a method that accurately measures changes in the force applied to individually moving teeth is lacking. Specifically, the orthodontic force applied by a wire is commonly measured using the three-point bending test⁸ or by using force sensor⁹ or strain gauges¹⁰,¹¹. However, the three-point bending test only measures the force applied to the center of three adjacent teeth and when used alone cannot reveal the effect of the position of either adjacent tooth. Additionally, the method of attaching a strain gauge to a dental cast using metal pillars can only measure the positional relationship at a single time point during long-term treatment⁰,¹¹.

Therefore, the present study was conducted to develop a new method for quantifying the force exerted on individual teeth by an orthodontic wire in order to
determine how the force changes dynamically in the living body over time. To accomplish this, we fabricated a series of dental casts by means of optical impressions and a three-dimensional (3D) printer to accurately replicate the intraoral structures of patients undergoing orthodontic treatment; we then fitted these models with Ni-Ti wire and subjected them to bending load tests.

MATERIALS AND METHODS

Materials

We studied three adult patients who visited the Department of Orthodontics at Showa University Dental Hospital for non-extraction orthodontic treatment (three women, mean age: 28.6±10.1 years). The amount of dental crowding in each patient was 0.0–4.0 mm (mild crowding), 4.0–8.0 mm (moderate crowding), and 8.0 mm or more (severe crowding). Subjects selected for this study met the following criteria: crowding with a total arch length discrepancy of −8.0 mm or less; non-extraction treatment decided at the orthodontic diagnosis; absence of congenital diseases that could affect jaw growth or malocclusion (e.g. a cleft lip and palate); and no history of systemic disease.

At each visit from initiation to the completion of the leveling process, 3D digital data of the maxillary dental arch were obtained by using an optical impression-taking instrument (3Shape TRIOS Intraoral Scanner, 3Shape, Copenhagen, Denmark). Stereolithographic (STL) data acquired from optical impression-taking were used to measure the changing force applied on one crowded tooth and the dynamic movement of that tooth in three dimensions until leveling was complete.

This study was approved by the Institutional Review Board of Showa University Dental Hospital (approval number: SUDH0017).

Methods

1. Experiment I: Creating the dental casts for the bending load test

1) Generating the dental casts

STL data of the maxillary dental arch were acquired by optical impression-taking at each visit. The STL data were obtained at the initiation of leveling (STL-1) as well as at the second (STL-2), third (STL-3), and fourth (STL-4) leveling visits. These visits were scheduled roughly 30 days apart. The period from STL-1 to STL-2 comprised stage 1, the period from STL-2 to STL-3 comprised stage 2, and the period from STL-3 to STL-4 comprised stage 3 (Fig. 1). For each of the three patients, data were collected for one crowded anterior tooth: the target tooth was the upper-left central incisor (UL1) for the patient with severe crowding, the upper-right lateral incisor (UR2) for the patient with moderate crowding, and the upper-left lateral incisor (UL2) for the patient with mild crowding.

The STL data were used to create dental casts reproducing the patient’s teeth, which were used in the bending load test. Geomagic FreeForm Touch X CAD software (3D SYSTEMS, Rock Hill, NC, USA; hereafter “FreeForm”) was used to trim the brackets on the test teeth. Subsequently, a high-precision 3D printer (AGILISTA-3200, KEYENCE, Osaka, Japan) was used to produce dental casts of the patient’s teeth using epoxy resin (Fig. 2). Indenters used in the bending load test were created using the same method (Fig. 3).

2) Installing the brackets and archwire

For the patients in this study, we used zirconia self-ligation brackets (MANEWVER®, GC ORTHOLY, Tokyo, Japan) which produce a lower frictional force than conventional brackets12). After using a 3D printer to produce dental reproduction casts for the bending
load test (Fig. 4a), a carbide bar was used to grind the brackets away from the teeth that had not been trimmed (Fig. 4b). Brackets were then bonded onto the ground surfaces of the printed model (Fig. 4c) to accurately reproduce the position of the actual brackets (Fig. 4d). Using the same method, a bracket was bonded onto the indenter produced for the bending load test (Fig. 3c), and a 0.012-inch Ni-Ti archwire (ORTHOLINE ARCHWIRE, SE200, MART35, Shofu, Kyoto, Japan) was set in the brackets. We used a Ni-Ti archwire that did not exhibit the temperature sensitivity of a Ni-Ti alloy wire, with added copper and full transformation into austenite by heating at 27.0°C.

