Original Article

Non-invasive evaluation of periodontal ligament stiffness during orthodontic tooth movement

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ABSTRACT

Objectives: To evaluate the longitudinal changes in periodontal ligament (PDL) stiffness during orthodontic tooth movement using the Advanced System for Implant Stability Testing (ASIST).

Materials and Methods: ASIST measurements of maxillary canines that were actively retracted into an extraction space were collected approximately once per month for 12 adolescent female patients. The ASIST Stability Coefficient (ASC) values, which are directly related to PDL stiffness, were determined for each visit to examine longitudinal changes for individual canines as they were exposed to different forces (approximately 80 and 150 g) during retraction.

Results: The pattern of longitudinal changes in ASC was similar for both canines (regardless of the two force levels applied) in individual patients and across patients. All patients showed some decrease in ASC, with an average maximum reduction in stiffness of 73.4 ± 7.7%. Some recovery was observed for most patients; however, none of the patients had the PDL stiffness return to the pre-treatment value at the final measurement appointment which was some time close after space closure was completed. On average, the ASC value at the final measured visit was 48.1 ± 12.2% of the initial value. No measurements are available after removal of orthodontic appliances and during retention.

Conclusions: The ASIST was able to detect changes in PDL stiffness during orthodontic treatment, providing some insight into the mechanical changes that occur at the tooth root interface. (*Angle Orthod.* 2019;89:228–234.)

KEY WORDS: Periodontal ligament; Orthodontic tooth movement; Tooth stability; ASIST

INTRODUCTION

Tooth stability is an important measure in the assessment of oral health and the periodontal ligament (PDL) plays a major role in providing this stability.[1–3] The PDL acts as the interface between the tooth root and the surrounding alveolar socket.[4] The PDL is an important element in the biological response to orthodontic tooth movement. Orthodontic forces are sometimes applied constantly over extended periods of time. Orthodontic tooth movement is associated with remodeling in the dental and periodontal tissues including changes at the molecular, cellular, and tissue levels.[5–9] It is generally accepted that orthodontic forces cause bone resorption on the compression side and bone apposition on the tension side of the PDL through a complex biological response, ultimately resulting in tooth motion toward the compression side.[1,5–7] It is important to understand the changes in mechanical properties associated with these reported biological changes during orthodontic treatment. Thus, it is useful to measure tooth mobility or PDL stiffness during such treatment. Also, it is important to understand the posttreatment PDL stiffness values as they likely play a major role in immediate orthodontic relapse.

The Periotest (Medizintechnik Gulden, Modautal, Germany) is a commercially available system that was

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developed to monitor the mobility and damping of natural teeth by measuring the acceleration in response to an applied impact.[10] The impact event comprises approximately half of one cycle at the fundamental frequency of vibration of the system, and the time for this half cycle to occur is termed the contact time. The contact time is used to calculate a Periotest value (PTV), which is then related to clinical tooth mobility through a simple correlation.[10] The PTV ranges between −8 and +50 with lower numbers representing stiffer systems. The Periotest is a widely used clinical tool;[11–15] however, it has several limitations. The geometry and inertia parameters of the tooth and biological system are not considered in the Periotest measurement and PTV calculation. Thus, any connection between the PTV and the actual mechanical properties of the PDL is unclear.[15,16] Furthermore, the Periotest uses a filtered acceleration signal, which removes significant information contained in the system response.[15–18]

More recently, the Advanced System for Implant Stability Testing (ASIST) was developed to evaluate interface stiffness properties. The ASIST has been applied to bone anchored implants[15] and natural teeth.[16] The same idea of interface integrity can be applied to both of these applications where the stability of the system is related to the stiffness at the interface.[16,17] The ASIST uses a similar impact technique to the Periotest; however, a more accurate acceleration response is captured and an analytical model of the biological system is included, allowing the measure to better isolate the mechanical properties of the interface tissue from the specific implant/abutment system or tooth being considered.[15,16] This allows improved direct comparisons between different implant systems, different teeth, and different patients. In the application to natural teeth, the assumptions to model the damping at the interface become more important to adequately capture the viscoelastic response of the PDL.

