Original Article

Biomechanical validation of an artificial tooth–periodontal ligament–bone complex for in vitro orthodontic load measurement

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ABSTRACT

Objectives: To develop an artificial tooth–periodontal ligament (PDL)–bone complex (ATPBC) that simulates clinical crown displacement.

Material and Methods: An ATPBC was created. It had a socket hosting a tooth with a thin layer of silicon mixture in between for simulating the PDL. The complex was attached to a device that allows applying a controlled force to the crown and measuring the resulting crown displacement. Crown displacements were compared to previously published data for validation.

Results: The ATPBC that had a PDL made of two types of silicones, 50% gasket sealant No. 2 and 50% RTV 587 silicone, with a thickness of 0.3 mm, simulated the PDL well. The mechanical behaviors (1) force-displacement relationship, (2) stress relaxation, (3) creep, and (4) hysteresis were validated by the published results.

Conclusion: The ATPBC simulated the crown displacement behavior reported from biological studies well. (*Angle Orthod.* 2013;83:410–417.)

KEY WORDS: Periodontal ligament (PDL); Sliding mechanics; Mechanical property; Force and displacement

INTRODUCTION

A tooth moves in response to an orthodontic load system. Quantification of the orthodontic load system (M and F in Figure 1a) on the tooth is required to evaluate various appliance designs, to optimize the tooth movement, and to reduce side effects during an orthodontic treatment. Because of instrumental limitations, in vivo load quantification is not feasible; thus, in vitro measurement is needed.

Sliding mechanics are commonly used for space closure in orthodontic treatment (Figure 1b). However, only limited studies[1] have been conducted to quantify the resulting load system on the tooth because of its mechanical complexity. The mechanics allow the crowns of the moving teeth to slide on an archwire serving as a guide when an activation force, Fa, is applied. The load system sensed by the tooth depends on several factors, including the stiffness of the archwire and the interaction between the bracket and the archwire, especially the amount of crown displacement when an activation force is applied. The force, Fa, causes the tooth to tip, which results in the bracket-archwire interaction. The archwire deforms because of the interaction, creating an anti-tipping moment. Further tipping causes root and bone interaction. The resulting reaction force and the anti-tipping moment resist further crown tipping. The load system eventually reaches equilibrium. The load system sensed by the tooth at the bracket is the vectorial sum of the activation force and the reactions. Therefore, the force measurement accuracy depends on the accuracy of the crown (bracket) displacement. The periodontal ligament (PDL) dominantly affects the crown displacement and thus needs to be simulated when the load system is measured in vitro. Therefore, the ability to correctly simulate the crown displacement as well as other mechanical behaviors of the tooth-PDL-bone complex (TPBC) is critical for the in vitro measurement of the load system.

The behavior of the TPBC of living tissues in terms of crown displacement was investigated. Christiansen and Burstone[2] quantified the crown displacements in

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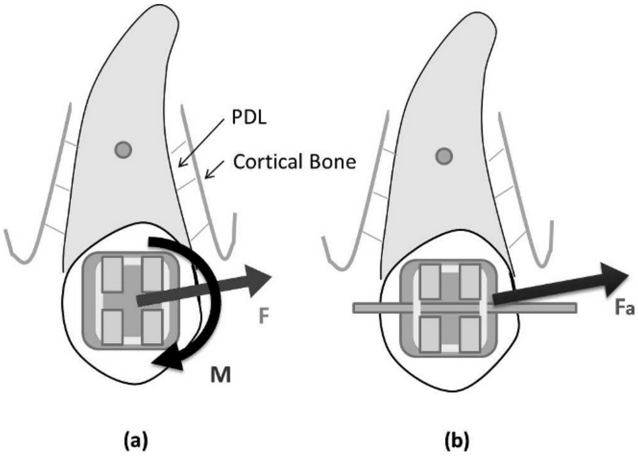

Figure 1. Load system on a tooth and the sliding mechanics used to translate the tooth.

response to applied forces on the human maxillary central incisors in vivo. Yoshida et al.[3] and Ralph[4] studied the elastic properties of the PDL in human subjects. Dorow et al.,[5,6] Tohill et al.,[7] Komatzu et al.,[8] and Natali et al.[9] studied the viscoelastic behavior of the PDL using pig samples. Jónsdóttir et al.[10] also reported the creep behaviors of the beagle PDL. These studies provided good references for the behaviors of the TPBC of living tissues. However, an artificial tooth-PDL-bone-complex (ATPBC) that exhibits similar crown displacement as well as its viscoelastic behaviors for in vitro studies has not been reported.