2. Experiment II: Analysis of the dynamic positioning
1) Measurement of the distance moved
Tooth movement was assessed at each visit by superimposing STL data in a 3D analysis using Avizo Ver 6.3.1 (FE, Hillsboro, OR, USA). Superimposition was achieved by selecting 40 points on the palatal rugae, in a stable region of the hard palate, and superimposing the STL data using these points. Arbitrary points were
selected on enlarged images of the superimposed data, and the distance the brackets had moved was measured (Fig. 5). Superimposition of the STL data and the measurement of the distance moved were performed three times by the same practitioner to eliminate inter-observer error, with a 1-week interval between each measurement.

2) Verification of the superimposition accuracy
The accuracy of the maxillary arch superimposition was verified by superimposing two sets of the same STL data (STL-1) (Fig. 6) and assessing the accuracy of the combined image. The same STL data were superimposed 30 times by the same evaluator, and the resulting superimposition error was 104.0 (±114.0) μm.

3. Experiment III: Bending load testing method
1) Bending load test
Bending load testing of the wire was performed using a universal testing machine (Type 5500R, Instron, Norwood, MA, USA), with the dental casts bonded to the platform using super glue. The dental models had sufficient flexural strength such that they did not warp during the bending load tests. Deflection and loading-unloading data were acquired by lowering the indenter at a crosshead speed of 0.50 mm/s, applying the same amount of deflection at each treatment stage. Subsequently, the indenter was retracted at the same speed until an unloaded state was achieved, with zero deflection. To simulate intraoral conditions during the bending load test, the testing environment was maintained at 37°C and the dental reproduction casts and brackets were sprayed with artificial saliva (Saliveht Aerosol, TEIJIN PHARMA, Chiyoda, Japan) that was pre-warmed to 37°C in a specimen incubator.

The bending load test started with the Ni-Ti wire in its natural position, as attached (Fig. 7a), and the maximum deflection point was the point at which the bracket on the indenter contacted the tooth at the...
measurement site (Fig. 7b). The archwire was then unloaded, returning the indenter to the starting point (Fig. 7c). The indenter then moved perpendicularly to the tooth at the measurement site (Fig. 7d).

The resilience exerted by the superelasticity of the Ni-Ti wire is represented by the area under the unloading curve. The orthodontic force (resilience) exerted in each dental model can be considered as the integral of the distance moved between stages, from the starting point of the bending load test, as measured on the dental cast. Image processing software (ImageJ) was used to calculate the number of shaded pixels at the measurement site, corresponding to the elastic energy (resilience), for comparison between stages. A typical loading-unloading curve and the corresponding resilience (number of shaded pixels) are shown in Fig. 8.

**Statistical analysis**

Data are shown as the mean±standard deviation. Mean values were compared using a paired one-way analysis of variance, followed by Tukey’s method for multiple comparisons. We used a significance level of $\alpha=0.05$ (two-sided); $p$-values<0.05 were considered statistically significant. Statistical analyses were performed using JMP* 15 (SAS Institute, Cary, NC, USA).

**RESULTS**

### Measurement of the distance moved

In the patient with mild crowding, the distance moved was 0.50 mm in stage 1, 0.42 mm in stage 2, and 0.34 mm in stage 3. In the patient with moderate crowding, the distance moved was 0.69 mm in stage 1, 1.14 mm in stage 2, and 0.57 mm in stage 3. In the patient with severe crowding, the distance moved was 0.20 mm in stage 1, 0.56 mm in stage 2, and 0.85 mm in stage 3 (Table 1, Fig. 9).

### Measurement of the changing load

In the patient with mild crowding, the resilience (number of shaded pixels) was 16,232 ($\pm$1,543) in stage 1, 5,051 ($\pm$653) in stage 2, and 3,602 ($\pm$472) in stage 3 (Fig. 10a). There was a significant difference in resilience between stage 1 and stage 2, and between stage 1 and stage 3 (Fig. 9a).