The objective of this study was to evaluate the longitudinal changes in PDL stiffness using the ASIST system throughout the course of orthodontic leveling, alignment, and extraction space closure through retraction of maxillary canines. It was hypothesized that the ASIST would be able to detect changes in PDL stiffness associated with orthodontic tooth movement.

MATERIALS AND METHODS

The details of the ASIST for natural teeth were described in Westover et al.,[16] and the method is summarized here. The ASIST uses an impact coupled with an analytical model of the system comprised of the tooth, the root interface (PDL), and the impact rod to estimate the PDL stiffness. The analytical model is a 3 degree-of-freedom system where a single-rooted tooth is modeled as an axisymmetric rigid body and the impact rod is modeled as a particle. The PDL is modeled as a distributed stiffness with viscous damping over the area of the tooth root. An accelerometer within the ASIST handpiece measures the acceleration during the impact with the tooth for 16 strikes over 4 s. The PDL stiffness is estimated by correlating the measured acceleration with the output of the analytical model. The outcome measure is the ASIST Stability Coefficient (ASC), which is a nondimensional value directly related to the PDL stiffness and normalized to a nominal stiffness value. Thus a higher ASC value indicates a stiffer PDL or lower tooth mobility. In previous applications of the ASIST, the ASC value for the PDL was found to be approximately two orders of magnitude lower than for bone anchored implants.[15,16]

ASIST measurements were collected for 12 adolescent female participants (aged 12–15 years). Participants were recruited from the pool of patients participating in a randomized clinical trial (RCT) at the University of Alberta Graduate Orthodontic Clinic. Approval was obtained from the University of Alberta Health Research Ethics Board and all participants provided informed consent. The sample was adequate to assess differences in tooth movement rates based on two distinct forces (approximately 80 g and 150 g). Approval was obtained from the institutional ethics board and all participants provided informed consent. All participants required extraction of the maxillary first premolars for overjet reduction. For each patient, ASIST measurements were recorded for the two maxillary canine teeth at approximately 12 visits over a 1-year span (range: 11–14 visits). At each visit, three ASIST measurements were typically collected for each tooth (range: 1–5 measurements). In some cases, no usable measurements were collected for a tooth at a particular visit due to an error in the data collection. In total, six out of 296 measurements were excluded for this reason. The ASIST measurements were taken on the center of the buccal surface of the orthodontic bracket placed on the maxillary canines for consistency in measurement location across visits.

At the initial visit, the first maxillary premolars were extracted and full fixed orthodontic appliances (Ormco Orthos, Orange, CA) were placed. The participants attended several appointments during the initial alignment and leveling phase. Following this, an osseointegrated paramedial palatal implant (Straumann, Basel, Switzerland) was installed to provide maximum posterior anchorage (a transpalatal arch was anchored to the implant and the palatal surfaces of the upper molars) during the retraction phase. Canine retraction was achieved through custom-bent hooks (one 0.018″ × 0.025″ stainless steel wire inserted in the vertical slot of the brackets labially and another similar one bonded to the palatal surface) and shape memory alloy retraction springs (Nickel-Titanium closed coil springs; Ormco) applied both labially and palatally. This system was engineered to attempt bodily translation of the maxillary canines during premolar extraction space closure (Figure 1). Forces were applied to the two canines such that the force on one tooth (80 g) was approximately half the force on the other tooth (150 g) and these force levels were randomly assigned to each tooth (left and right) for all participants. Spring adjustments were made at subsequent follow-up visits to maintain the desired force. Following the space closure phase, participants continued with their remaining orthodontic treatment.

