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Accuracy of a smartphone-based orthodontic treatment monitoring application

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Dentistry at Virginia Commonwealth University.

by

Heather B. Moylan
D.D.S., Louisiana State University School of Dentistry, 2016
B.F.A., Louisiana State University, 2012

Thesis Director: Eser Tüfekçi, D.D.S, M.S., Ph.D., M.S.H.A.
Professor, Department of Orthodontics

Virginia Commonwealth University
Richmond, VA
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Abstract

ACCURACY OF A SMARTPHONE-BASED ORTHODONTIC TREATMENT MONITORING APPLICATION

By Heather B. Moylan, D.D.S.

A thesis submitted in partial fulfillment of the requirements for the degree of Master of Science in Dentistry at Virginia Commonwealth University.

Virginia Commonwealth University, 2018

Thesis Director: Eser Tüfekçi, D.D.S., M.S., Ph.D., M.S.H.A
Professor, Department of Orthodontics

Objectives: Dental Monitoring® ("DM," Dental Monitoring, Paris, France), is a cloud-based software that allows orthodontists to track patients' treatment remotely. The purpose of this study was to investigate the accuracy of the software in making linear measurements.

Methods: Patients took intraoral photographs using the DM application, immediately followed by impressions for plaster models. Intercanine and intermolar width and arch depth measurements were made by DM and compared to measurements made on the plaster models. Data was analyzed using two one-sided t-tests for equivalence with equivalence bounds of +/-0.5mm. Significance level was set at 0.05.

Results: Thirty sets of measurements were compared. The intercanine and intermolar measurement differences were on average 0.17mm and -0.02mm, respectively, and were deemed equivalent. The arch depth measurements had an average difference of -0.54mm and were deemed not equivalent.

Conclusion: The monitoring software seems to provide an accurate assessment of linear tooth movements.

Introduction

With recent advances in digital and informational technology, telemedicine and teledentistry have gained acceptance in the delivery of healthcare to patients living in remote places with limited or no access to care. Teledentistry is defined as the use of electronic technology or media, including interactive audio and video, for the purpose of diagnosing or treating a patient or consulting with other health care providers regarding a patient's diagnosis or treatment.[1] These communication technologies are thought to increase access to care, improve the delivery and the management of care, and decrease the cost of healthcare.[1-3]

In a 2011 study, Glazer et al.[4] investigated the efficiency of speech therapy provided through telecommunications. The authors reported that teledentistry was successful in significantly improving post-operative functional outcomes following cleft palate repair in rural and underserved international populations. Similarly, in 2016, Hughes et al.[5] evaluated the reliability of remote digital video in the preoperative diagnosis of cleft lip and palate in resource-poor settings of rural Ecuador. The results of this study found a substantial agreement and reliability between in-person and remote digital video assessments for the cleft lip patients; however, the agreement was moderate for the cleft palate patients and poor for the alveolar cleft patients. Nevertheless, the authors concluded that teledentistry could serve as a reliable way to make diagnoses in low- and middle-income countries where access to care is limited. Furthermore, it was suggested that the interactive technology used for the preoperative evaluation of the less severe cases could improve clinical effectiveness while reducing cost.

In orthodontics, teledentistry was used as early as 2008. Berndt et al.[6] reported that interceptive treatments provided by general dentists who were remotely supervised by orthodontists using teledentistry were effective in reducing the severity of malocclusions in disadvantaged children who did not have access to a specialist. Favero et al.[7] also concluded that teledentistry is particularly useful in orthodontics because minor emergencies such as discomfort due to an appliance or elastomer ligature displacement can usually be solved at home without an orthodontic office visit. Another study[1] that assessed the validity of a teledentistry system for initial orthodontic examinations reported that screening and accepting orthodontic referrals based on clinical photographs was comparable to those of in-office visits in the clinical decision-making process.

With the routine use of intraoral scanners and digital cameras, clinicians can now take advantage of digital models and photographs to analyze and review cases, and to communicate among doctors, patients, and labs. One recent revolutionary technology is Dental Monitoring™ (DM, Paris, France), which is a cloud-based software that allows orthodontists to track their patients' treatment remotely. DM allows tracking of tooth movement using photographs taken by the patient through a smartphone application and communicates this information to the doctor.

The DM technology consists of three integrated parts: the iOS (Apple Inc., Cupertino, CA). or Android (Google, Mountain View, CA) smartphone application, a patented tooth movement-tracking algorithm, and a web-based Doctor Dashboard. To initiate remote monitoring, the orthodontist uploads a stereolithography (STL) file of the patients' initial models to the Dental Monitoring platform to define the baseline tooth position. Between orthodontic appointments, patients use the smartphone application and specific Dental Monitoring cheek retractors to take photos remotely at intervals requested by the treating doctor. For each of these

new photo exams, DM builds an updated digital model of the teeth. DM's patented algorithm then calculates tooth movements such as intrusion, extrusion, space closure, and torque are quantified and shared with the orthodontist.

The Doctor Dashboard is the orthodontist's interface with the software, and it contains multiple tools to assess tooth movement. The activity graph (Figure 1) gives an overall graphic visualization of tooth movement per arch. The doctor can use it to quickly determine whether an appliance is active or passive. A separate graph quantifies the movements of individual teeth (Figure 2). Six linear and angular measurements are given: mesial/distal translation, extrusion/intrusion, buccal/lingual translation, buccal/lingual torque, rotation, and mesial/distal angulation. The photo viewer allows comparison between two selected time points (Figure 3). With one click, the clinician can view side-by-side photos of the two time points taken from similar angles. The doctor can also replay the motion of the teeth during treatment using the software's 3D Matching feature, which superimposes previous models on the current photos to illustrate the evolution of tooth movement (Figure 4).

DM allows orthodontists to track treatment progress in real time on a weekly basis. An alert can be requested when a preset objective has been achieved, such as a specific amount of space opening or space closure. A team of DM doctors also review the remote exams and are able to send an alert if a problem is detected, such as a broken appliance, poor hygiene, or gingival recession. In this way, many appointments requiring a simple evaluation may be eliminated, and it is possible that the use of this technology could decrease cost and chairside time while improving delivery of orthodontic care.

Although Dental Monitoring is commercially available and is perceived by many clinicians as a valuable tool for the treatment of orthodontic patients, to date there are no studies that have evaluated the reliability and accuracy of the software. Therefore, the purpose of this study was to investigate the reliability and accuracy of the DM system in patients who are undergoing orthodontic treatment with a rapid maxillary expander (RME). Specifically, intercanine, intermolar, and arch depth measurements made by the software were compared to measurements made on plaster models produced during in-office visits.

