# Resistance force of magnetic attachments against external lateral displacement

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## Introduction

Support, retention, and bracing or resistances against lateral forces are the three fundamental aspects required for stability of dentures during function[1)]. Elements of a denture such as abutments, proximal plate, connectors, occlusal rests, clasps, reciprocators and base plate, contribute towards stability solely or in combination. Dental magnetic attachments are devices incorporated into the abutments to offer retention and support with minimal bracing (horizontal stability) [2)]. These characteristics are absent in other abutment devices. The use of magnetic attachments eliminates most of the rotational and lateral forces which are detrimental to the longevity of a tooth's root[3)]. Use of magnetic attachments also allows for a decrease in abutment teeth loading forces which is an advantage, but a compromise in terms of denture functionality. However, it is possible to actively increase force generated by bracing components using magnetic attachments of improved root cap shape or using MT crown[2)].

Dental magnetic attachments are associated with weak bracing force because only frictional force of the mating face provides resistance to external forces acting in the horizontal direction. The magnets attractive force is not directly involved[2)]. Generally, when force is exerted on an object placed on a horizontal surface in an attempt to slide it laterally, static friction provides a counter force. Static friction force shows the greatest magnitude just before the object starts to move. It is termed as the maximum static friction. Maximum static friction Fs is proportional to the normal force N acting perpendicularly through the object to the contact surface. The proportionality constant $\mu_s$ at that point is called the coefficient of static friction, whose relationship is represented by the following equation (1).

$$F_s=\mu_s N \tag{1}$$

When the force applied to move the object becomes greater than $F_s$, the object starts to slide, and kinetic friction begins to act on the object instead of static friction. Kinetic friction is a smaller force than maximum static friction. It has been proven experimentally that kinetic friction $F_k$ is proportional to normal force N. The proportionality constant $\mu_k$ is called coefficient of kinetic friction, and the following equation (2) describes the relationship.

$$F_k =\mu_k N \tag{2}$$

The values represented by $\mu_s$ and $\mu_k$ are constants which are determined by properties of the contact surface, such as surface roughness, surface energy. The contact surface area and velocity of the moving object have no direct influence on the constants. The normal force N in most scenarios is the force of gravity acting on the object. Magnetic attachments possess a very small gravity due to their minute mass. Therefore, it is the attractive force of a magnet that predominantly acts as the normal force N. The bracing force of a magnetic attachment which is its resistance to forces that try to shift the magnetic assembly laterally from its keeper, is majorly dependent on the attractive force. Out of the few studies that investigated the friction force of magnetic attachments, only one study reported a magnetic attachment with a friction force of 70~90 g. It is a well-known that dental magnetic attachments are gentle on the roots of the abutment teeth, but the mechanism needs to be understood well by studying resistance force and its behavior against forces that cause lateral displacement.

## Objective

The purpose of this study was to demonstrate the resistance forces of a magnetic attachment against lateral displacement. The resistance and attractive forces of magnetic assembly and magnet against its keeper during lateral displacement were examined.

## Materials and Methods

### Dental magnetic attachment and magnet

A dental magnetic attachment, Physio Magnet 5213 (magnetic assembly: 5.2 mm in diameter and 1.3 mm in height, with keeper: 5.2 mm in diameter and 0.8 mm in height, Morita) was used in this study. The set is subsequently referred to as magnetic attachment. A magnet, cylindrical neodymium magnet (Nd-Fe-B: 5.0 mm in diameter and 1.5 mm in height, Trusco) was used. The cylindrical neodymium magnet was combined with the Physio Magnet keeper. The set is hereinafter referred to as magnet. In order to have the magnet and keeper in a position whereby their centers match, the magnets diameter must be smaller than the keepers[4)]. Therefore, the magnet selected for use in this study had a slightly smaller diameter than the keeper's.

### Experimental device

The retentive force measuring device used in this study matches the basic description in ISO 13017:2020[5)]. It was connected to a digital force gauge (ZPS, Imada). The device was installed in a universal testing machine (AGS-5kNG, Shimadzu) which controlled the crosshead speed.