Limited studies on the displacement of simulated ATPBCs have been conducted. Badawi et al.[11] and Cao[12] developed rigid tooth adaptors, which could not be used to simulate the viscoelastic properties of the human PDL. Other researchers[1,13–17] reported that thin films made of the materials silicone rubber, special glue, urethane plastic, or polyvinylsiloxane impression materials can be used to simulate PDL within a certain range. However, these studies focused only on individual behavior. A more reliable ATPBC should exhibit all the major behaviors, including the force-displacement relationship, stress relaxation, creep, and hysteresis. These behaviors affect the load system and thus need to be simulated correctly.

Previously, orthodontic load systems were measured on the devices with the tooth fixed to the load cell.[11,18,19] There was no PDL; thus, the clinical crown displacement was not allowed. The fixed connection is reasonable for evaluating the load system of a loop or segmental wire because the wire is ligated to the brackets and there is negligible relative motion between the bracket and the wire. For sliding mechanics, the load depends on the relative motion. The fixed connection makes the measurement unreliable. Having a validated ATPBC to replace the fixed connection is critical for quantifying the load for sliding mechanics.

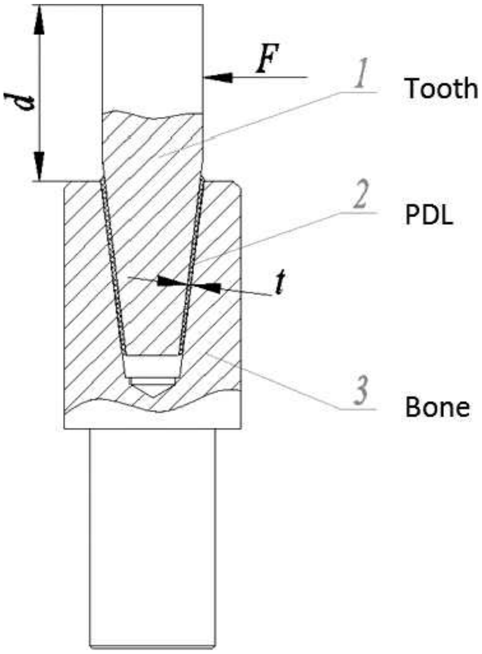

Figure 2. Schematic diagram of the artificial tooth–periodontal ligament–bone complex (ATPBC).

The objective of this study is to seek suitable materials to simulate human PDL and validate an ATPBC based on the resulting crown displacement in response to an orthodontic force. The ATPBC will be used for in vitro quantification of the load system of sliding mechanics.

MATERIALS AND METHODS

An ATPBC was created. The complex has a socket hosting the tooth with a thin layer of silicon mixture in between simulating the PDL (Figure 2). The artificial tooth with a conical aluminum root resided in the conical aluminum socket. A thin film of a mixture of gasket sealant No. 2 (GS) and RTV 587 silicone (RTV; Henkel Corp, Düsseldorf, Germany) was created to simulate the human PDL. GS is viscous, and RTV is primarily elastic. The mixture formed a flexible film with controllable viscous level by adjusting the ratio of the two materials. The GS/RTV ratios tested were 70:30, 60:40, 50:50, 40:60, and 30:70. The thickness of the film can also be adjusted by changing the height *d* (Figure 2), which also affects the crown displacement.

