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Reliability and Accuracy of a Novel Photogrammetric Orthodontic Monitoring System

Vahe Ohanesian

LOMA LINDA UNIVERSITY
School of Dentistry
in conjunction with the
Faculty of Graduate Studies

Reliability and Accuracy of a Novel Photogrammetric Orthodontic Monitoring System

by

Vahe Ohanesian

A thesis submitted in partial satisfaction of
the requirements for the degree
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Each person whose signature appears below certifies that this thesis in his opinion is adequate, in scope and quality, as a thesis for the degree of Master of Science.

____, Chairperson
Joseph Caruso, Professor of Orthodontics and Dentofacial Orthopedics

____
Joseph Kan, Professor of Restorative Dentistry

____
Kitichai Rungcharassaeng, Professor of Orthodontics and Dentofacial Orthopedics

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ABBREVIATIONS

T1	Time Point 1
T2	Time Point 2
Rx	Buccal / Lingual Torque
Ry	Mesial / Distal Rotation
Rz	Mesial / Distal Angulation
Tx	Mesial / Distal Translation
Ty	Extrusion / Intrusion
Tz	Buccal / Lingual Translation
STL File	File format for stereolithography CAD software
True	Change measured when comparing intraoral scanner at time point 1 and intraoral scanner at time point 2
Pt1/T1	Change measured when comparing intraoral scanner at time point 1 with Dental Monitoring'sTM video scan at time point 1- first of two video scans taken by patient.
Pt2/T1	Change measured when comparing intraoral scanner at time point 1 with Dental Monitoring'sTM video scan at time point 1- second of two video scans taken by patient.
Op/T1	Change measured when comparing intraoral scanner at time point 1 with Dental Monitoring'sTM video scan at time point 1- taken by operator.
Pt1/T2	Change measured when comparing intraoral scanner at time point 1 with Dental Monitoring'sTM video scan at time point 2- first of two video scans taken by patient.
Pt2/T2	Change measured when comparing intraoral scanner at time point 1 with Dental Monitoring's™ video scan at time point 2- second of two video scans taken by patient.

Op/T2	Change measured when comparing intraoral scanner at time point 1 with Dental Monitoring's^{TM} video scan at time point 2- taken by operator.

ABSTRACT OF THE THESIS

Reliability and Accuracy of a Novel Photogrammetric Orthodontic Monitoring System

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Master of Science in Orthodontics and Dentofacial Orthopedics
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Dr. Joseph Caruso, Chairperson

Purpose: This study quantitatively investigated the reliability and accuracy of Dental Monitoring's™ proprietary orthodontic tracking system in comparison to an established reference.

Materials and Methods: Intraoral scans (True Definition Scanner, 3M™) and video scans (iPhone 7, Apple™) were taken of 30 subjects undergoing comprehensive orthodontic treatment at Loma Linda University's Graduate Orthodontic Clinic at T1 (initial) and T2 (3 months later). At each time point, an intraoral scan was taken by the operator followed by three video scans- two taken by the patient and one by the operator. Three linear and three angular measurements were analyzed using Dental Monitoring's™ tracking system for all comparisons. Accuracy was determined by comparing orthodontic movement tracked by Dental Monitoring's™ video scans against those measured via superimposition of STL files generated from the reference scanner using Friedman's analysis (α=.05). Intra-operator and inter-operator variability were evaluated and expressed as the intraclass correlation coefficient.

Results: Surface tolerance analysis demonstrated a maximum mean global error of 100 microns associated with the reference scanner. No statistically significant differences were observed between the reference and Dental Monitoring's™ system for the three linear parameters ($p > .05$); angular parameters showed statistically significant differences ($p < .001$). No statistically significant differences were observed when comparing upper vs lower or anterior vs posterior dentition ($p > .05$). First molar teeth showed statistically significantly greater deviation than central incisors or canines ($p < .05$). Excellent correlations were observed ($ICC > .90$) between sequential video scans taken by study participants and between video scans taken by the operator compared to those taken by study participants.

Conclusions: The study demonstrated a high level of accuracy when comparing movements tracked by Dental Monitoring^{TM} system against those of the reference scanner. No macro-level differences were detected in the accuracy of the proprietary system when comparing upper vs lower arches or anterior vs posterior sextants. Micro-level differences were noted as the study found greater deviation associated with first molars as compared to central incisors and canines; despite being deemed clinically insignificant. The proprietary system exhibited high levels of both intra-user and inter-user reliability.