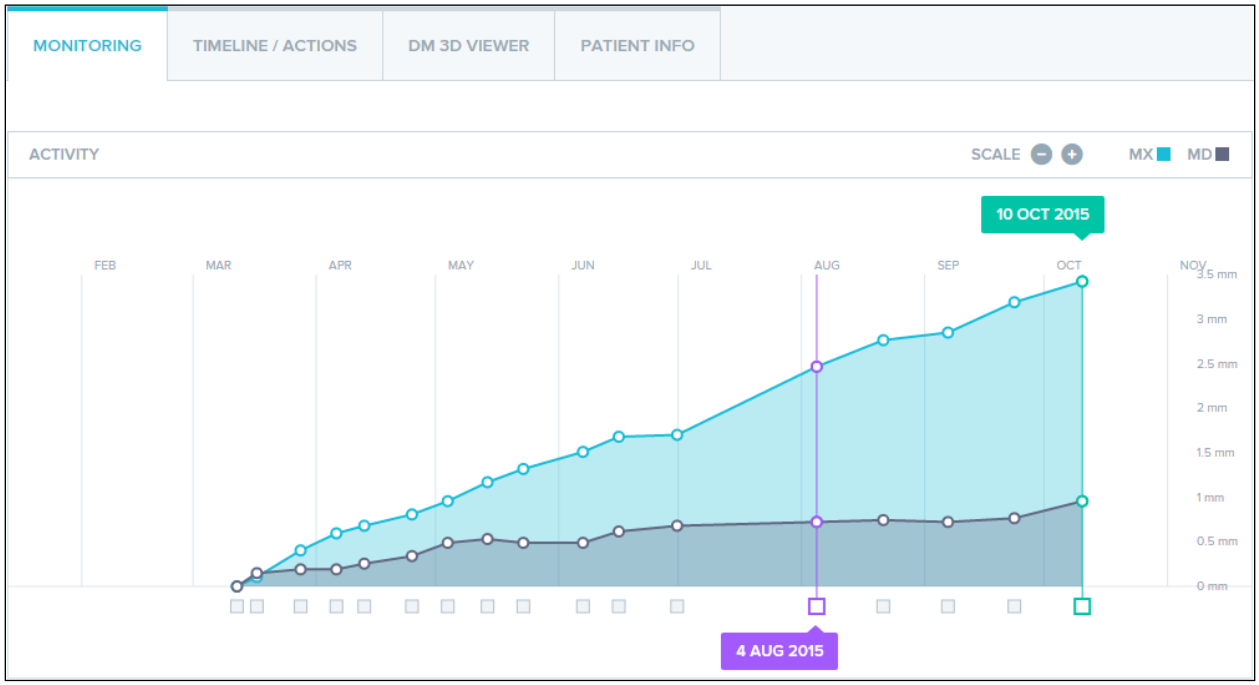


Figure 1. Treatment activity graph. This graph measures the movement of the maxillary (blue) and mandibular (gray) teeth for sixteen intervals over seven month.

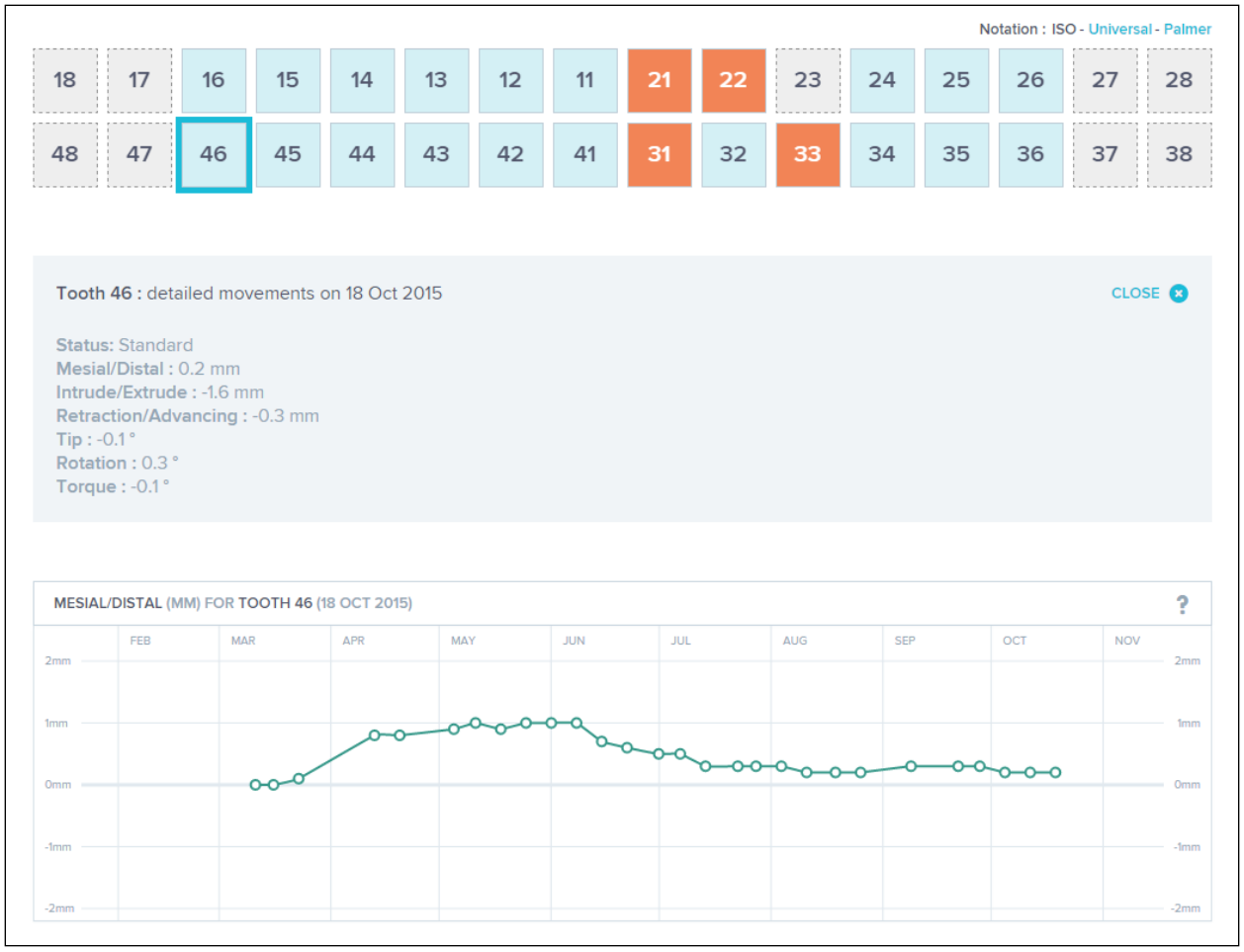


Figure 2. Individual tooth movement table. These tables show movements for an individual tooth. Linear measurements are given for mesial/distal translation, extrusion/intrusion, and buccal/lingual translation. Angular measurements are given for buccal/lingual torque, rotation, and mesial/distal angulation.