The load-displacement behaviors of the ATPBC were studied using a custom-made device, consisting of a load cell and a micrometer head with a nonrotating spindle. The device allows applying a force to the crown and measuring the resulting crown displacement (Figure 3). A Nano 17 F/T load cell (ATI Industrial

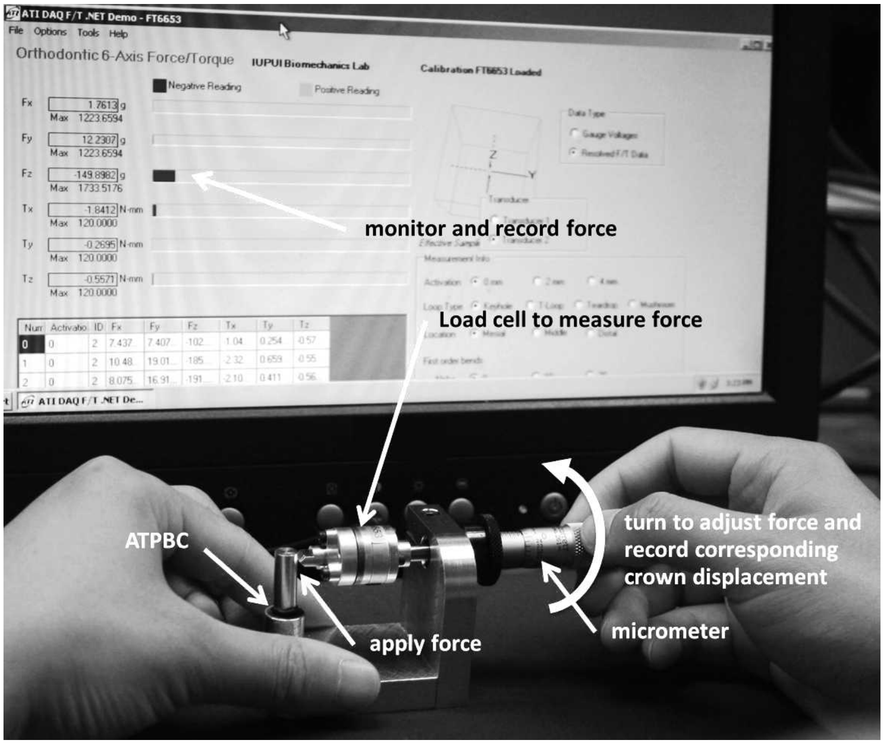

Figure 3. The experimental setup. The device consists of a load cell and a micrometer head with a nonrotating spindle. The device allows applying a force to the crown of the artificial tooth–periodontal ligament–bone complex and measuring the resulting crown displacement.

Automation, Apex, NC) was used to measure the applied force. The sensing range and resolution of the load cell is $-17\sim+17$N and 7×10^{-4}N, respectively. The load cell is serially aligned to the spindle and a probe. The micrometer applies a controlled displacement to the probe via a connector, applying a measurable force to the crown of the ATPBC. The micrometer head displacement (No. 261L, L S Starrett Company, Athol, Mass) has an accuracy of $\pm$0.00254 mm and a travel of 12.7 mm. The force-displacement relationship was obtained by turning the micrometer head and recording the readings of the transducer and the micrometer.

The following mechanical behaviors were investigated: (1) force-displacement relationship, (2) stress relaxation, (3) creep, and (4) hysteresis. The applied forces on the crown ranged from 0 to 500 cN based on the common force range used for orthodontic tooth movement. The stress relaxation behavior was tested by instantaneously loading the crown to 500 cN and then holding the displacement and reading the force relaxation as the time elapsed for 30 minutes. The creep behavior was obtained by constantly applying a force on the crown, which was achieved by turning the micrometer for 30 minutes. The induced displacements reflected the creep of the ATPBC. Finally, the hysteresis behavior was obtained by first gradually loading the ATPBC to a fixed displacement (0.25 mm) and then gradually unloading it with a uniform rate of 0.025 mm/s.

To ensure that the ATPBC behaves similarly to the reported behaviors, the proportion of the silicon materials and the thickness were adjusted to identify the best combination using the reported human force-displacement relation as the criterion.[2] The best combination was then tested on other behaviors for the validation. Five trials were conducted for each behavior. Therefore, for each testing point, there was a mean, an absolute deviation, and a standard deviation. The mean standard deviation (MSD), which refers to the mean of the standard deviation of different testing points of a curve, was obtained for assessing the level of variation of the five trials. The mean absolute deviation (MAD) was obtained for assessing the deviation of a curve from the reported ones.