The ASIST analytical model requires an estimate of the geometric and inertia properties of the tooth.[16] Cone-beam computed tomography (CBCT) scans were obtained for both maxillary canines for each participant before and after treatment (NewTom 3G, Aperio Services, Verona, Italy). The maxillary canine mass and geometry parameters were estimated from the three-dimensional reconstructed models from the initial CBCT data. Scanning parameters were 110 kV, 6.19mAs, and 8 mm aluminum filtration. The images were converted to a digital imaging and communications in medicine (DICOM) format with a voxel size of 0.25 mm using the NewTom proprietary software. CBCT data were obtained for the primary RCT to properly plan the paramedical implant location.

Additionally, the ASIST analytical model requires an estimate of the strike location on the tooth as measured from the top of the crown. The exact striking height during data collection was not recorded but the approximate location was known as the measurements were consistently taken on the orthodontic brackets on the canine crown. The center of the bracket was positioned 5 mm below the canine tip. So this value was estimated and fixed in the model. A striking height of $L_o = 6$ mm below the tip of the crown produced an appropriate model response for the data.[16]

Finally, an estimate of the damping within the system was included in the analytical model. Viscous damping was assumed at the PDL with negligible damping in the rest of the system. The damping coefficient (c) is related to the damping ratio of the higher frequency component of the acceleration signal (ζ_2) through the following equation:

$$c = \gamma\sqrt{m_t}\sqrt{k}\zeta_2$$

where m_t is the mass of the tooth, k is the stiffness per unit area of the PDL, and γ is a proportionality constant, which was estimated to be 1000 based on visual appraisal of the fit between the modeled and measured acceleration signals and fixed for all analyses. Note that ζ_2 is estimated from the measured acceleration signal through a curve fitting procedure in the data processing phase of the analysis.[15]

Figure 1. Clinical photos showing the in vivo mechanical model.

The ASIST procedure was used to analyze the clinical data to determine the ASC values for each visit throughout orthodontic treatment. The primary outcome measures were the longitudinal changes in ASC for individual patients. Longitudinal changes in ASC were compared for both teeth in individual patients and across patients. After checking for data distribution normality, a paired t test ($P < .05$) was used to compare ASC values at the final visit with initial, pretreatment values. For comparison between left and right side values an independent Student's t test was used ($P < .05$). Additionally, the damping ratio of the higher frequency component of the acceleration signal was investigated through descriptive statistics as a secondary outcome measure to provide an understanding of the damping within the ligament tissue.

RESULTS

Figure 2 shows the measured accelerometer data and resulting model prediction for several visits throughout treatment for one example patient. The