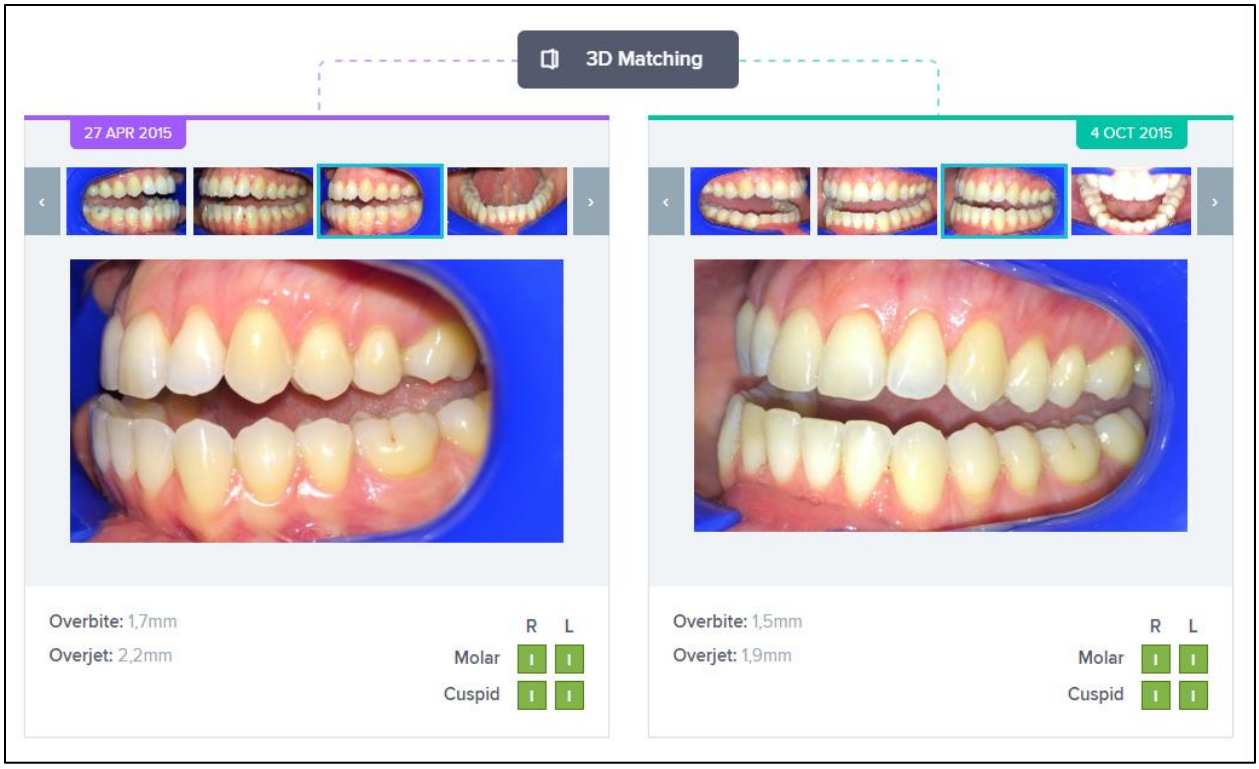


Figure 3. Photo viewer. The doctor can easily compare photos of two time points taken from a similar angle. Clicking on one of the thumbnail images automatically opens the corresponding view for the other time point.



Figure 4. 3D Matching. Models of the previous tooth positions are superimposed on the current photos to illustrate the tooth movement in three dimensions.

Participants and Study Design

Prior to the study, approval from the Institutional Review Board of Virginia Commonwealth University and parental consent forms along with patient assent forms were obtained. Subjects (n=12) between the ages of 8 and 16 were recruited among VCU Orthodontic Clinic patients seeking orthodontic treatment that required maxillary expansion. The following selection criteria were used:

1) Good overall health
2) No craniofacial syndrome
3) Maxillary first molars and either both canines or both first premolars erupted
4) Teeth with a normal crown morphology

At the initial appointment, study participants received the Dental Monitoring cheek retractors and were trained to use the smartphone application to take their intraoral photographs. To circumvent the possibility of patients forgetting to take their photos at home at the required time, the training session and all subsequent photographic exams were conducted in the clinic using the investigator's iPhone 6 Plus (Apple Inc., Cupertino, CA). At the following appointment, the RME was delivered, and digital images of the maxillary and mandibular arches were taken with a single iTero Element intraoral scanner (Align Technology, San Jose, CA). The maxillary arch, mandibular arch and both arches in occlusion were uploaded to the Dental Monitoring platform in the STL format to serve as a baseline. At this time, the patient also completed and uploaded a set of photographs with the application. To simulate the patient using the application outside of the clinic setting, minimal assistance was given during the photographic exam. Immediately after the patient finished his or her set of photographs, the

investigator took a separate photographic exam for independent assessment by Dental Monitoring. After the photographs were completed, one operator took alginate impressions of the maxillary and mandibular arches and poured plaster models (Fujirock, GC America, Alsip, IL). The plaster models served as the gold standard to measure the movements of the maxillary molars and canines assessed by Dental Monitoring. To assess error in the impressions and plaster models, the intercanine width was measured intraorally and on the models.

The study was carried out during the active phase of palatal expansion treatment until the amount of the maxillary expansion was deemed satisfactory by the treating orthodontist. Patients were scheduled for weekly clinical observations. During these observation visits, the alginate impressions, intraoral intercanine measurement, and photo-taking protocol was repeated as described above. For the majority of subjects, there were two follow-up appointments following RME delivery. No intraoral scans were taken at these subsequent appointments.

To evaluate the accuracy of the Dental Monitoring system in making linear measurements, the intercanine and intermolar distances and the arch depth measurements were carried out on the plaster models using the following methods (Figure 5):

1) Intercanine distance (IC, mm): the straight distance between the cusp tips of the right and left canines or the center of the wear facets in cases of attrition
2) Intermolar distance (IM, mm): the straight distance between the tips of the mesiobuccal cusps of the right and left maxillary first molars[8]
3) Arch depth (AD, mm): the perpendicular line constructed from the contact point of the central incisors to the intermolar distance line[9]

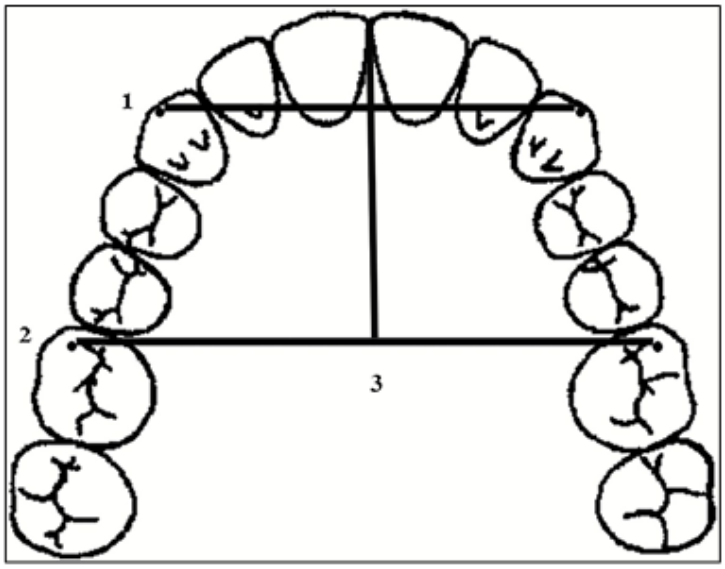


Figure 5. Intercanine (1), intermolar (2) and arch depth (3) measurements. Adapted from Yilmaz et al.[10]

Statistical Analysis

All measurements were performed using digital calibers by one calibrated operator. After an initial calibration, the method error was calculated from double measurements of 10 randomly selected plaster models re-measured after an interval of two weeks. Intraclass Correlation coefficient was used to assess the accuracy of the single measurer and with an independent reviewer. Two one-sided tests for equivalence were performed between the provider's measurements and the two measurements from the Dental Monitoring™ application based on either the patient photographic exams or the provider photographic exams. Equivalence bounds were set at +/-0.5mm. Rate of successful photographic exams between patients and the provider were compared using chi-squared test.