CHAPTER ONE

REVIEW OF THE LITERATURE

An objective evaluation of the clinical accuracy of a commercially available orthodontic monitoring system must begin by establishing the clinical validity of the reference being used for comparison. Digital intraoral scans using the 3M True Definition Scanner stored in the common STL file format will serve as the clinical reference in this study. An evaluation of the clinical validity of the reference will begin with an overall assessment of digital intraoral impressions within the field of orthodontics.

Grünheid et al. examined the accuracy of digital intraoral scans in comparison to conventional alginate impressions.[1] Intraoral scans of fifteen patients using the LAVA COS scanner were compared with digital models generated from alginate impressions. Additionally, digital models were made from 5 plaster models using both intraoral scanners and model scanners. Accuracy was evaluated by quantitative analysis of digitally superimposed models using the Bland Altman method. The study determined that there was no statistically significant difference between digital models made using the intraoral scanners, alginate impressions or orthodontic model scanners.[1] This indicated a relatively high degree of accuracy with digital intraoral scans used for orthodontic purposes when compared to conventional modalities with proven results.

A similar study was conducted by Sevcik et al. that compared the accuracy of 4 different intraoral scanners including: 3M TrueDef, CERECBluecam-Sirona, iTero-CADENT and Trios-3Shape scanners.[2] The study used a master plaster model with embedded cylinders for which the dimensions were measured to a 2-micron accuracy. Each scanner was used to scan the master model for a total of 10 times and the distances were analyzed using metrology software. The study concluded that the 3M TrueDef scanner exhibited the highest accuracy and consistency amongst the four scanners.[2] A similar study was conducted by Van der Meer et al. which compared the predecessor of 3M's True Definition scanner, Lava COS, to the iTero and CEREC systems. The study concluded that the Lava COS system exhibited the highest degree of accuracy and the most consistent error level of all three scanners.[3] The study being proposed will implement the 3M True Def scanner. As demonstrated by the aforementioned studies, the clinical validity of the proposed reference for comparison has been established by the current body of literature.[1-3]

Considering that the 3D models generated by the 3M True Def scanner will serve as the reference in the proposed study, it is most prudent to judiciously evaluate the inherent error associated with the scans. Such error in the precision of the scanner can then be considered when assessing the accuracy and reliability of the commercial photogrammetric system. In order to determine the precision of the designated scanner utilized for the proposed study, a quantitative analysis will be carried out using metrologic software designed for evaluating 3D measuring data from STL files. Such computer software will be utilized to determine both the average global error and the maximum local error associated with the designated scanner being used as the reference for comparison. With that said, the accuracy of such software-based metrics needs to be examined. A study conducted by Zilberman et al. compared the accuracy of cast measurements using physical models and digital calipers to virtual models and measurement software (OrthoCAD).[4] Results showed both methods as being highly valid and reproducible for tooth size (mesiodistal widths) and arch width measurements (intercanine and intermolar widths).[4] Therefore, the use of metrologic software for acquiring measurements from 3D virtual models has been supported by the literature.[4]

Given that the proposed study relates to the implementation of machine vision technology for tracking orthodontic tooth movement, it is warranted to examine the general application of this technology prior to reviewing its application in the field of orthodontics. Machine vision technology has its origin in the industrial arena within the manufacturing sector for automation and image processing purposes. It has been utilized for barcode identification, object sorting, quality control, circuit board inspection, etc.[5] Patel et al. studied the application of machine vision technology for the inspection of fruits and vegetables, evaluation of grain quality and quality control of other food products.[5] In the security industry, machine vision technology has been applied to biometric authentication. Wildes et al. studied a system built upon machine vision tools for the purpose of iris recognition.[6] Within the medical field, machine vision technology is currently being implemented for diagnostic and monitoring purposes. Specifically, Zhao et al. studied the application of computer vision and motion tracking during a transcatheter intervention procedure. The study describes the application of machine vision technology for annulus measurement, valve selection, catheter placement, etc.[7] As illustrated by the above studies, machine vision technology has shown proven success in fields ranging from industrial manufacturing to medicine.[5-7]