In the patient with moderate crowding, the resilience was 39,609 ($\pm$7,404) in stage 1, 39,698 ($\pm$7,698) in stage 2, and 17,031 ($\pm$3,085) in stage 3 (Fig. 10b). There was a significant difference in resilience between stage 1 and stage 2, and between stage 2 and stage 3 (Fig. 9b).

In the patient with severe crowding, the resilience was 19,265 ($\pm$3,593) in stage 1, 45,888 ($\pm$3,852) in stage 2, and 40,460 ($\pm$3,475) in stage 3 (Fig. 10c). There was a significant difference in resilience between stage 1 and stage 2.

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**Table 1  Measurements of tooth movement at each stage obtained by superimposing the STL data**

|                | stage 1 (mm) | stage 2 (mm) | stage 3 (mm) |
|----------------|--------------|--------------|--------------|
| Mild crowding  | 0.50*        | 0.42*        | 0.34*        |
| Moderate crowding | 0.69*     | 1.14*        | 0.57*        |
| Severe crowding | 0.20*       | 0.56*        | 0.85*        |

*ICC>0.8*
Fig. 10 Loading-unloading curves obtained from the bending load test.

a: Mild crowding: ① stage 1; ② stage 2; ③ stage 3. b: Moderate crowding: ① stage 1; ② stage 2; ③ stage 3. c: Severe crowding: ① stage 1; ② stage 2; ③ stage 3. STL, stereolithographic; STL-1, first visit; STL-2, second visit; STL-3, third visit; STL-4, fourth visit.

DISCUSSION

The properties of Ni-Ti render it difficult to represent resilience as a formula. In the present study, we developed a method for measuring the force applied to individual teeth, as well as the dynamic location of a single crowded tooth over time, and used ImageJ processing software to determine and compare the elastic energy in terms of the number of shaded pixels. During leveling, the Ni-Ti wire is considered to exert a weak force due to its low elastic modulus, applying a weak orthodontic force over a long period of time due to its superelasticity; however, we showed that the actual energy exerted by the Ni-Ti wire is also largely affected by other factors, including the amount of crowding, the layout and relative positions of existing teeth, and the crowding of surrounding teeth. Orthodontic wire is meant to subject the teeth to mechanical stress continuously over the course of treatment. In our bending load tests, we observed that the forces exerted by the Ni-Ti wire decreased in magnitude as the unloading continued. Similar behavior is seen in clinical settings: dentists fit the wire to apply a constant load, which decreases over time.

stage 2, and between stage 1 and stage 3 (Fig. 9c).
time, as the associated teeth move. The dynamic nature of this behavior guided our decision to conceptualize the orthodontic force in terms of resilience, instead of the vertical (axial) load, in the present study.

In the patient with mild crowding, the resilience and distance moved were largest in stage 1, likely because the crowding decreased in stages 2 and 3. The mildness of the tooth crowding likely allowed for early tooth movement, with leveling progressing smoothly. In the patient with moderate crowding, the resilience was almost identical in stage 1 and stage 2; however, the distance moved was greater in stage 2, likely because the surrounding teeth were less crowded in stage 2, and the force of the Ni-Ti wire was less likely to be lost to the brackets on either side of the target tooth. Furthermore, the slight increase in the dental arch width that accompanied the improvement in crowding likely allowed the target tooth to move to the labial side. Both the load and distance moved were smaller in stage 3 because the crowding was already reduced to a mild level. Note that in stage 1, the tooth was subjected to a large load, yet moved only a short distance; in stage 2, the displacement was greater despite the smaller load. Hence, the resilience values derived for these two stages (i.e. from the loading-unloading curves) were very similar (see Fig. 10b).

In the patient with severe crowding, the resilience was smallest in stage 1, likely because the excessive crowding by surrounding teeth restricted the movement. Although the distance moved was smaller than that in stage 3, the resilience was largest in stage 2, likely because movement was impaired by severe crowding, despite the large force applied to the tooth. Although the resilience was smaller than that in stage 2, the distance moved was the greatest in stage 3, indicating that tooth movement was most efficient in stage 3.