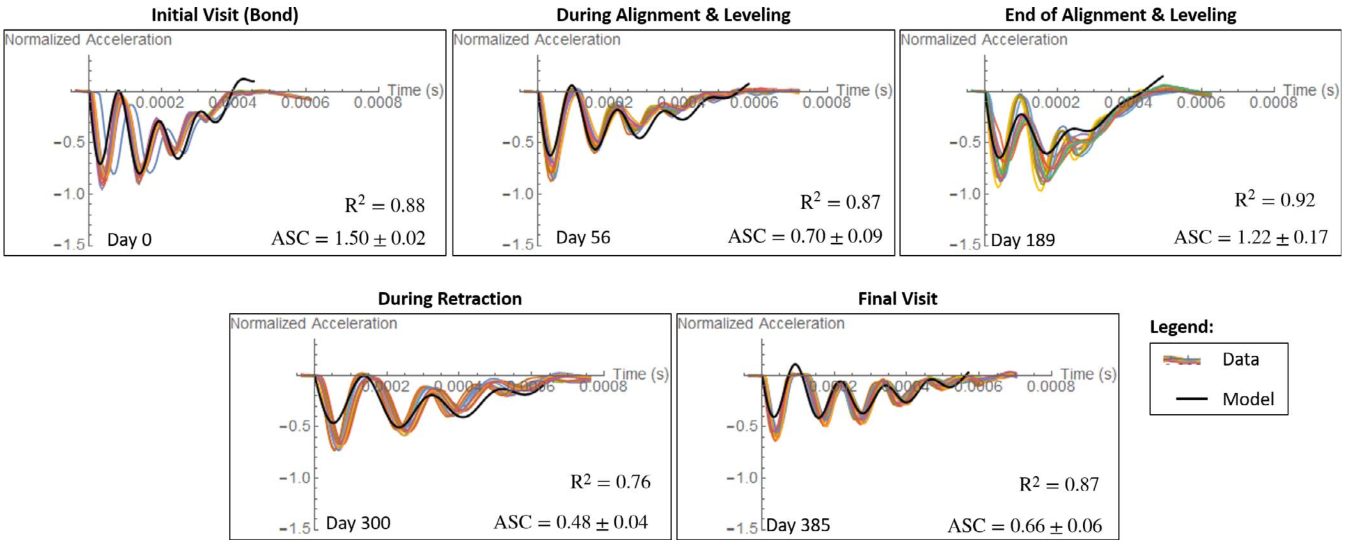

Figure 2. Measured accelerometer data (colored lines) and model predicted response (black line) for Patient 1 (AS) tooth ID 13. Each plot shows an example of the data and model fit for one clinic visit (visit day indicated on each figure). The ASC values are average ± SD for repeated measures on each day.

figures show one example measurement from the visits indicated. The ASC values are also shown on the figures and are reported as the average ± SD for repeated measures at each visit. It can be seen from the figure that there was a good fit between the model and the measured data for each case. There were clear differences in the measured acceleration response at the different times during treatment, which are reflected in the calculated ASC values. For this example patient, the maximum ASC occurred at the initial visit before treatment (ASC = 1.50). There was a reduction in stiffness during the alignment and leveling phase with a drop in ASC to 0.70 followed by an increase in stiffness at the end of that phase (ASC = 1.22). There was another reduction in stiffness during the space closure phase with a minimum ASC of 0.48 followed by a slight increase at the final visit (ASC = 0.66).

Figure 3 shows the longitudinal changes in ASC throughout treatment for all patients. The reported values are the average of repeated measures at each visit and the error bars show one standard deviation. The results are reported for both maxillary canine teeth. No significant differences were found between average ASC values for left and right teeth across patients ($P = .21$). Both teeth tended to show a similar pattern of longitudinal changes in ASC for individual patients and the pattern of longitudinal changes was relatively similar across patients. All patients showed some decrease in the PDL stiffness (as measured by the ASC value) during the course of orthodontic treatment. The maximum reduction in stiffness was 73.4 ± 7.7% (average ± SD) over all the teeth examined. All patients showed a substantial reduction in ASC following the initial visit (during the alignment and leveling phase). Many patients showed a slight recovery in the ASC value following the alignment and leveling phase, which was then followed by a second decrease in ASC during the space closure phase. Some recovery was again observed for most patients at the final check-up; however, none of the patients had the ASC return to the pretreatment value by the end of the study period. Across all patients, the ASC at the final visit (ASC = 0.67 ± 0.17) was significantly lower than the ASC at the initial visit (ASC = 1.46 ± 0.37) with $P < .001$. On average, the ASC value at the final visit was 48.2 ± 12.2% of the value at the initial visit.

The damping ratio of the higher frequency component of the measured acceleration was found to be 0.119 ± 0.068 with a range of 0.040–0.917. There was one dataset that had an unusually high damping ratio (0.917). Removing this outlier from the clinical dataset resulted in an average damping ratio of 0.116 ± 0.049 and a range of 0.040–0.422.

