In orthodontic treatment, it is critical to apply the optimal force to the brackets on each tooth to ensure effective tooth movement and reduce discomfort due to the biological reaction of the periodontal tissue. Treatment using contemporary edgewise appliances is widely accepted in orthodontics. For the initial and alignment phases of orthodontic treatment using contemporary edgewise appliances, the shape memory and super-elastic properties of nickel-titanium alloy archwires are thought to correspond with physical properties to provide light continuous force for tooth movement\(^1\); therefore, these wires have become widely accepted\(^2,3\). These physical properties of nickel-titanium alloy archwires have been tested using a three-point bending machine, in which the wire is pushed and deflected by a rod and the force from the wire produced at a single point is measured\(^2,4,5\).

The following factors are thought to affect the force magnitude at each tooth: the ligation method used for the archwire\(^6-12\); the diameter of the archwire\(^13\); and the inter-bracket distance\(^7\).

In traditional or standard edgewise brackets, the archwire is ligated to the bracket using stainless steel ligature wires. However, ligation using wires requires longer chair time, and requires greater investment in staff training\(^14\). As clinicians generally prefer a simplified treatment method that reduces chair time, the ligation method using elastic module became popular with the increasing use of contemporary preadjusted edgewise brackets. Further attempts to reduce chair time for ligating wire have been made. The first self-ligating bracket, the Russel attachment, was invented in the 1930s\(^15\). Several kinds of self-ligating brackets became commercially available during the 1980s and 1990s\(^16,17\), and have become used in clinical practice today\(^18\), however, the clinical advantages of using self-ligating brackets is still controversial despite the fact that they significantly reduce ligating time. Recently, force magnitudes of nickel-titanium alloy archwires with different ligation methods have been compared using a modified three-point bending test. Brackets were bonded to a metal block\(^6-8,13\) or resin formed model\(^9,13\) and the force from the ligated and deflected nickel-titanium alloy archwires were measured at a single point. Significant differences in the force magnitude from the archwire were found when using a stainless steel ligature, elastic module, and the self-ligating method\(^6-8,13\).

Nickel-titanium alloy archwires of 0.014 or 0.016 inch (0.36 or 0.41 mm) diameters are frequently used for the initial stage of orthodontic treatment since these smaller diameters provide lighter force, thus reducing patients’ discomfort. However, the selection of an archwire and archwire size depends on the type of the patient’s original malocclusion, the clinician’s educational background, and the appliance system being used. Although variation exists, Lombardo \textit{et al.}\(^13\) compared the force magnitude of 5 sizes of nickel-titanium alloy round archwires and observed an approximately 50% increase in the force magnitude when the diameter increases 0.002 inch. Since they measured the force at a point of an archwire, the magnitude of force at several different points as force delivery could not be clarified. In addition, changes in force delivery by the effect of different archwire sizes also remain unclear.
Badawi et al.\textsuperscript{10} incorporated 6-axis force sensors into a new measurement device called the Orthodontic Simulator (OSIM). This device uses metal blocks as simulated teeth that are aligned into a model of a maxillary dental arch. Each metal block can be moved horizontally and vertically to simulate tooth displacement, thus allowing the measurement of the force from a nickel-titanium alloy archwire delivered to several metal blocks. Fok et al.\textsuperscript{11,12} also used OSIM to simulate maxillary high canine malocclusion and compared the force from a nickel-titanium alloy archwire delivered to several when using elastic ligation and self-ligation. However, to date, no study has determined the force distribution in the mandibular arch.

Inter-bracket distance is generally much smaller in the mandibular arch than in the maxillary arch, and this may affect the force magnitude. Although various crowding patterns can be observed in clinical cases of malocclusion, crowding of the mandibular anterior teeth is a common problem in orthodontic patients. In particular, mandibular lateral incisor linguoversion is reported to be a major pattern encountered in Japanese orthodontic patients\textsuperscript{19}.

Even in a single tooth displacement, such as mandibular lateral incisor linguoversion, continuous archwires are ligated to the edgewise brackets, and the archwire provides force to not only the displaced lateral incisor bracket, but also to the other incisor brackets. Therefore, to clarify the force magnitudes delivered to the 4 mandibular incisors, it is necessary to perform measurements with a multi-sensor device.

The present study used a multi-sensor measuring system to compare the force magnitudes delivered by nickel-titanium alloy archwires to each mandibular incisor bracket using two ligation methods and two archwire sizes in a simulation of mandibular right lateral incisor linguoversion.