### Measurement of resistance force of a magnetic attachment or magnet and keeper against external forces that cause lateral displacement

As shown in the Figure 1, aluminum jigs were fixed with their long axis in a vertical plane. One jig was fixed to the lower table of the measuring device whereas the other was fixed onto the upper table. A magnetic assembly and magnet combined with keeper were fixed onto the jigs using cyanoacrylate adhesive with the long axis in a vertical plane as shown in Fig 1. The magnetic assembly or magnet was pulled upwards so that the mating faces slide against each other at the crosshead speed of 1mm/min, and the resistance force measured by the force gauge. Recording of measurements was done at a sampling rate of 1 kHz until the magnetic assembly or magnet completely separated from the keeper. After the measurement, the time values were converted to distance to generate a displacement distance-resistance curve.

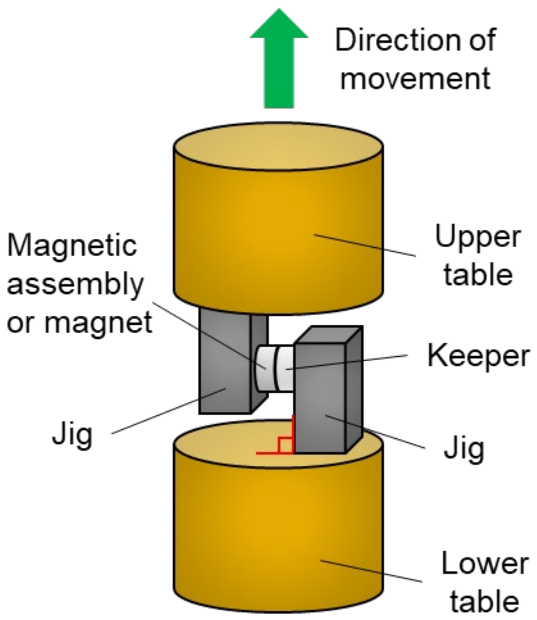


Fig. 1Set up of the sample mounted on device to measure resistance forces

### Measurement of attractive force during lateral displacement

The measuring device, magnetic attachment and magnet were set up in accordance with the test method of ISO 13017[5)], and retentive force (attractive force) was measured at crosshead speed of 2 mm/min. The measurements started when the magnetic assembly or magnet had its center aligned to that of the keeper. Attractive force measurements were done at intervals of 100 μm horizontal displacement of keeper. The experiment was run until the magnetic assembly or magnet completely separated from its keeper.

## Results

### 1. Resistance force of magnetic attachment or magnet and keeper against external forces that cause lateral displacement along the mating face

The displacement -resistance force curve of the magnetic attachment is shown in Figure 2. The horizontal axis shows the distance of horizontal shift (displacement) by the magnetic assembly away from the keeper whereas the vertical axis shows the resistance force measured. The resistance force just before the magnetic assembly started to move (maximum static friction force) was 1.78N. Once the assembly started to move, the force dropped drastically to 1.34 N. Afterwards, the resistance force increased as the distance approached 0.25 mm, then decreased with increasing distance. The curve had several inflection points. Beyond 5.2 mm, the resistance dropped to zero.