Results

The intraclass and interclass correlation coefficients for repeated measurements for all parameters were near perfect (Table 1).

A total of 30 examinations were measured by both the provider and the mobile application based on patient photos and 28 examinations were measured by both the provider and the mobile application based on provider photos.

In terms of photo quality, 6% of the photos taken by patients were deemed insufficient (n=2 out of 30) compared to 4% of the photos taken by the provider (n=1 out of 28). This difference was not significant (p-value=0.6133).

The intercanine and intermolar measurements were equivalent within +/- 0.5mm with both the patient and the provider photos (Table 2). Arch depth measurements were not equivalent with either the provider or the patient photographic exams. Bland-Altman plots to demonstrate the average differences between the sets of measurements are given in Figures 6 and 7.

The average absolute differences between the manual measures and the application using patient photographic exams and provider photographic exams are given in Tables 3 and 4, respectively.

Table 1. Accuracy of measurements between the two raters.

	Operator 1 (intra)	Operator 2 (intra)	Operators 1 & 2 (inter)
Inter-Canine	0.998	0.996	0.997
Inter-Molar	0.993	0.997	0.996
Arch Depth	0.998	0.995	0.994

Table 2. Average difference and equivalence bounds for intercanine and intermolar widths and arch depth measurements between direct measurements and software measurements using patient or provider photographic exams.

	Patient Photographic Exams			
	Average Difference	**90% CL**		**Equivalent (+/-0.5mm)**
Intercanine	0.17	0.00	0.34	Equivalent
Intermolar	-0.02	-0.26	0.29	Equivalent
Arch Depth	-0.54	-0.93	-0.14	Not Equivalent
	Provider Photographic Exams			
	Average Difference	**90% CL**		**Equivalent (+/-0.5mm)**
Intercanine	0.18	0.00	0.36	Equivalent
Intermolar	0.10	-0.14	0.34	Equivalent
Arch Depth	-0.26	-0.59	0.06	Not Equivalent

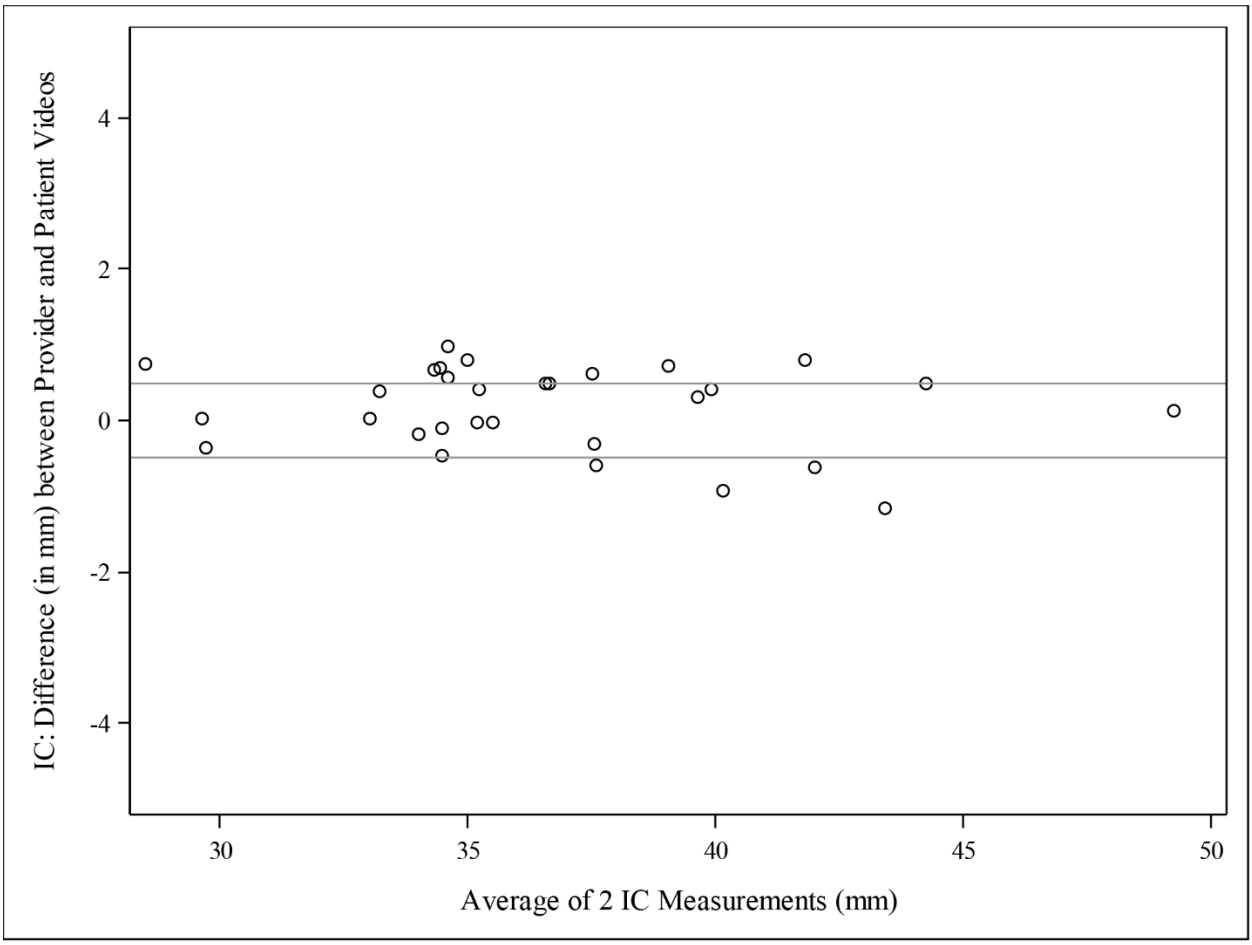


Figure 6. Bland-Altman plot showing differences for intercanine width between provider measurements and software measurements from patient photographic exams.