RESULTS

The mechanical behaviors of the ATPBC are given in Figures 4–7. MSDs and MADs were included in the figures. Figure 4 shows the force-displacement relationship of the ATPBC. The effects of the GS/RTV ratios on the force-displacement relationship of the ATPBC were presented. The result of human TPBC in Christiansen's report was also included for comparison, which was obtained using a comparable setup.[2]

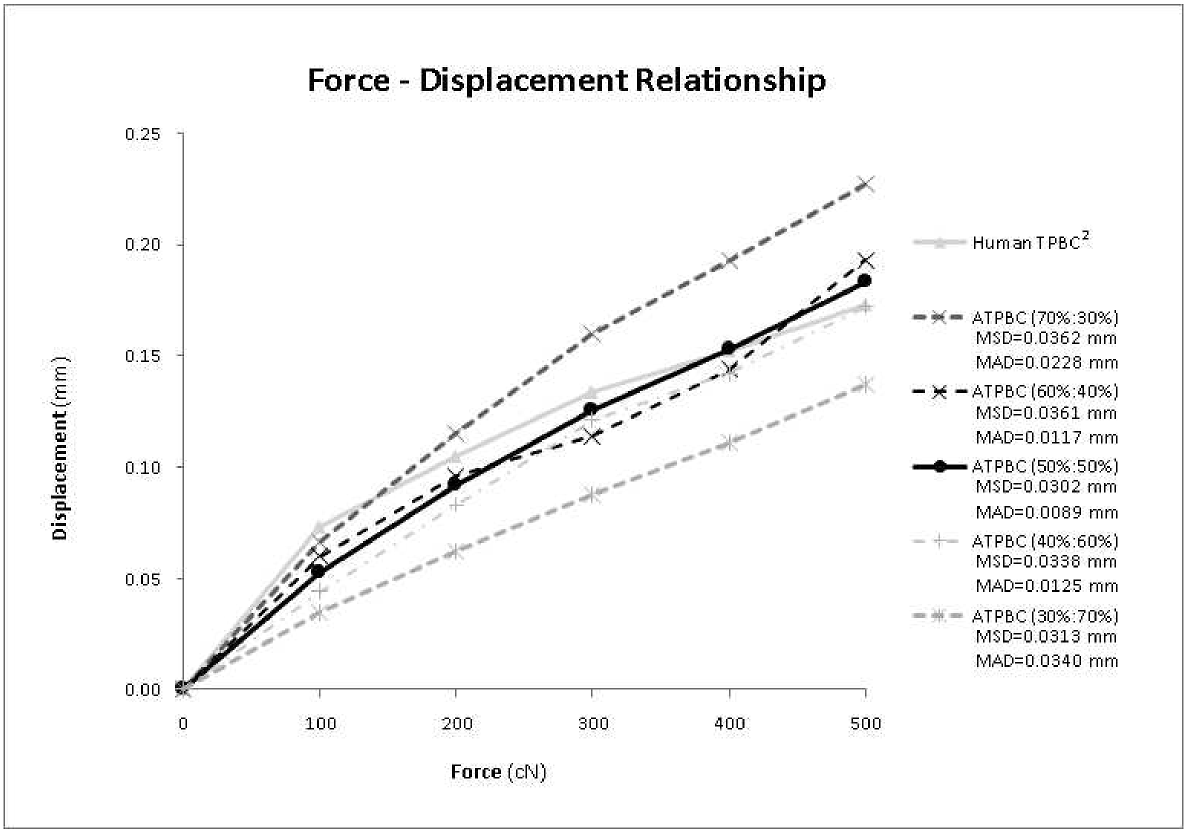

Figure 4. Force-displacement relationships of the artificial tooth–periodontal ligament–bone complex with different gasket sealant No. 2 RTV 587 silicone ratios. The curves were compared with the result of the human TPBC.