DISCUSSION

This study presented an evaluation of the longitudinal changes in mechanical properties of the maxillary canine PDL during orthodontic alignment and retraction as measured by the ASIST. Using the ASC value as the outcome measure, all patients showed a substantial decrease in PDL stiffness during treatment. The patients showed some recovery in ASC at the end of the evaluation period (approximately 1 year); however, they did not reach the pretreatment value in any of the cases. Similar patterns of longitudinal

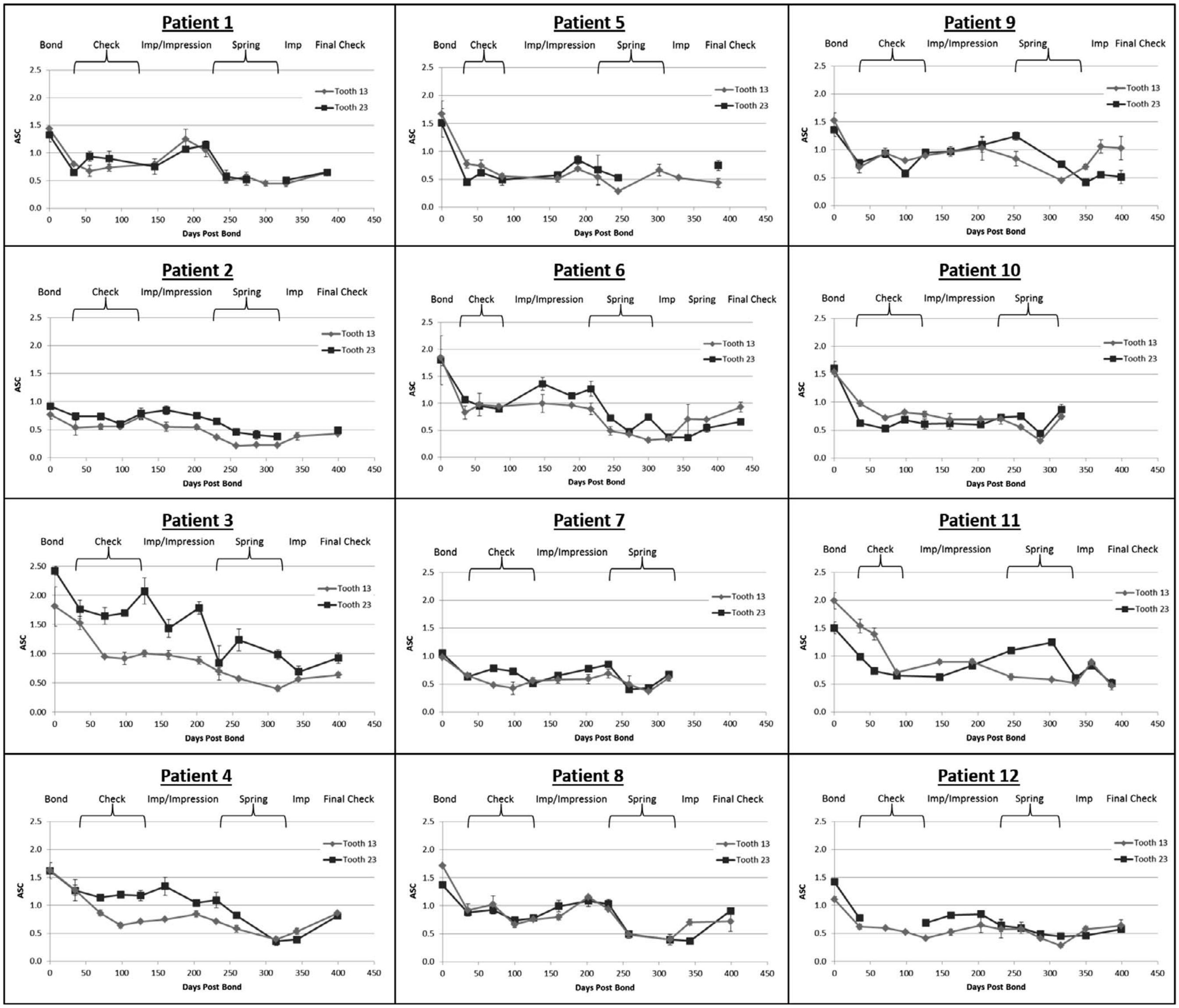

Figure 3. ASC measurements for tooth ID 13 and 23 for all patients. Reported values are the average of repeated measurements and error bars show one standard deviation.

changes were observed across patients. Additionally, both teeth in individual patients showed similar patterns of longitudinal changes regardless of the force level applied. This was particularly interesting since different magnitudes of orthodontic forces were applied to each tooth in an individual patient with one tooth having approximately twice the force applied compared to the other tooth. In this sample, stiffness values at the end of the assessment period were less than 50% of the initial values. This study did not explore if and how long it may take for PDL stiffness values to return to pretreatment values.