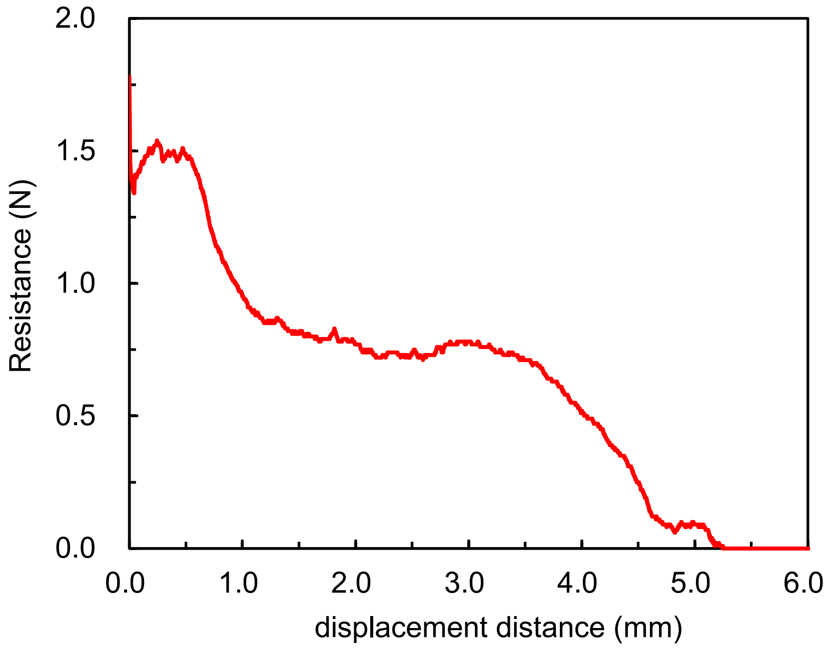


Fig. 2 The displacement distance-resistance force curve of the Physio magnetic attachment

The displacement distance-resistance force curve of the neodymium magnet -keeper is shown in Figure 3. The resistance force just before the initial movement of the magnet (maximum static friction force) was 0.39 N. Afterwards, the force dropped to 0.37 N then showed a transient rise and fall at 0.54 mm. Beyond that, the force increased monotonically with the increase in distance. As the distance exceeded 4.5 mm, the resistance force decreased to reach zero at 6.4 mm. The decline in resistance force to zero from 5.1 mm distance point, showed a smooth convex shape.

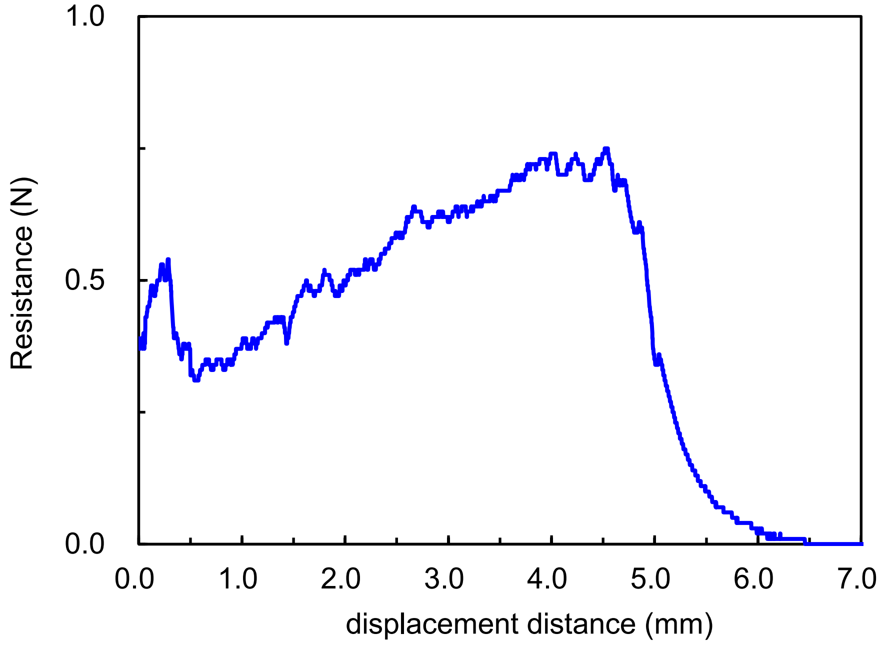


Fig. 3The displacement distance-resistance curve of neodymium magnet-keeper

**2. Horizontal displacement and magnetic attractive force**

The relationship between horizontal displacement and the attractive force of magnetic attachment and neodymium magnet are shown in Figure 4 and Figure 5 respectively. In both cases, the attractive forces decreased with increasing displacement and showed multiple inflections.