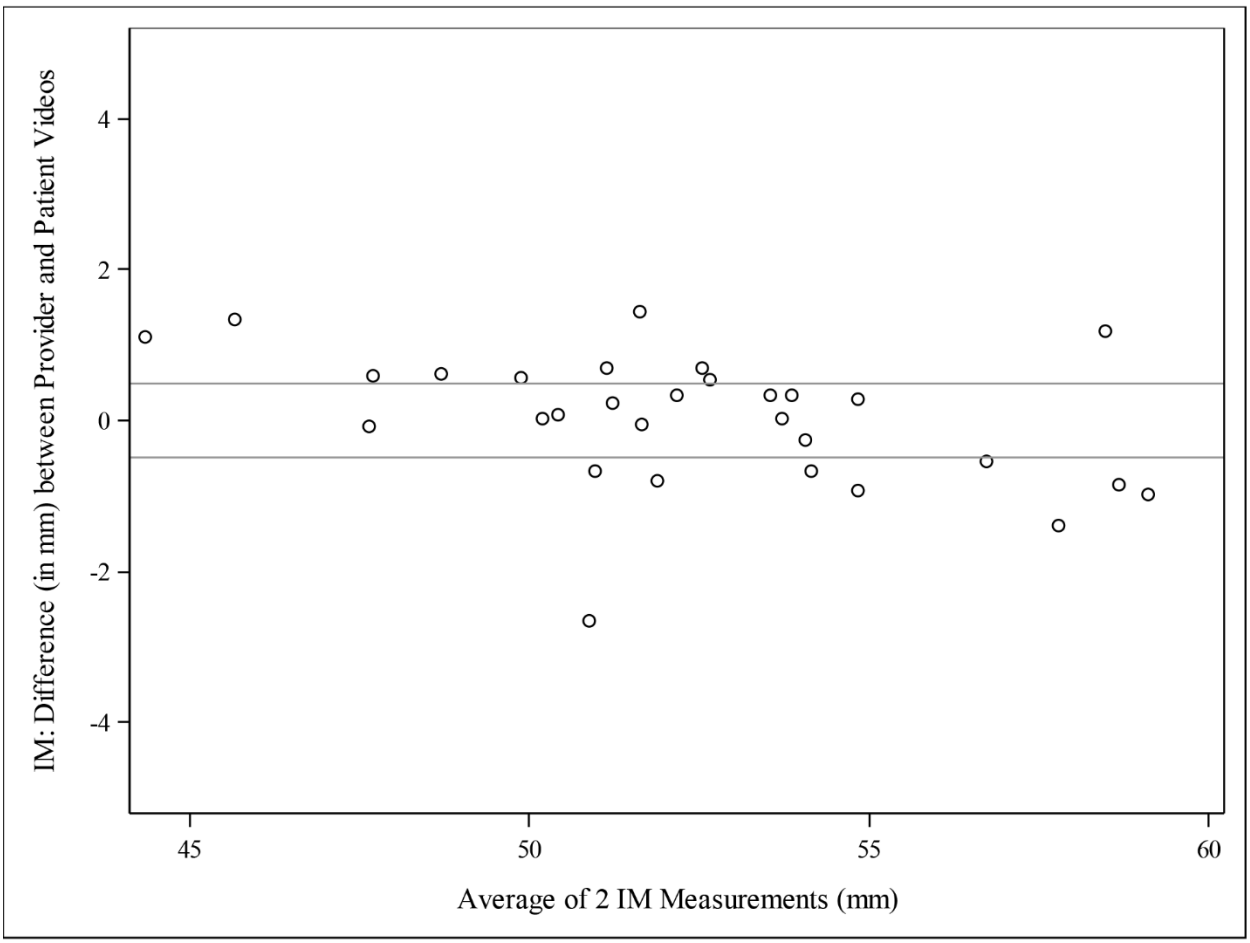


Figure 7. Bland-Altman plot showing differences for intermolar width between provider measurements and software measurements from patient photographic exams.

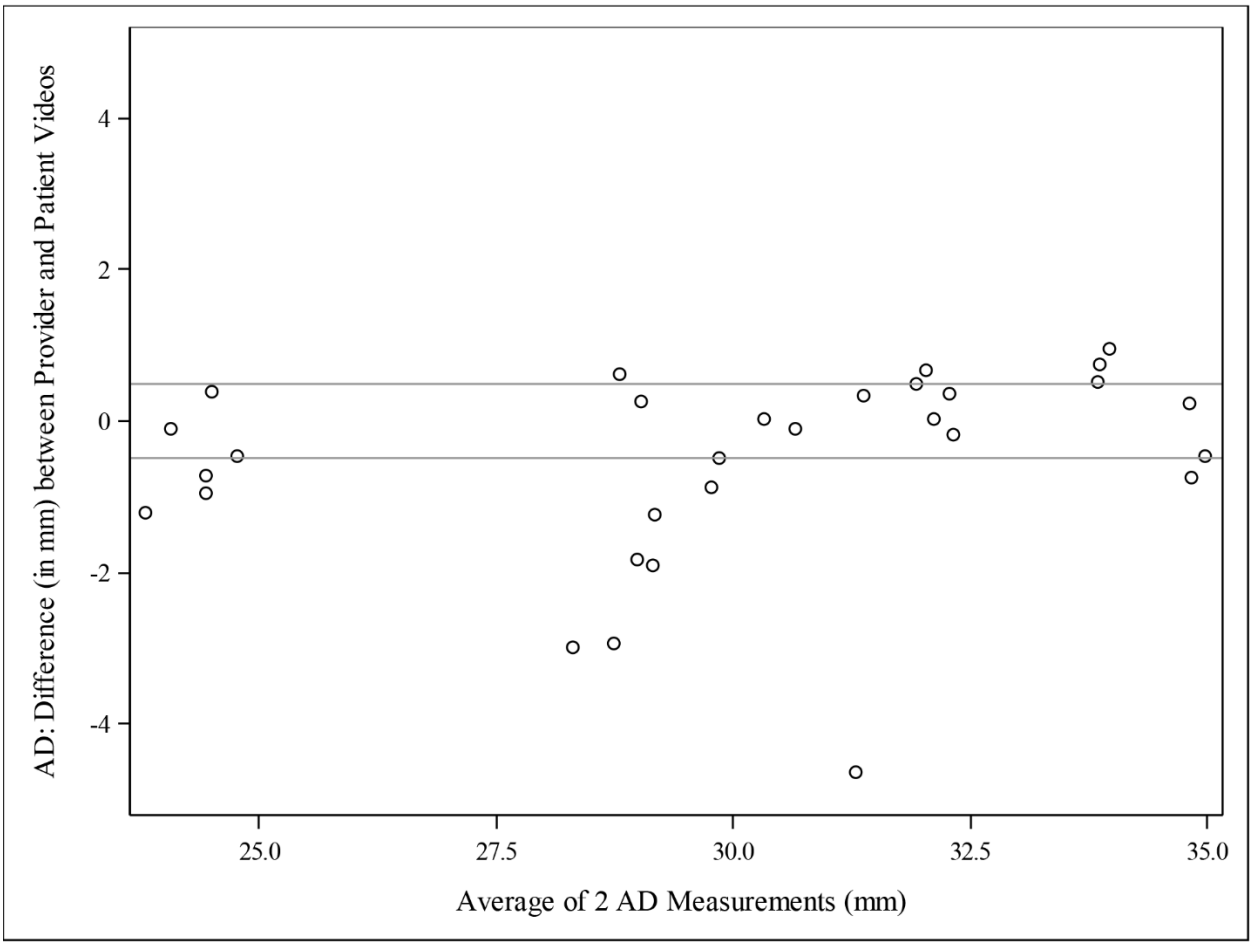


Figure 8. Bland-Altman plot showing differences for arch depth between provider measurements and software measurements from patient photographic exams.