The proposed study attempts to evaluate the clinical accuracy of a commercial orthodontic monitoring system that utilizes motion tracking technology to provide large scale informatics for comprehensive orthodontic therapy. A review of current and past literature reveals that digital photogrammetry has been applied to dentistry and orthodontics on much smaller scales. Hlongwa et al. used digital macro-photogrammetry to assess the 3-dimentional motion of a canine undergoing retraction.[8] The investigators took digital photos at multiple clinical follow-up appointments which were then used to generate computer images for analysis of movement based upon X, Y, and Z coordinates. The case report demonstrated that "digital macro-photogrammetry can be applied in orthodontics to monitor orthodontic tooth movement".[8] Furthermore, the case report noted the advantages of photogrammetry in terms of it being "cost effective and measurements can be made on site as the use of computers and digital photographs have been incorporated in the majority of orthodontic practices".[8]

Further light was shed on the application of motion tracking technology to orthodontic treatment via a prospective study performed by Marini et al. which analyzed the 3-dimensional changes in the palate during RPE treatment.[9] The study examined linear and volumetric dimensions of the palates of thirty crossbite cases undergoing RPE treatment at three time points: beginning of treatment, after removal of the RPE and following retention for 3 months, and six months following removal of the expander. Marini et al. observed a "significant relapse in the transverse diameter in all patients six months after appliance removal, although the palatal volume remained stable".[9]

Sander et al. performed a study that provides significant foundational background for the study being proposed by this review.[10] The prospective study analyzed the accuracy of a novel photogrammetric system being used to gather 3-dimensional quantitative information for canine retraction using the Hybrid Retractor ™. The DMP system utilized laser markings on various brackets and a milled frame with a 3-D control point system whose coordinates were known. Considering that the Hybrid Retractor ™

has known biomechanical effects through extensive investigation, it served as an ideal appliance for examining the accuracy of a novel “contactless” measurement system.[10] Sander et al. used digital macro-photogrammetry to examine the translational and rotational movement of 20 canines that were distalized using the Hybrid Retractor ™ during the course of treatment.[10] The accuracy of the DMP technique was compared to control measurements taken every 4 weeks. The results demonstrated an error of less than 0.1mm in the x, y, and z dimensions and the investigators further outline various factors which could have improved the accuracy to 1 micron.[10] Overall, the study demonstrates the potential benefits of using a DMP system to monitor tooth movement during the course of treatment in order to make necessary adjustments and corrections to optimize quality assurance.[10] This relates closely to the intended purpose of the commercial orthodontic monitoring system being investigated by the proposed study.

To further expand upon the application of DMP technology to tracking orthodontic tooth movement, Toodehzaeim et al. investigated the accuracy of analyzing digital photographs with AutoCAD software as means of measuring tooth movement.[11] The prospective study involved eighteen patients for which three intraoral buccal digital images were taken and analyzed using the AutoCAD software and intraclass correlation coefficients.[11] Toodehzaeim et al. concluded that “the introduced method is an accurate, efficient and reliable method for the evaluation of tooth movement”.[11]

In relation to data analysis and the quantitative assessment of accuracy and reliability, the current body of literature demonstrates a wide array of potential statistical approaches. Zaki et al. conducted a systematic review of the statistical methods used to test for agreement amongst medical instruments measuring continuous variables.[12] The systematic review concluded that the Bland-Altman method is the most popular statistical approach used in testing for agreement.[12] In addition to the Bland-Altman test, the study highlighted the widespread use of the correlation coefficient (r), intraclass correlation coefficient (ICC), and means comparison/significance test.[12] The proposed study will utilize such statistical analyses when comparing the commercial photogrammetric system to the reference in order to determine its relative accuracy and reliability.

In conclusion, it has been demonstrated by the aforementioned studies[8-11] that digital macro-photogrammetry and machine vision technology have the potential to revolutionize orthodontic monitoring in order to optimize the efficiency and quality of orthodontic treatment. Given the wide variety of digital macro-photogrammetric systems available for obtaining quantitative information for orthodontic purposes, system specific investigations are warranted to evaluate the accuracy and reliability of such systems until a more standardized platform is established. The proposed study aims to establish the accuracy of a specific commercial system that utilizes DMP technology along with a tracking algorithm to achieve the above stated objectives.

CHAPTER TWO

RELIABILITY AND ACCURACY OF A NOVEL PHOTOGRAMMETRIC ORTHODONTIC MONITORING SYSTEM

Abstract

Purpose: This study quantitatively investigated the reliability and accuracy of Dental Monitoring's™ proprietary orthodontic tracking system in comparison to an established reference.