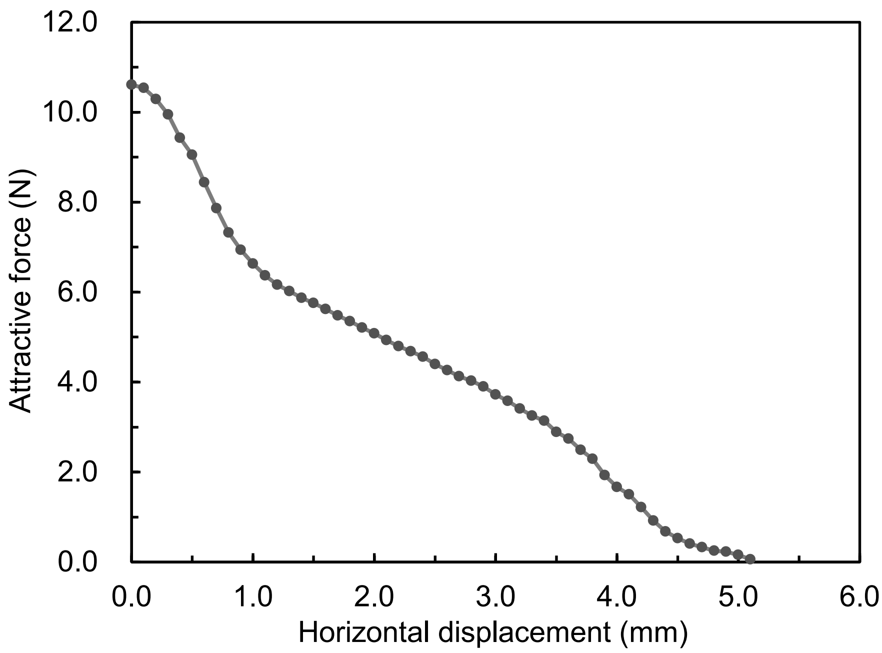


Fig. 4The attractive force against horizontal displacement in magnetic attachment

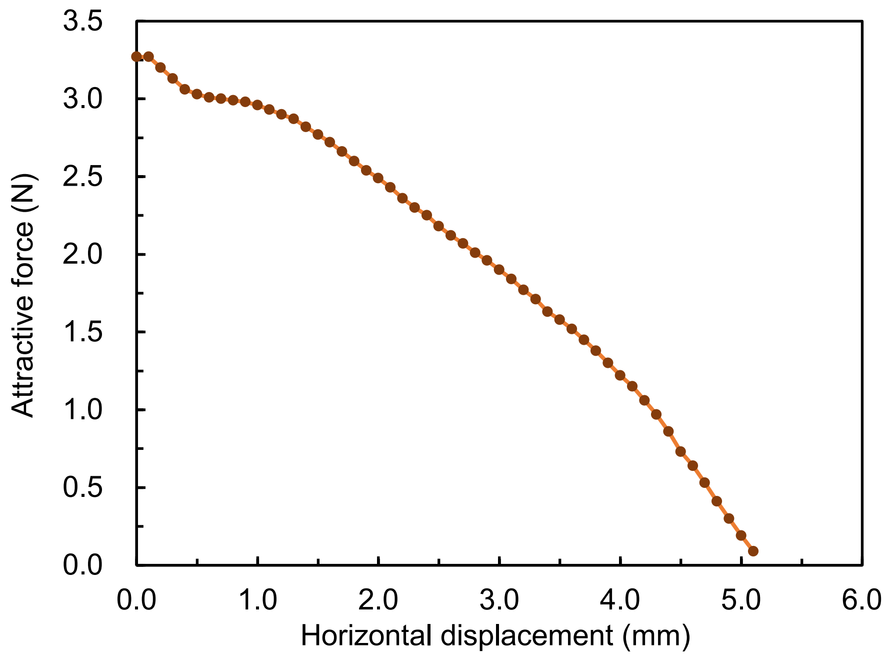


Fig. 5 The attractive force against horizontal displacement of neodymium magnet and keeper

## Discussion

### 1. Resistance force of magnetic attachment against external forces that cause lateral displacement along the mating face

In this study, the mating face of the magnetic attachment was fixed onto the measuring device with the long axis parallel to the vertical plane so that only the attractive force of the magnet affects the normal force which in turn relates to friction force. The maximum static friction was determined from the resistance displacement curve. Normal force N is the attractive force at zero displacement. The coefficient of static friction was calculated using equation (1). The kinetic friction which is active soon after the magnetic assembly or magnet starts to move, was derived from the resistance displacement curve. The coefficient of kinetic friction was calculated using equation (2). The calculated coefficients of static friction and of kinetic friction for the magnetic attachment 5213 were equal to 0.17 and 0.13 respectively. The values reinforced a well-known concept of, coefficient of static friction being greater that of kinetic friction. Ishihata et al. in a previous study[3)] reported that the frictional force of a magnetic attachment was about 1/3 its attractive force. The coefficient of friction in that study was about 0.33. The large difference between the two studies is that the material of the magnetic attachments used was different. The magnetic attachment in Ishihata et al.'s study was made of stainless steel and experimental magnetic alloy E[6)], while the magnetic attachment used in this study was made of magnetic stainless steel. The coefficient of friction exhibited by a pair of contacting surfaces is highly dependent on the different material deformation characteristics and the surface roughness.