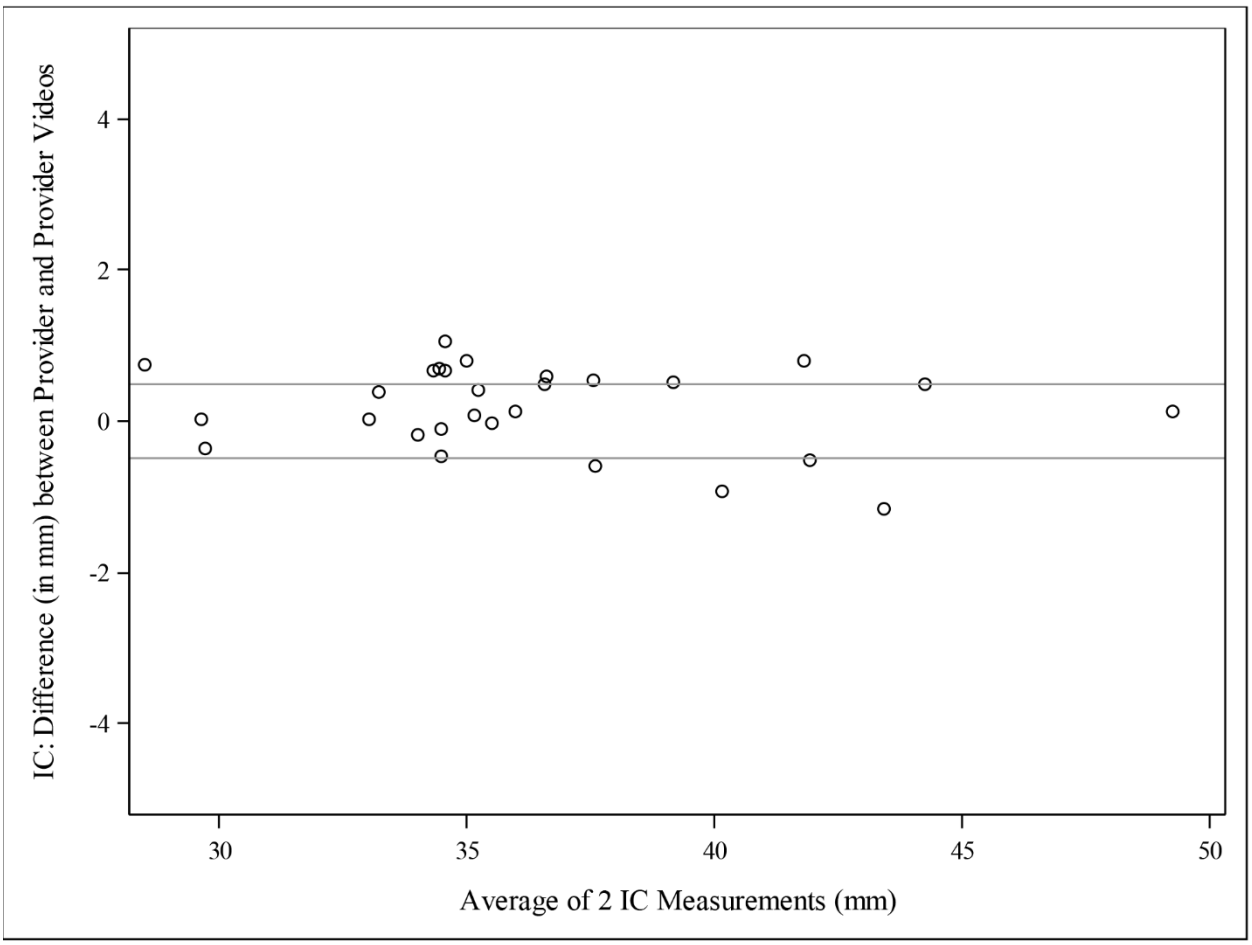


Figure 9. Bland-Altman plot showing differences for intercanine width between provider measurements and software measurements from provider photographic exams.