MATERIALS AND METHODS

A newly developed multi-sensor measuring system (Fig. 1) was used to measure the force delivered to the 4 incisor brackets\textsuperscript{20}. In this system, 14 metal blocks were aligned to coincide with the averaged mandibular arch form of the Japanese normal occlusion\textsuperscript{21}. Four six-axis force sensors (Fig. 1a) were connected to four incisor metal blocks that represented the 4 mandibular incisors: the right lateral (42), the right central (41), the left central (31), and the left lateral (32) incisors. Micrometers (Fig. 1b) were used to adjust the position of the metal blocks in a labio/buccolingual direction, and a laser sensor fixed to the system allowed the amount of displacement of each metal block to be determined with a resolution of 0.001 mm, thus the operator was able to consistently create simulations of a labially or lingually displaced tooth by adjusting position of the metal blocks. Orthodontic brackets made of 17-4 stainless steel with a 0.022\texttimes{}0.027 inch slot (Damon Q,Ormco, Orange, CA, USA) and molar tubes (peerless cast buccal tube, Ormco, Orange, CA, USA) were then welded onto the labial/buccal surface of the blocks. The system is maintained at a consistent temperature of 37°C in a chamber.

The coordinate system of each tooth is as follows. The X-axis shows the labio/buccolingual direction (lingual: positive, labial/buccal: negative). The Y-axis shows the horizontal direction (right: positive, left: negative), while the Z-axis shows the extrusion/intrusion direction (extrusion: positive, intrusion: negative). The values of the X, Y, and Z coordinates could also be exported from the system in Comma Separated Values (CSV) format for analysis.

A perfectly aligned arch form was initially created using a guide wire. Then, the position of the metal blocks was adjusted until the force of the X, Y, and Z coordinates from the 0.017\texttimes{}0.025 inch stainless-steel guide wire

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**Fig. 1** Upper view of the multi-sensor measuring system.
(a): Six-axis force sensors connected to the metal blocks representing the 4 mandibular incisors measure the force delivered to the brackets welded to the blocks. (b): Micrometers used to adjust the positions of the metal blocks. The horizontal and vertical positions of each tooth could be changed in 0.001-mm increments to simulate the mandibular dental arch and tooth displacement. (c): Enlarged view of metal blocks aligned to Japanese normal occlusion and right lateral incisor displaced 2.0 mm lingually.
ligated to the brackets was less than 0.2 N. The same procedure was then repeated using a 0.019×0.025 inch stainless-steel guide wire. In a previous study with three-point bending test, displaced maxillary lateral incisor and the adjacent incisor and canine would be simulated. In this method, the amount of displacement of 2 mm were expected to be the most adequate clinical setting for measuring super-elasticity of nickel-titanium alloy archwire, and this setting have been the most commonly used. In addition, lingually displaced mandibular lateral incisor were frequently seen in orthodontic patient with crowding. Therefore, the mandibular right lateral block (42) was moved 2.0 mm lingually to achieve a simulation of mandibular right lateral incisor linguoversion (Fig. 1c).

Two sizes of nickel-titanium alloy archwires with a diameter of 0.014 (014NT) and 0.016 (016NT) inches (Sentalloy Medium, Tomy/GAC International, Tokyo, Japan) were inserted to the brackets and tubes for testing. Two different methods were used to ligate the archwires to the brackets. In conventional ligation (CL), archwires were ligated by an elastic module (Power O 110, Ormco, Glandol, CA, USA) using a needle holder. In self-ligation (SL), the slides built into the brackets were closed to hold the archwire in the slot. In the present study, force magnitudes were measured 10 times for two archwire sizes (0.014 and 0.016 inches) and for two ligation methods (SL and CL), and a total of 40 measurements were made. The order of measurements with those factors of archwire sizes, ligation methods were randomized using random number list.

All data were analyzed using the Statistical Package for the Social Science Version 21.0 (SPSS Inc., Chicago, USA). The level of significance was set at 5% (p<0.05). The force of the X, Y, and Z coordinates were summed and calculated as the force magnitude using the equation: force magnitude=$\sqrt{Fx^2+Fy^2+Fz^2}$. Means and standard deviations were calculated for the force magnitude in the 014NT and 016NT archwires using SL or CL methods on each bracket. The effects of archwire size (014NT and 016NT), ligation method (CL and SL), and bracket (42, 41, 31, and 32) on the means of force magnitudes were analyzed by 3-way analysis of variance (ANOVA) and the Bonferroni’s multiple comparison tests (p<0.05).