MAD data ranging from 0.0089 to 0.0340 mm show that the force displacement varied significantly, depending on the GS/RTV ratio. More GS resulted in less stiffness but more nonlinearity. The 50:50 combination resulted in a force-displacement curve that had a minimum MAD from the curve reported. With this combination, the ATPBC's behavior on creep, stress relaxation, and hysteresis was tested. For comparison purposes, the forces in Figures 5–7 were normalized by the maximum load. Figure 5 shows the time-force relationship that characterizes the stress relaxation process of the ATPBC. The characteristic parameters are the initial force drop and the time to reach the steady state. The results demonstrated that an initial force of 500 cN dropped to 70% on average within 5 minutes, and then the curve plateaued. Figure 6 shows the time-displacement relationship, which characterizes the creep process. The important parameter is the initial displacement rate. The result showed the measured crown displacement as the time elapsed under a constant force of 500 cN. The large displacement at an average rate of 0.012 mm/min occurred initially, which lasted only a few minutes. Then the displacement slowed, and the rate reduced to about 0.0016 mm/min. Figure 7 shows the loading and unloading curves, which characterize the hysteresis of the ATPBC. The key parameters are the residual displacement when completely unloaded and the loading rate. The result showed the average residual displacement of 0.1 mm, which was about 40% of the initial value under the loading rate of 0.025 mm/s.

DISCUSSION

The ATPBC in this study was validated experimentally. The validation aimed at (1) ensuring that the human tooth's load-displacement relationship is preserved and (2) ensuring that the ATPBC exhibits similar viscoelastic behavior to that reported previously, which includes stress relaxation, creep, and hysteresis. Unfortunately, the reported data were not from the same species, and they are the only data available at present. However, they are all from in vivo biological studies, so typical biological behavior is preserved.

A mixture of two materials, GS (viscous) and RTV (elastic), was used to provide the viscoelastic behavior of the PDL. Our data showed that adjusting the GS/RTV ratio alters the crown displacement response (Figure 4). Aluminum was used to substitute bone and