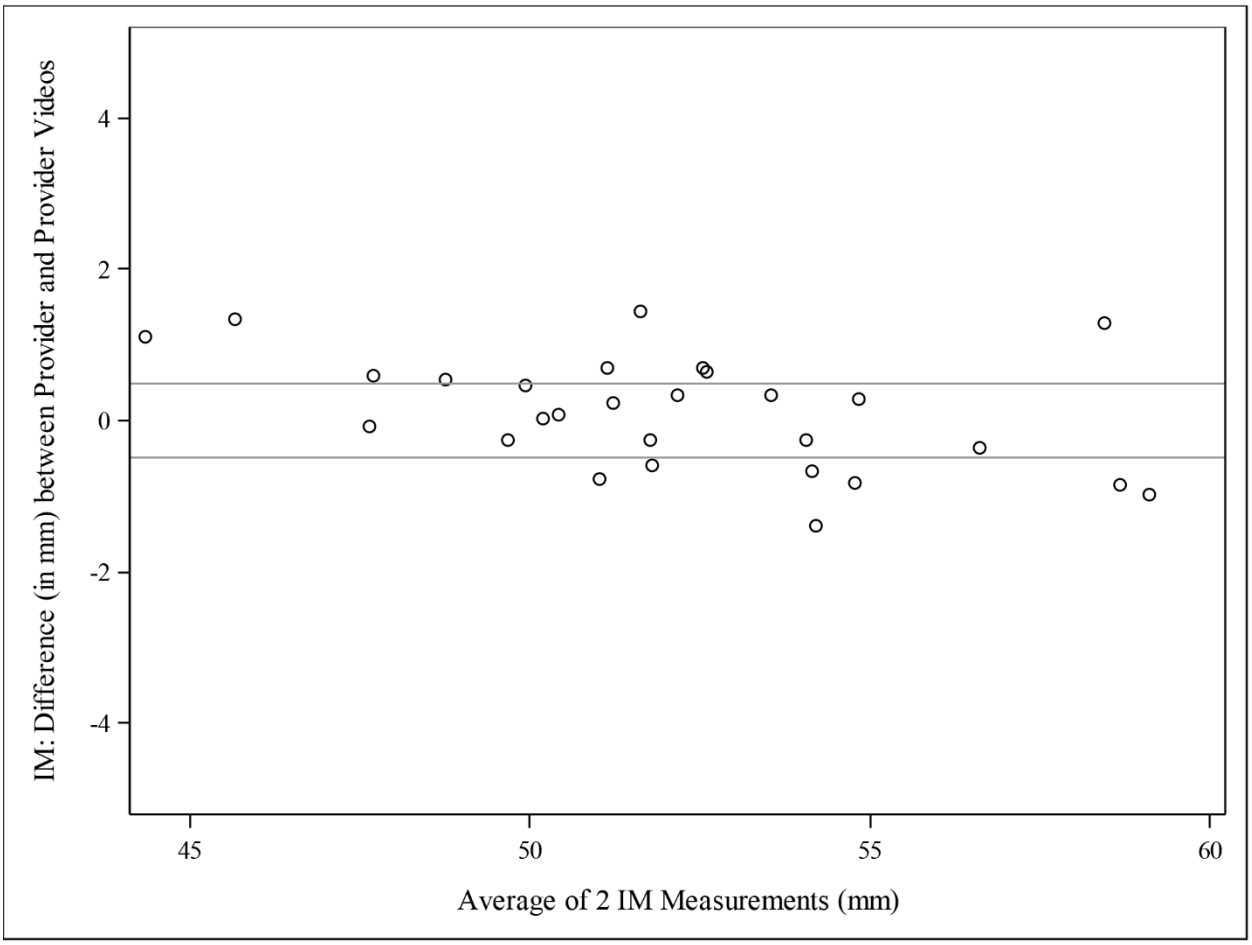


Figure 10. Bland-Altman plot showing differences for intermolar width between provider measurements and software measurements from provider photographic exams.

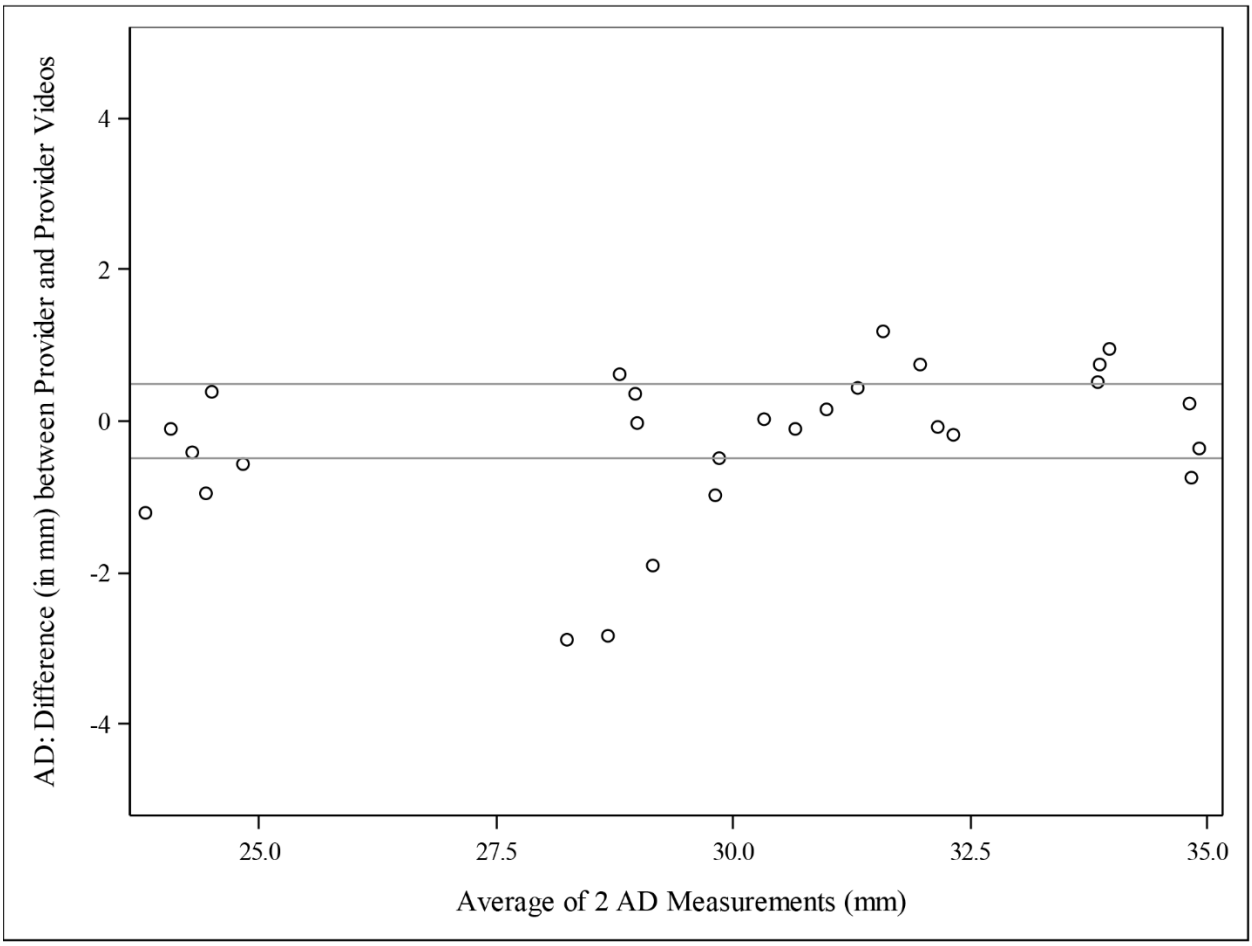


Figure 11. Bland-Altman plot showing differences for arch depth between provider measurements and software measurements from provider photographic exams.

Table 3. Average absolute difference of patient photographic exams.

	Patient Photographic Exams			
	Average Absolute Difference	**SD**	**Min**	**Max**
Intercanine	0.48	0.30	0.02	1.17
Intermolar	0.68	0.56	0.02	2.65
Arch Depth	0.91	1.03	0.03	4.63

Table 4. Average absolute difference of provider photographic exams.

	Provider Photographic Exams			
	Average Absolute Difference	**SD**	**Min**	**Max**
Intercanine	0.48	0.32	0.02	1.44
Intermolar	0.62	0.41	0.02	1.17
Arch Depth	0.72	0.74	0.03	2.89

Discussion

Digital technology has paved the way for a paradigm shift in a multitude of industries, including retail, real estate, entertainment, education, and healthcare. The ability to rapidly gather, analyze, and disseminate large quantities of data through digital networks has revolutionized the world. According to founder and executive chairman of the World Economic Forum, Klaus Schwab, a Fourth Industrial Revolution is now underway, characterized by the fusion of physical, digital, and biologic spheres.[11] Dental Monitoring® and other biometric devices are examples of the technology that defines this era.

According to Schwab, customers' needs are the epicenter of the new economy, with the smartphone as the hub.[11] In orthodontics, the use of a monitoring application may enable clinicians to closely follow their patients' treatment with fewer office visits, which reflects a more patient-centered approach. By setting notification preferences when a predetermined amount of space opening, space closure, or expansion has been achieved, unnecessary evaluation appointments may be eliminated. Some patients may even be able to receive treatment for an orthodontic emergency from home if the orthodontist can visualize the problem with photos through the application. Also, the monitoring software could analyze tooth movement changes in retention compared with a post-treatment baseline to determine the necessity of retention appointments.