Tooth mobility has been shown to increase during orthodontic treatment and decrease following a retention phase as measured by the Periotest.[14] Additionally, orthodontic tooth movement has been associated with biological changes at various tissue levels.[5–9] The reduction in ASC value during treatment in this study suggested a corresponding reduction in PDL stiffness, which was consistent with findings reported in the literature. These changes reflected clinical findings where teeth are mobile to different degrees when archwires are temporarily removed for oral hygiene or archwire change purposes. Again, as these patients were not followed during the retention phase, it was not possible to report if the ASC values will eventually return to the pretreatment values.

The ASC value reported in this study was a normalized value that is directly related to a representation of the PDL stiffness defined by an analytical model.[16] The PDL is a complex, viscoeleastic tissue with different behavior under short and long term loading.[2,3] The ASIST uses an impact technique applying rapid loading to the tooth; thus, the ASC value is associated with a dynamic PDL stiffness. In this study, significant changes in the dynamic stiffness of the PDL were shown, as measured by the ASC, associated with orthodontic tooth movement.

In regard to the clinical importance of these results, the ASIST can provide a valuable tool to clinically monitor the PDL stiffness of natural teeth that are undergoing orthodontic tooth movement. In this study, changes were detected in ASC during orthodontic tooth movement, providing insight into the mechanical changes that occurred at the tooth root interface during treatment. It would have been interesting to assess changes at the end of full orthodontic treatment and follow the values during retention. Normalization of those values could be related to increased tooth stability after orthodontic treatment.

Clinically, mobility scores are assigned to teeth when assessing their mobility in day-to-day orthodontic practice when a tooth is considered to be behaving abnormally. The ASIST could be used in those cases to provide a more specific and reliable reference value compared to visual and tactile assessment. This could also apply to assessment of mini-screw stability immediately after insertion and during their use. The clinical importance of improved measurements should be tested to support its generalized use.

The present study had several limitations that should be noted. First, as mentioned already, the PDL stiffness associated with the ASC measure was a representation of the physiological tissue based on the defined analytical model. The PDL was modeled as a uniform, linear stiffness, distributed over the area of a paraboloid-shaped root. Viscous damping was included in the PDL model to simulate the damping within the tissue. It is important to be aware that these assumptions simplified the complex behavior of the PDL, and the ASC measure was meant to provide an estimate of the dynamic PDL stiffness within the context of these assumptions. Secondly, it is important to understand that handpiece positioning, including striking height and angle from the horizontal, may have had a significant effect on the experimentally measured acceleration signal.[18] Thus, it is important to follow a strict measurement protocol during testing. A measurement protocol and reliability measurements have been investigated for use of the ASIST with implants,[18,19] and a similar measurement protocol was followed in this study. However, a better understanding of the reliability in experimental measurement with natural teeth and a measurement protocol specifically developed for this application would be beneficial. Additionally, since the PDL width was not measured in this study, it was not possible to comment directly on the relationship between ASC value and PDL width. Actual tooth movement was not measured during treatment, so a correlation was not provided in terms of a specific change in ASC associated with a specific amount of tooth movement. Measurements immediately after orthodontic appliance removal and during retention are not available. How the ASC values are modified at those stages is unknown. Finally, this study considered only single-rooted teeth. Application of the ASIST to multirooted teeth is an important extension of this work that should be considered in a future study.

CONCLUSIONS

- At the end of the assessment period (end-of-space closure), PDL stiffness values were less than 50% of the pretreatment ones.
- Differences in two orthodontic forces (approximately 80 g vs 150 g) did not affect the observed treatment changes.

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