To detect the reliability of measurement by six-axis force sensors, the standardized stainless steel weights with 50 g and 100 g were put onto each sensor and forces of Fx, Fy and Fz direction to the sensors were measured. Force magnitudes were calculated and the following equation was used to calculate the error of measurement:

$$\text{Error} = \frac{\text{FMW} - \text{W}}{\text{W}} \times 100,$$

Where W is the amount of standard test weight, FMW is force magnitude calculated from the measurement by the sensor using the weight. Mean of the error was 2.8%, and the range was from 1.2% to 5.0%, although these results could not be simply compared to the reliability of Badawi’s OSIM, these are similar to the range of the manufacturer’s estimate and it is considered as acceptable reliability for this study.

To evaluate the influence of intra-operator error, a single operator (K.T.) repeated the same measurements more than 24 h after the first measurements. The error obtained by Dahlberg’s formula was 0.16 N in CL and 0.06 N in SL, respectively, which are considered to be acceptable.

The same measurement procedures were also performed by another operator after more than 24 h from the first measurements to detect inter-operator reliability. The difference between the 2 measurements was evaluated by Dahlberg’s formula. The error was 0.15 N in CL and 0.05 N in SL, which are considered to be acceptable for the purposes of this study.

RESULTS
The results of the 3-way ANOVA revealed significant effects of archwire size, ligation method, and bracket, however, no interaction was found between archwire size and ligation method, ligation method and bracket, and archwire size and bracket.
size and ligation method (Table 1).

The mean force magnitudes for each incisor bracket significantly decreased in the order of 42, 41, 31, and 32 \((p<0.01, \text{ Fig. 2})\). For 014NT, the mean force magnitudes were significantly larger in CL than in SL at all 4 incisor brackets \((p<0.05)\), except 41; however, the mean force magnitude at 41 was significantly smaller in CL than in SL \((p<0.01, \text{ Fig. 3})\). For 016NT, the mean force magnitude was significantly larger in CL than in SL at all 4 incisor brackets, except 41 \((p<0.05)\). Statistically significant differences in the mean force magnitude at 32 were observed between the ligation methods. In SL, the mean force magnitude at 32 was 0.01 N in 014NT and 0.01 N in 016NT. However, in CL, the mean force magnitude at 32 was 0.57 N in 014NT and 0.53 N in 016NT (Table 2). Although the mean force magnitude of 016NT was larger than that of 014NT \((p<0.01)\), archwire size did not significantly affect the mean force magnitude at 32 in both CL and SL (Fig. 3).

![Fig. 2](image2.png)

**Fig. 2** Pooled means and standard deviations of the 40 measurements of force magnitudes for each mandibular incisor bracket were calculated and compared each other by using Bonferroni’s multiple comparison test. Significant differences were observed from 42 to 32 \((**: p<0.01)\).

![Fig. 3](image3.png)

**Fig. 3** Means and standard deviations of the force magnitude of 014NT and 016NT archwires using the SL and CL methods, and the results of a 3-way ANOVA with Bonferroni’s multiple comparison test (a) to (d).

(a): At 42, the mean force magnitude was significantly larger in CL than in SL \((p<0.01)\). The mean force magnitudes were significantly larger in 016NT than in 014NT using both ligation methods \((p<0.01)\). (b): At 41, the mean force magnitude was significantly smaller in CL than in SL for 014NT \((p<0.01)\); however, no significant difference between SL and CL was observed for 016NT. The mean force magnitudes in 016NT were significantly larger than those in 014NT with both ligation methods \((p<0.01)\). (c): At 31, the mean force magnitude was significantly larger in CL than in SL \((p<0.05)\). The mean force magnitudes were significantly larger in 016NT than in 014NT using both ligation methods \((p<0.01)\). (d): At 32, the mean force magnitude was significantly larger in CL than in SL \((p<0.01)\). No significant differences were observed between 014NT and 016NT.

\((**: p<0.01, *: p<0.05, \text{ N.S: not significant})\)
The mean force magnitude at the right lateral incisor bracket observed in present study is similar to the force magnitude observed in the study by Montasser et al.\(^9\). Regarding the optimal force, Proffit\(^1\) stated that during initial alignment it is better to tip crowns than displace the root apices, and that to produce the most efficient tipping movement, the archwires should provide light, continuous force of approximately 50 g (approximately 0.5 N). The results of the present study suggest that the force magnitude delivered by 0.014 inch nickel-titanium alloy archwires, which are initially used in the alignment phase to lingually displace teeth, may exceed the optimal level suggested by Proffit. However, the optimal force magnitude for 4 incisor teeth in alignment phase to lingually displace teeth, may exceed the range produced with conventional ligation. This indicates that in conventional ligation, a greater number of teeth may be influenced by deflecting archwires compared to self-ligation.