According to estimates provided by Dental Monitoring®, the error margin for measurements is, on average, 0.05mm for linear movements (closer to 0.07mm for the posterior segment) and 0.5° for tip, torque, and rotation. These values are less than those found in this study. The difference between the investigators' and DM's measurements were slightly greater

for intermolar than for intercanine distance, supporting DM's disclosure of greater error in the posterior segment. A likely reason for this difference could be the difficulty in capturing the posterior teeth in the photographs. A photographic exam consists of three sets of photographs taken by the patients with the cheek retractors in place. The first two are similar, with the patient turning his or her head side-to-side to capture the anterior teeth and the buccal segments from the facial view. The difference between these two sets of photographs is that the first one is with the patient biting, and the second one is with the teeth slightly apart. The third and final set of photographs captures the occlusal views while the patient opens wide and moves his or her head up-and-down, simultaneously changing the angle of the camera to record the occlusal aspects of both arches. This is somewhat difficult to do, especially in capturing the posterior teeth. Since the current study evaluated the parameters related to palatal expansion, the measurements were made from the occlusal photographs, which could be less accurate due to the difficulty in obtaining photographs of good quality. Thus, measurements of the anterior region or areas of direct vision may be closer to DM's range of error than the posterior region.

If the photographic exams are of insufficient quality, the software does not build a new digital model or take measurements. Instead, the patient receives an e-mail approximately one day later informing him or her of the inadequate photos and prompts a new photo exam. At the start of the experiment, several of the exams were of insufficient quality for processing, but this was not known until the following day. Because the study design called for patients to take the photos in the clinic, the photos could not be repeated. Therefore, the study design was modified so that the patient took his or her own photographic exam, immediately followed by the investigator taking a separate photographic exam of the patient. This way, it was more likely that there would be enough data for the study. A secondary purpose was that it could be determined if

there was a difference in the photo quality when the exams are performed by the patient versus a trained orthodontic specialist. There was no significant difference in the number of rejected photo exams between the photographs taken by patients those taken by the investigator, at 6% versus 4%, respectively.

The quality of instruction when teaching patients to use the application likely affects photo exam quality. The quality of the patients' photographic exams appeared to improve over the study period, and this may be attributed to better patient training towards the end of the study as the investigator gained experience with the software. If a clinician is going to implement the monitoring software into his or her practice, it may be beneficial to designate to one employee the duty of teaching patients to use the application.

Measurements of arch dimensions were made on plaster models because they are still considered to be the gold standard, though digital models may be reaching a tipping point in replacing plaster models as the gold standard. Multiple studies have confirmed the accuracy of measurements taken on digital models, particularly intra-arch measurements.[12-14] However, some studies have found small but statistically significant differences between measurements taken on plaster and digital models.[15,16] No studies have examined the accuracy of digital models with an appliance in place, such as an RME. Therefore, in this study, the plaster models with the appliances were used to make the measurements.

While plaster models are considered to be the truest reproduction of the dentition, there is inevitably some degree of inaccuracy.[13] It has been well-documented that alginate shrinkage is time-dependent.[17,18] To minimize distortion, impressions were made and poured immediately by one operator. However, no studies were found that investigate the effect impressing over an RME or other appliance on alginate distortion, introducing a variable of unknown significance.

New Fujirock® Type IV die stone has a linear setting expansion of 0.08%, according to the manufacturer. A study comparing seven types of die materials found that a similar Type IV stone had expansion values between 0.16-0.30%,[19] although this was not the same product used in this study. There are two possible methods to eliminate the inaccuracies caused by model-making procedures. One could make intraoral measurements and compare them to measurements made by the software. In theory, this would be the best way to ensure accuracy of the investigator's measurements, but in reality, this would be extremely difficult due to space constraints and visual limitations of working in the oral cavity, and would likely produce more error than model fabrication. Another option would be to perform an in-vitro study on a mannequin. However, the trade-off for increased accuracy of provider measurements would be a large reduction in clinical relevance compared with an in-vivo study. Thus, this study utilized plaster models with great effort to make them as accurate as possible, but the inherent inaccuracies in model-making introduce a potential source of error in the investigators' measurements.

The intercanine and intermolar measurements were made directly on the models and showed very strong agreement between the two operators. The arch depth measurement was more difficult. This was measured as a line along the palatal suture connecting the middle of the contact point of the maxillary central incisors with the line representing the intermolar width. Because the point along the intermolar width was not along the tissue surface, arch depth was measured indirectly on a standardized photo of the models. A given model was measured four times (twice by two raters), but these four measurements were taken from the same photo. Thus, it is possible that a slight change in angulation of the model when taking the photo could affect the arch depth. The precision between the two raters for arch depth was excellent, but this does not necessarily equate to accuracy. The larger difference between the investigators' and the

software's measurements for arch depth may reflect difference in the measurement method rather than a true error in the software's calculations.

Equivalence bounds of +/-0.5mm were chosen based on the study by Sweeney et al.[20] Those authors chose these bounds on the basis of the American Board of Orthodontics' incremental measures in grading casts as well as clinical relevance. They measured the accuracy of the articulation of maxillary and mandibular models with different bite registration materials by measuring the distance between points the upper and lower pair of a given tooth (i.e. maxillary first molar and mandibular first molar). These distances are far shorter than the cross-arch measurements used in the current study, so using equivalence bounds of +/-0.5mm may be stringent beyond what is clinically relevant. The other disadvantage of calculating results based on the mean's relationship to the equivalence bounds is that a simple "equivalent" or "not equivalent" may not accurately reflect the true data set. While the intercanine and intermolar means were equivalent between direct and photographic measurements, this does not paint a clear picture of the range of difference values. The average absolute difference gives a clearer summary of the difference between the two measurements.

It is likely that the range of error found in this study is not clinically significant, but its relevance should be interpreted by the clinician. In practice, seldom is precision within tenths of millimeters required. Measuring devices such as a periodontal probe or ruler may occasionally be used to aid in clinical decision-making, but they are typically accurate to a half-millimeter at best. More often, an orthodontist relies on visual inspection when evaluating the amount of tooth movement required and achieved. Thus, with average absolute differences of less than 1mm for all parameters, the accuracy of the monitoring software's measurements is likely to be sufficient for use in clinical practice.

Conclusions

- Intercanine and intermolar measurements made by the investigators and the monitoring software were equivalent within 0.5mm, while arch depth was not.
- There is insufficient evidence of a difference in quality when the photos are taken by patients versus by a clinician.
- The clinical significance of the findings should be interpreted by the clinician.
- Provided the quality of the photos is acceptable, the use of monitoring software can be reliable in making clinical decisions in the anterior region and areas of direct view in the oral cavity.

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