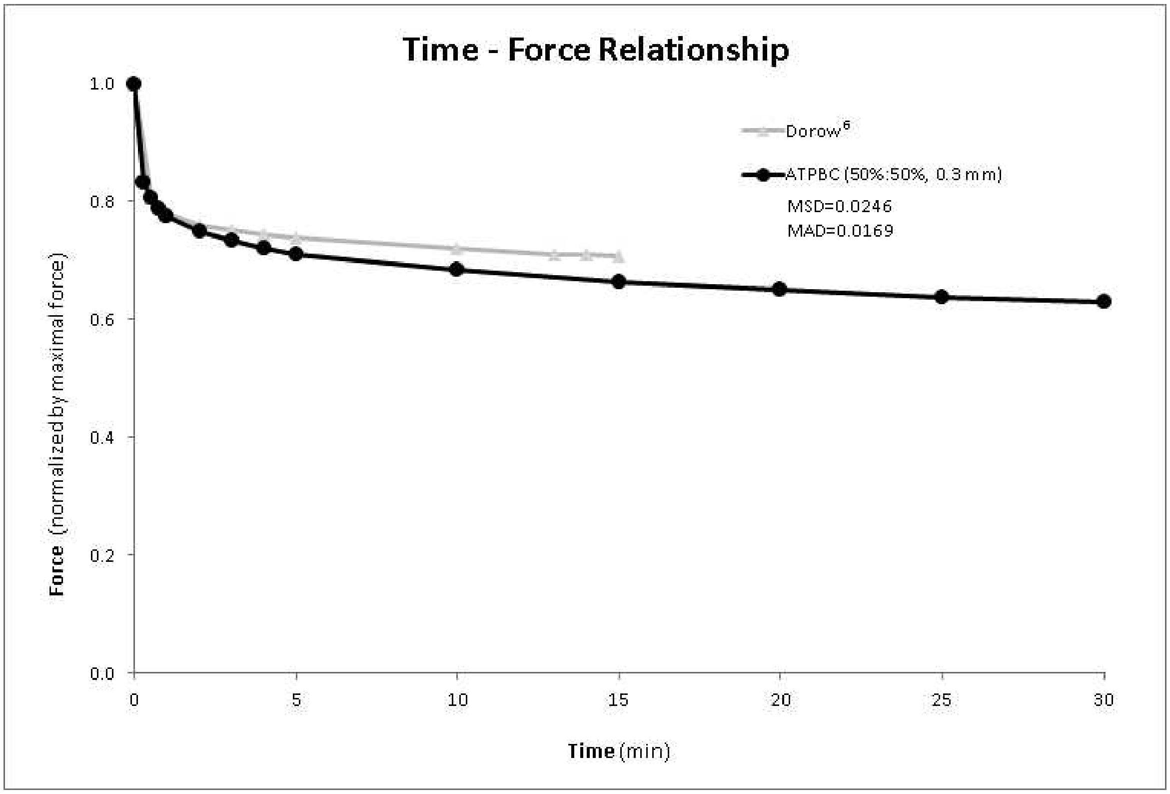

Figure 5. Stress relaxation behavior of the selected artificial tooth–periodontal ligament–bone complex, which was compared with the result published.[6] The force was normalized by the maximum load applied for comparison purpose.

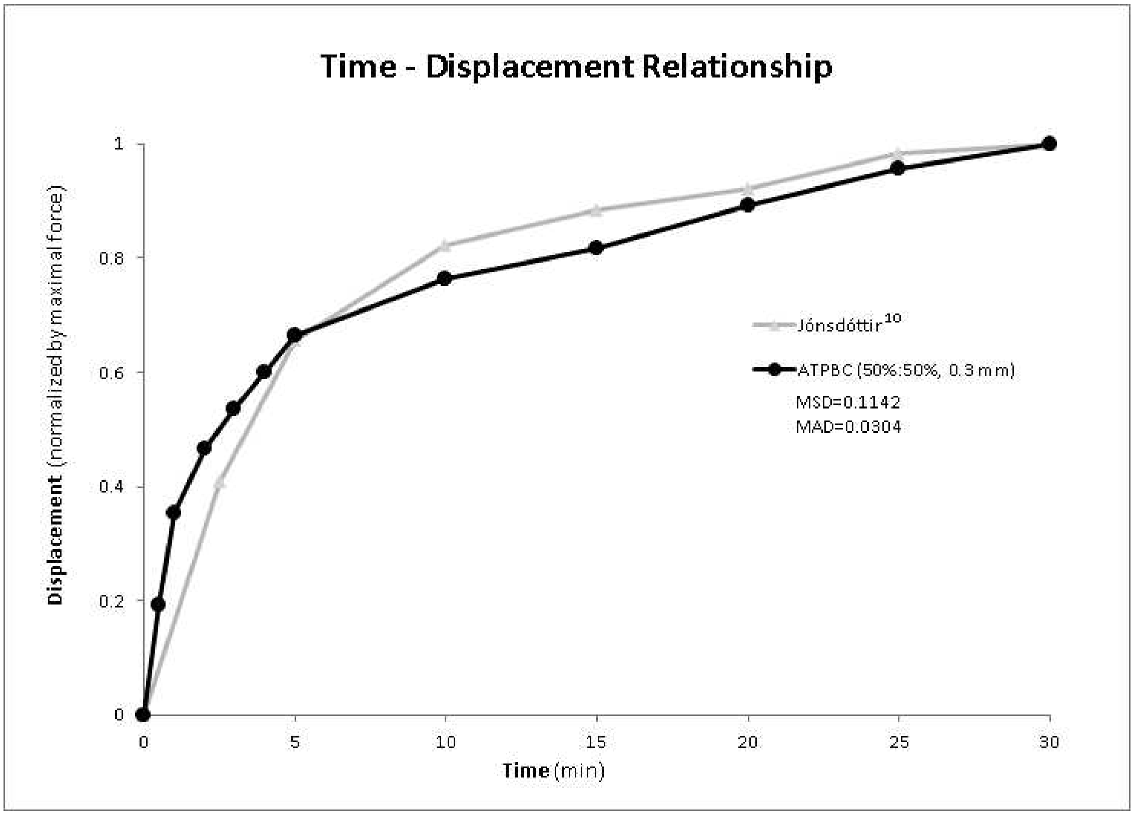

Figure 6. Creep behavior of the selected artificial tooth–periodontal ligament–bone complex, which was compared with the result published.[10] The force was normalized by the maximum load applied for comparison purpose.