Since the 6-axis force sensors fixed to the multi-sensor measuring system used in present study can measure the three-dimensional force applied to the 4 incisor brackets, analyzing these forces clarifies the biomechanics of the alignment phase of orthodontic treatment. However, since the primary objective of this research was to determine the mean force magnitude of nickel-titanium alloy archwires to the 4 incisor brackets, an equation was used to calculate the sum of the force of the X, Y, and Z axes, and therefore, the direction of the force at the 4 incisor brackets could not be clarified. To more thoroughly clarify the direction and magnitude of the force delivery from nickel-titanium alloy archwires, future studies should analyze the force in the X, Y, and Z axes.

Furthermore, the mean force magnitude at 31 and 32 were significantly larger in CL than in SL. This indicates that in conventional ligation, a greater number of teeth may be influenced by deflecting archwires compared to self-ligation.

On the other hand, the mean force magnitude at 32 observed in SL was 0.01 N. The present simulation of the mandibular arch also showed that the range of the mean force magnitude produced by nickel-titanium alloy archwires with self-ligating brackets was narrower than the range produced with conventional ligation, which was similar to the results of Fok’s simulations of the maxillary arch.\(^{11,12}\)

<table>
<thead>
<tr>
<th>Archwire</th>
<th>Ligation method</th>
<th>42 Mean (SD)</th>
<th>41 Mean (SD)</th>
<th>31 Mean (SD)</th>
<th>32 Mean (SD)</th>
</tr>
</thead>
<tbody>
<tr>
<td>014NT</td>
<td>SL</td>
<td>2.00 (0.08)</td>
<td>0.88 (0.05)</td>
<td>0.26 (0.02)</td>
<td>0.01 (0.01)</td>
</tr>
<tr>
<td></td>
<td>CL</td>
<td>2.44 (0.11)</td>
<td>0.60 (0.13)</td>
<td>0.43 (0.07)</td>
<td>0.57 (0.13)</td>
</tr>
<tr>
<td>016NT</td>
<td>SL</td>
<td>3.40 (0.08)</td>
<td>1.55 (0.08)</td>
<td>0.49 (0.04)</td>
<td>0.01 (0.01)</td>
</tr>
<tr>
<td></td>
<td>CL</td>
<td>3.61 (0.19)</td>
<td>1.44 (0.18)</td>
<td>0.67 (0.16)</td>
<td>0.53 (0.07)</td>
</tr>
</tbody>
</table>

\(^{11,12}\)
The multi-sensor measuring system used in the present study does not include the simulation for root of teeth and alveolar bone to analyze the force magnitude to these structures. However, orthodontic force on fixed appliances can clinically be controlled by archwires, or auxiliary materials such as coil springs and elastomeric chains. These materials are directly fixed to a bracket or tube on a tooth crown. Clinical significance of clarifying adequate orthodontic force may be determined by measuring force magnitude at bracket and tube. Therefore, the multi-sensor measuring system was developed to measure the force at the brackets on the simulated mandibular arch.

In the present study, when the archwire size was changed from 0.014 inch to 0.016 inch, the mean force magnitude at 42 increased by 48% to 70%. This result is close to the previous study that reported approximately 50% of increases in force magnitude by increasing 0.002 inch of archwire size. Furthermore, the present study also found that the mean force magnitude at 41 increased by 76% to 140%, and the mean force magnitude at 31 increased by 55% to 88%. These increases in the mean force magnitude at the 41 and 31 brackets indicate that diameter of nickel-titanium archwires affects not only the lingually displaced right lateral incisor bracket, but also affects the adjacent right central incisors and the left central incisors in mandibular right lateral incisor linguoversion.

CONCLUSIONS

The force magnitude delivered by nickel-titanium alloy archwires and brackets using a conventional ligation method with an elastic module was higher than the force magnitude delivered when self-ligation with a slide.

In the simulation of mandibular right lateral incisor linguoversion, the range of the force distribution to 4 incisor brackets was narrower in self-ligating brackets than the range in conventional ligation brackets.

The minimum increase in the diameter of the tested nickel-titanium alloy archwires showed significant increases in force magnitude in two adjacent teeth despite the use of different ligation methods.

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