The above findings reveal that a large degree of crowding impairs tooth movement and results in a large amount of friction between the wire and bracket slots, preventing the smooth movement of the wire through adjacent brackets, and thereby preventing the wire from exerting a continuous weak load. This supports the findings of a previous study of the effects of bracket friction on orthodontic force. The frictional force between the bracket slots and archwire is likely affected by the severity of crowding, and when this frictional force is excessive (i.e., a frictional/orthodontic force ratio exceeding 1.0), it reportedly restricts the sliding mechanics of the archwire through the bracket slots. Lubrication is an important factor in reducing friction between the archwire and bracket slots. Consequently, in this study we used artificial saliva, pre-warmed to 37°C in a specimen incubator, for lubrication. We also used zirconia self-ligation brackets, which produce a lower frictional force than conventional brackets.

On the other hand, as the leveling proceeds, the overall amount of crowding in the dental arch decreases, and friction between the bracket and wire decreases over time. Therefore, as time passes from the initial state, the friction restraining the movement of the wire through the bracket slots is reduced. This allows the wire to pass through the brackets without resistance and to more effectively exert force on crowded teeth. Thus, a weaker orthodontic force is more easily applied. In other words, the Ni-Ti wire can exert the characteristic weak elastic force it applies when returning to its normal shape from a high degree of bending deflection. However, as leveling progresses to a point of almost no crowding, the 0.012-inch Ni-Ti wire will apply very little orthodontic force. This study confirmed that, in patients with a relatively small amount of crowding (mild or moderate crowding), Ni-Ti wire with unchanging thickness cannot continue to apply sufficient orthodontic force as the amount of crowding improves. Practitioners must increase the wire size as the amount of crowding changes, and finer improvements in crowding require skilled judgments regarding the wire material and sizing. The force applied to the teeth changes substantially depending on how the treatment progresses and the amount of crowding in an individual patient. Physics-oriented experiments measure loads at a single point under static conditions, but in a clinical setting, such loads are not applied consistently.

Ni-Ti alloy wire is commonly used for the initial leveling step in orthodontic treatment. Compared to stainless steel and other types of wire that exhibit normal elasticity, Ni-Ti wire offers the advantage of exerting a constant and moderately low orthodontic force during the tooth movement process. The three-point bending test is a typical physics-oriented test used to study Ni-Ti alloy wire, and previous studies using this test revealed a horizontal region in the loading-unloading curve of Ni-Ti alloy wire, thereby showing that its superelasticity produces an almost constant load over a wide range of deformation. This allows for a large amount of bending deflection in the Ni-Ti alloy wire at a low elastic modulus. The force exerted by the Ni-Ti alloy wire in the process of recovering from this bending deflection is utilized as the orthodontic force.

A previous report showed that the use of excessive force resulted in significantly more cases of orthodontically induced inflammatory root resorption than the use of mild force. Even when the wire size is not changed, the force applied to each tooth may vary depending on the amount of crowding and the position. Therefore, optimum loading requires careful consideration of the malocclusion state and pathological status of each patient, with careful 3D positional analysis and material selection.

Overall, this study measured tooth movement based on STL data obtained by optical impression-taking. A 3D printer was used to produce a series of dental casts from the STL data of intraoral scans taken during ongoing orthodontic treatment, and the changing load that was actually applied to individual teeth was measured by performing bending tests on a wire attached to these models. Results obtained using this new method suggest that the load exerted by orthodontic appliances varies depending on the amount of crowding that is present. Evaluating individual patients using this method, which combines bending tests and 3D data, can allow for highly...
predictable orthodontic treatment.

CONCLUSIONS

Physics-oriented experiments measure single loads applied under static conditions. In this study, we used 3D data to generate an accurate reproduction of the actual intraoral conditions in patients undergoing treatment; this allowed us to measure changes in orthodontic force applied in living subjects. We found that single loads are not necessarily applied consistently in a clinical setting. Based on our results, we suggest that orthodontists should carefully consider the state of malocclusion, crowding, and pathological status of each patient, and perform careful 3D positional analysis and material selection to ensure optimal loading throughout treatment.

CONFLICTS OF INTEREST

The authors declare that there are no conflicts of interest associated with this work.

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