Friction force is proportional to the normal force but independent of the contact surface area (Amontons' law). Therefore, kinetic friction force was calculated at different positions of displacement using Equation (2), after acquisition of coefficient of kinetic friction and data on attractive forces at different positions. The results are shown in Figure 6 alongside the resistance force. If kinetic friction is the only force that resists the external forces responsible for lateral displacement of magnetic attachments, then the two sets of values would be identical and the two curves superimposed onto each other. However, in this case, the resistance force was larger than the kinetic friction force calculated. This implies that the resistance force measured includes laterally attraction force related to the magnetic attachments. The magnetic assembly creates a magnetic circuit on the mating face when in contact with the keeper which generates a strong attractive force. Even when the magnetic assembly has been displaced until it is no longer in contact with the keeper, a small attraction force towards the keeper persists. The small attraction force attempts to restore the magnetic assembly back in contact with the keeper. Therefore, the measured resistance force is the sum of kinetic friction force acting along the mating face and the attraction force due to the magnetic fields.

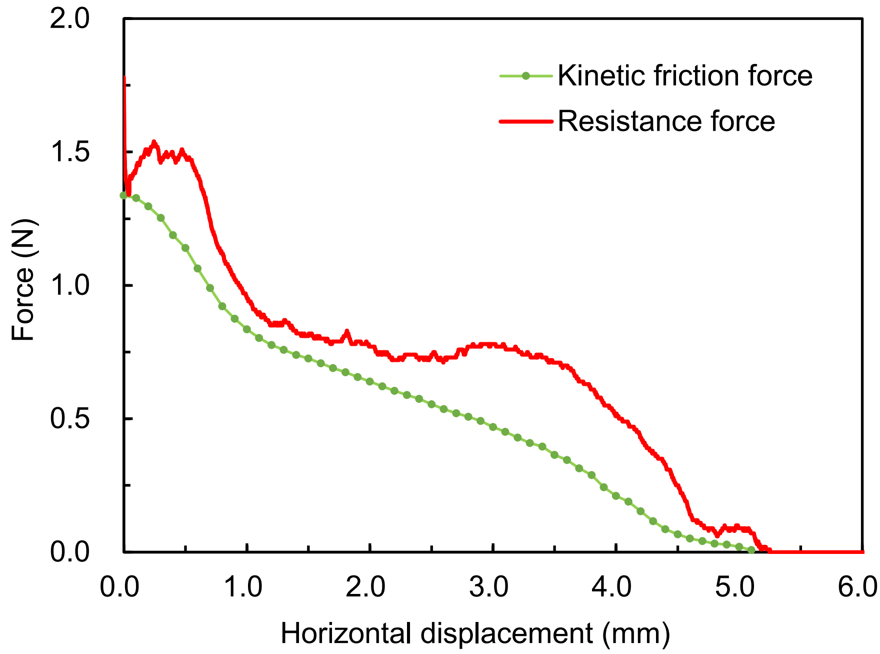


Fig. 6 Kinetic friction force and resistance force corresponding to different positions of horizontal displacement of magnetic attachment

The difference between the resistance force and the kinetic friction force was calculated to obtain the attraction force of the magnetic attachments in each position. Using the coefficient of static friction and attractive force values at each position, the maximum static friction force exerted at each position of lateral displacement was obtained using formula (1). The results are shown in the Figure 7. As demonstrated on this figure, the attraction force that attempts to restore the magnetic assembly into congruence with the keeper is generally smaller than the maximum static friction force. Therefore, the attraction force does not automatically get an already displaced magnetic attachment back to its original position with keeper or move further.