Materials and Methods: Intraoral scans (True Definition Scanner, 3M™) and video scans (iPhone 7, Apple™) were taken of 30 subjects undergoing comprehensive orthodontic treatment at Loma Linda University's Graduate Orthodontic Clinic at T1 (initial) and T2 (3 months later). At each time point, an intraoral scan was taken by the operator followed by three video scans- two taken by the patient and one by the operator. Three linear and three angular measurements were analyzed using Dental Monitoring's™ tracking system for all comparisons. Accuracy was determined by comparing orthodontic movement tracked by Dental Monitoring's™ video scans against those measured via superimposition of STL files generated from the reference scanner using Friedman's analysis (α=.05). Intra-operator and inter-operator variability were evaluated using the intraclass correlation coefficient and post-hoc analysis of the Friedman's test.

Results: Surface tolerance analysis demonstrated a maximum mean global error of 100 microns associated with the reference scanner. No statistically significant differences were observed between the reference and Dental Monitoring's™ system for the three linear parameters ($p > .05$); angular parameters showed statistically significant differences ($p < .001$). No statistically significant differences were observed when comparing upper vs lower or anterior vs posterior dentition ($p > .05$). First molar teeth showed statistically significantly greater deviation than central incisors or canines ($p < .05$). Excellent correlations were observed (ICC $>.90$) between sequential video scans taken by study participants and between video scans taken by the operator compared to those taken by study participants.

Conclusions: The study demonstrated a high level of accuracy when comparing movements tracked by Dental Monitoring™ system against those of the reference scanner. No macro-level differences were detected in the accuracy of the proprietary system when comparing upper vs lower arches or anterior vs posterior sextants. Micro-level differences were noted as the study found greater deviation associated with first molars as compared to central incisors and canines; despite being deemed clinically insignificant. The proprietary system exhibited high levels of both intra-user and inter-user reliability.

Introduction

Statement of the Problem

The ability to accurately and consistently monitor orthodontic change throughout the treatment process is an essential component to effectively managing the care of a patient. With the advent of technology driven by artificial intelligence, there is significant potential for streamlining and optimizing the various processes associated with the execution of orthodontic treatment. As an emerging technology, remote orthodontic monitoring systems based on machine learning require clinical evaluations for accuracy and reliability in comparison to well-established industry standards.

The clinical validity of digital intraoral scanners has been extensively proven to align with that of long-standing conventional modalities used for dental impressions and bite registrations.[1] In addition, studies have previously quantified the inherent error associated with digital intraoral scanners produced by various manufacturers.[2-3] Thus, the current body of literature supports the use of digital intraoral scanners as clinical references for the evaluation of emerging technologies.[1-3]

In a similar manner, the application of software-based metrology to dental metrics has been previously explored by a study that demonstrated the high accuracy and reproducibility of the OrthoCAD software for measurements related to tooth size and arch width.[4] Similarly, the proprietary remote monitoring system under investigation by this study has incorporated machine vision technology into the process of tracking orthodontic movement. Given the extensive track record for the utilization of machine vision technology within the manufacturing, food and medical industries,[5-7] it comes as no surprise that such computational resources would be applied to the field of orthodontics.

More specifically, the literature has shown that the implementation of digital photogrammetry has the potential to be effective for monitoring orthodontic treatment.[8-11] Foundational studies conducted by Hlongwa et al. and Marini et al. provided a conceptual framework for the potential application of digital photogrammetry to tracking orthodontic movement.[8,9] A study involving a novel canine retractor demonstrated a high level of accuracy and reliability for translational and rotational measurements obtained by a system employing digital photogrammetric methods.[10] Finally, a landmark clinical study by Toodehzaeim et al. proved the efficiency, accuracy and reliability of analyzing orthodontic movement using digital photographs and the AutoCAD software, thus paving the way for the study at hand.[11]

The objective of this study was to quantitatively evaluate the accuracy and reliability of the first commercially available remote orthodontic monitoring system (Dental Monitoring™, Rocky Mountain Orthodontics). Such systems promise to improve the efficiency, precision and overall delivery of orthodontic treatment through the application of advanced technology. The information provided by this investigation is valuable to practitioners who wish to evaluate the performance of such technology for incorporation into their own practice.

Hypothesis

The null hypotheses of the study were as follows:

1) No statistically significant difference existed in movement tracking measurements made between the commercial photogrammetric system and the established reference.
2) No statistically significant variation existed between movement tracked by a series of scans taken by a given subject.
3) No statistically significant variation existed between movement tracked by scans taken by a given subject compared to those taken by the operator.