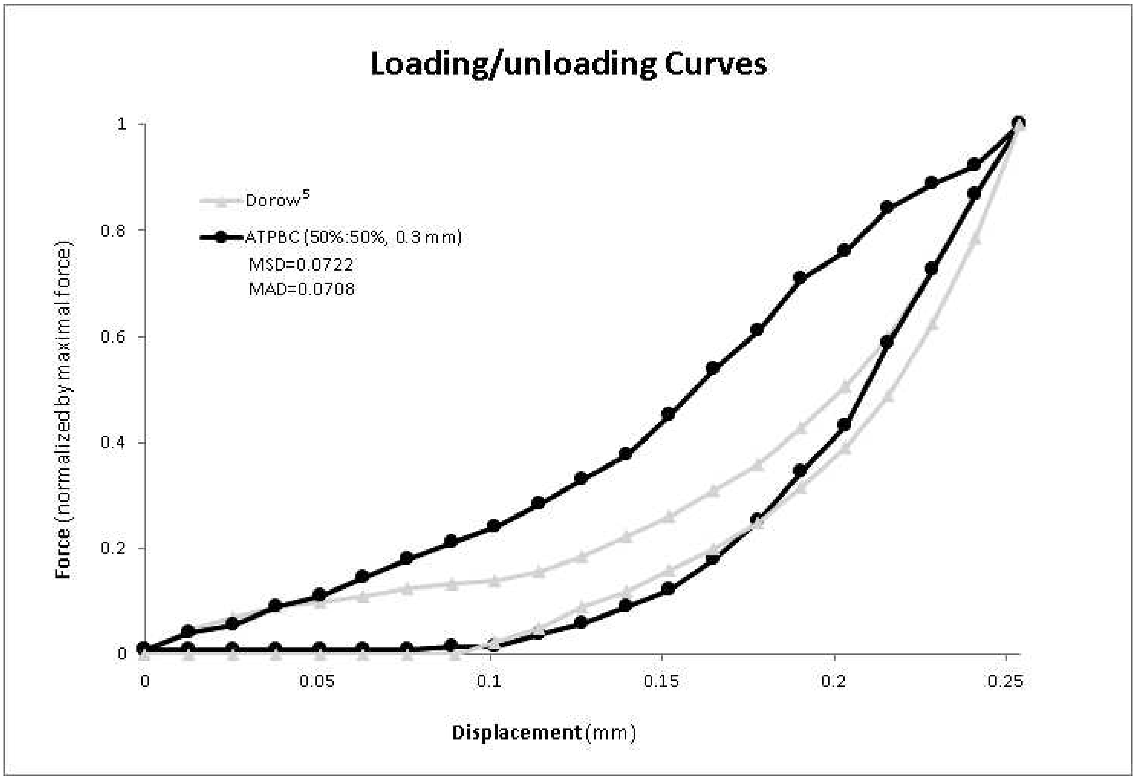

Figure 7. Loading and unloading curves of the artificial tooth–periodontal ligament–bone complex (hysteresis), which was compared with the result published.[5] The force was normalized by the maximum load applied for comparison purpose.

root because the deformation of the bone and the root played a negligible role in crown displacement compared with PDL, considering that the Young's modulus of the bone and root is far larger than that of the PDL. The same material was also used in the study by Burstone and Pryputniewicz.[14] The shape of the root and the socket is irrelevant because its effect has been included in the crown's displacement measurement. Only the displacement affects the load measurement.

The Load-Displacement Relationship

The load-displacement relationship of the newly designed ATPBC resembled the human data published, except for the linearity.[2] With a force of 400 cN, the measured crown displacement matched that reported by Christiansen and Burstone[2] (Figure 4). Typically, the orthodontic loading range is within 300 cN.[20] The maximum deviation of the two curves within the range was about 0.02 mm, which would provide a good first estimation of the load system. The MAD of the two curves was only 0.0089 mm. A good agreement was achieved.