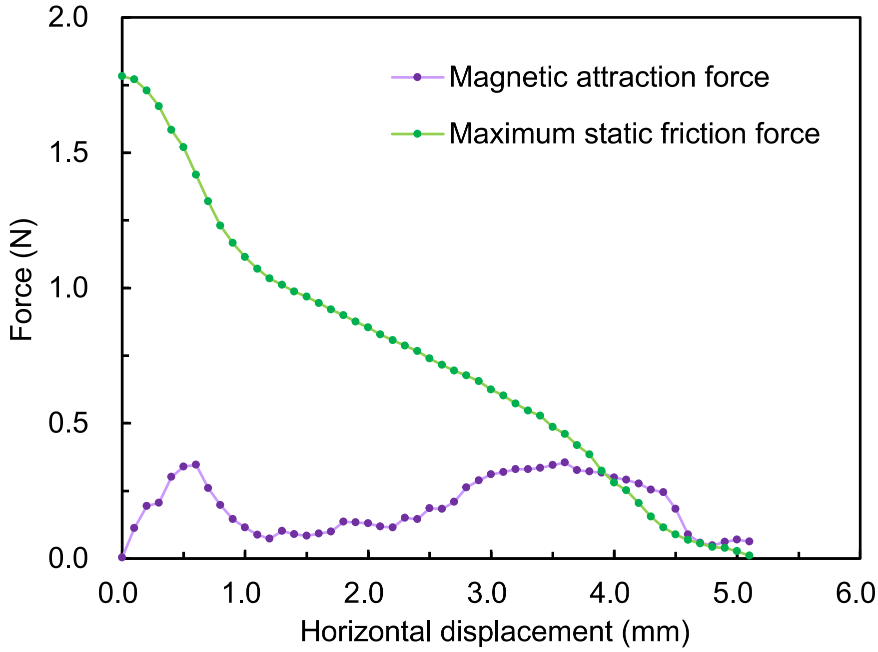


Fig. 7 Magnetic attraction force and maximum static friction force at each displaced position of magnetic attachment

**2. Resistance force of neodymium magnet against forces that cause lateral displacement along the mating face**

The coefficients of static and kinetic friction while using neodymium magnet were determined in a similar manner to that of magnetic attachment. The attained coefficients of static and kinetic friction were 0.12 and 0.11. Coefficient of static friction was larger than that of kinetic friction. Kinetic friction force at each position of lateral displacement was calculated in a manner similar to that of magnetic attachment. The data of kinetic force along with the resistance force are represented in a graph shown as in figure 8. Similar to the case of magnetic attachment, the resistance force was larger than the kinetic friction. This is because the attraction force between magnet and keeper even in their displaced condition is incorporated into the measured resistance force. The measured resistance force is the sum of the kinetic friction force at the mating face and the attraction force due to the magnetic force. Since neodymium magnets are characterized by open magnetic circuit, the magnetic fields from the bottom side (opposite to mating face) of the magnet and the exposed surface of the keeper generate an attraction force. This attraction force pulls the magnet back towards the fixed keeper. Contrary to the case of the magnetic attachment in which the resistance force quickly dropped to zero when the magnetic assembly completely separated from the keeper, the attraction force in this case persisted even after the separation point (distance of 5.1 mm). The above finding is a feature of open magnetic circuit, whose magnetic force after separation is inversely proportional to the square of the distance (inverse square law) causing the magnetic force to decrease slowly in a convex shape. On the other hand, the Physio magnetic attachment used in this study has a closed magnetic circuit in which the two poles close to each other undergo little magnetic flux leaks causing quick decay of magnetic force.

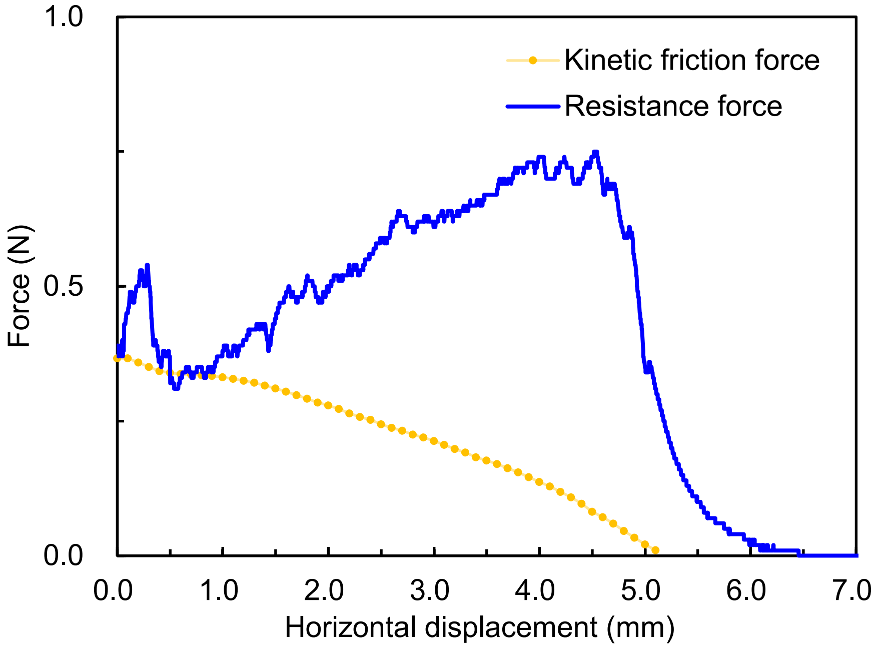


Fig. 8Kinetic friction force and resistance force corresponding to positions of lateral displacement of the neodymium magnet

The neodymium magnet's laterally attraction force and the maximum static friction force at each position of lateral displacement were determined in the same method as the magnetic attachment. The results are shown in the Figure 9. Unlike the magnetic attachment scenario, the magnets attraction force exceeded the maximum static friction force when the magnet was displaced significantly by more than 2.5 mm. The resultant force can restore the magnet to coincide with its keeper. The restoring force generated in the magnet combination used in this study was small, but it may be possible to increase it through use of certain selective combination of magnets. Although magnetic attachments are gentle on the tooth root, they act as weak bracing components. Clinical application of the restoring forces, would simplify alignment of the keeper to magnetic assembly. It may also be possible to develop a new magnetic attachment with enhanced bracing function using the information on the phenomenon of restoring forces.

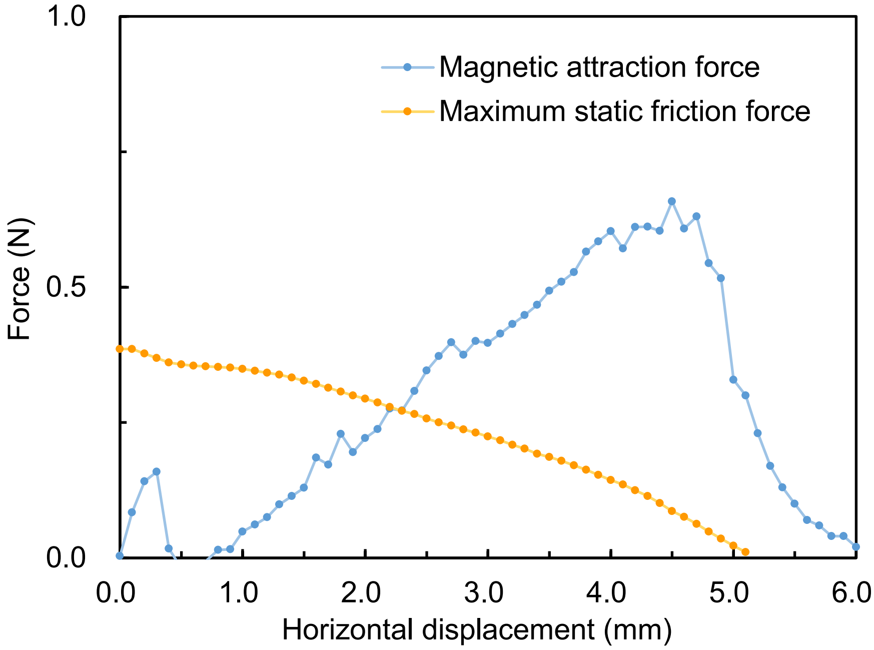


Fig. 9 Magnetic attraction force and maximum static friction at each position of the neodymium magnet

## Conclusion

The maximum friction force of the Physio Magnet 5213 recorded was 1.78 N. It was clearly demonstrated that besides frictional force, magnetic attraction force also influences the overall resistance force that stops displacement and restores a magnetic assembly to its keeper.


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