Stress Relaxation

Stress relaxation occurs in TPBC.[6,7] When a tooth is loaded, it displaces. When the displacement stops, the load decreases as time elapses. A similar phenomenon occurs in the ATPBC. Figure 5 demonstrates that an initial force of 500 cN dropped to 70% within 5 minutes, and then the curve plateaued. The phenomenon is similar to the stress relaxation of PDL samples from pig mandibles reported by Dorow et al.[6] and Tohill et al.[7] as well as samples from rabbit reported by Komatsu et al.[8] The MAD between the ATPBC's and Dorow's curves was 8.5 cN, which was 1.7% of the corresponding maximum force (Figure 5). In the study by Tohill et al., the initial force dropped to 72% on average after 35 seconds of stress relaxation, while ours dropped to 80% on average after 30 seconds. The difference in experimental setups may have caused the variation, which was small and unlikely to have any significant clinical impact.

Creep

Creep is another viscoelastic behavior of the TPBC. When a force is applied on the simulated crown and held constant, the induced tooth displacement decreases with time. Figure 6 shows the measured crown displacement as the time elapsed under a constant force of 500 cN. Large displacement at an average rate of 0.012 mm/min occurred within the initial 5 minutes. Then the rate reduced to about 0.0016 mm/min. Jónsdóttir et al.[10] reported similar behavior of the PDL of beagle dogs. A constant force of 100 cN was applied. The average rate of the initial phase was 0.018 mm/min, which gradually reduced to only 0.00017 mm/min. The two curves matched well. The MAD between the ATPBC and Jónsdóttir curves was 15.2 cN, which was 3% of the corresponding maximum force (Figure 6). The initial creep behaviors agreed well with that of Jónsdóttir. This is important because, when the initial force system of a sliding mechanics is measured, the crown displacement during the initial phase is of interest. The dog's data were used for the validation because no creep behavior of human PDL was reported. However, considering that the viscoelastic properties of the PDL of different mammalian species were similar,[6] our ATPBC was qualitatively validated.

Hysteresis

Hysteresis indicated how displacement changes when loading and unloading the crown. The newly designed ATPBC demonstrated hysteresis, which is similar to those reported.[4–6,9] Figure 7 shows results of loading and unloading behavior averaged based on five trials. The loading-unloading curves showed that the tooth was not able to return to its original position after every unloading procedure. This hysteresis was also observed in the experiments on biological PDL.[4–6,9] Dorow et al.[5] reported that the shape of hysteresis was affected by the loading velocity and also depended on the loading history. Our ATPBC has the average residual displacement at about 40% of the initial value under the loading rate of 0.025 mm/s, while in the experiments of Dorow et al., the residual displacement was about 34% of the initial value under the loading rate of 0.017 mm/s.[5] The MAD between ATPBC's and Dorow's curves was 35.4 cN, which was only 7% of the corresponding maximum force (Figure 7). The comparison indicated that the hysteresis property of the ATPBC is similar to that of the biological one.

The results demonstrate that the ATPBC preserves the general biological viscoelastic behavior and produces similar crown load-displacement relationship shown in human. This behavior is critical when the load system of sliding mechanics is measured. Thus, it can be used to quantify the load system of a sliding mechanics. However, the behavior is equivalent to a biological TPBC only from the perspective of crown displacement. It is not our intention to claim that the silicon mixture has the same mechanical properties of the PDL because these properties are sensitive to its internal structure, which consists of both fiber and matrix. The organization of the collagen fiber and its variation are unclear. The level of effects of the variation on the biomechanical behavior of the TPBC is still unknown. Further studies will be needed if the mechanical properties are of interest.

CONCLUSIONS

- An ATPBC has been designed and validated to simulate the clinical crown displacement.
- The results showed that the ATPBC with a mixture consisting of two types of silicones, 50% GS and 50% RTV, with a thickness of 0.3 mm, simulated the biological crown displacement of TPBC well.

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