Materials and Methods

Pre-Clinical Calibration

A pre-clinical bench-top evaluation was carried out to determine the error margin associated with the clinical reference (True Definition Scanner™, 3M). A designated scanner was utilized to scan a designated set of maxillary and mandibular plaster models by a single examiner. The scans were performed consecutively for a total set of 10 maxillary and 10 mandibular scans which generated 20 STL files. The same program-dictated time restrictions associated with scanning a live patient were applied to the simulation (maximum time per arch of 7 mins). The technique for the simulation differed from a live patient scan in terms of the (1) lack of powder application and (2) lack of need for isolation.

Following the scans, GOM Inspect 2016™ software (GOM Metrology Inc, Braunschweig, Germany) was used to quantitatively analyze the STL files (see Figure 1 below).

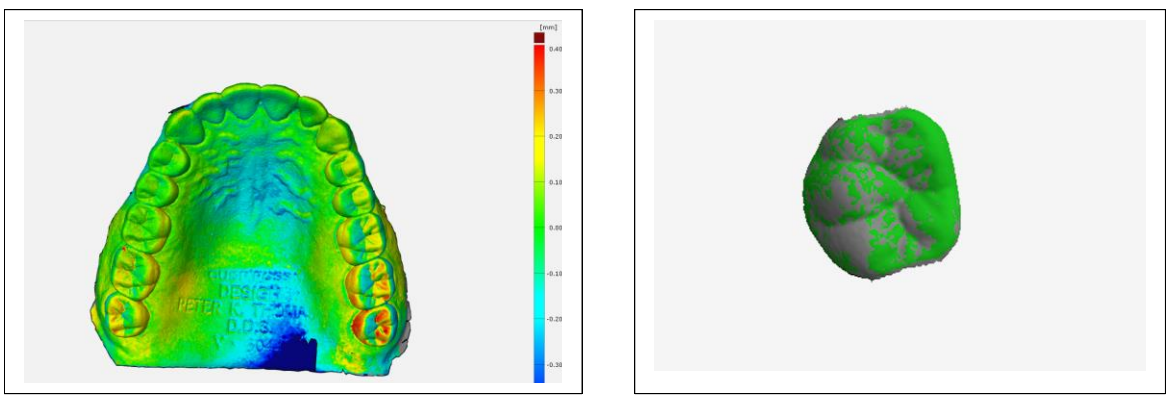

Figure 1. Sample Graphic of GOM™ Inspect Software Best Fit Superimposition- Global Error and Local Error Respectively

The level of precision associated with the designated scanner was determined by an engineering technique referred to as surface tolerance analysis. This quantitative analysis entails best fit superimpositions or matches which are used to quantify the level of deviation between models as the average distance between two corresponding surfaces after matching. This procedure employs the best fit method for surface-to-surface matching based upon the least-mean squared approach[13]. A single set of maxillary and mandibular STL files were randomly selected from the total set of twenty to serve as references for all comparisons. Segmentation of the dentition and removal of the soft tissue components were performed for all models. The maxillary and mandibular arches were evaluated separately thus eliminating any occlusion related considerations. The global error was determined by evaluating the best fit of a given arch on the reference arch. The local error was determined by evaluating the best fit of each tooth of a given arch on the corresponding teeth of the reference arch. The aforementioned technique provided the margin of error associated with the designated reference, which can then be considered when assessing the results of the proposed study.

Patient Selection

This study was approved by the Institutional Review Board (IRB) of Loma Linda University (LLU), Loma Linda, CA. Power analysis revealed that a sample size of thirty participants was required to achieve 80% power with a two-tailed significance level of 5%. Sample selection followed the opportunity sampling methodology due to the need for subjects who were willing and available. Study participants were drawn from the current population of active patients undergoing comprehensive orthodontic treatment at Loma Linda University Orthodontic Graduate Clinic at the time the study was being conducted. A single examiner (VO) performed all data collection throughout the entire process. Informed consent was obtained from participants and authorization was documented via a standardized form. Participants were selected to take part in the study based on the following inclusion and exclusion criteria as illustrated by Figure 2 below:

Inclusion Criteria

1. Comprehensive treatment (including early interceptive cases)
2. Cases in the early stages of treatment with significant movement anticipated

Exclusion Criteria

1. Compliance related challenges associated with behavioral, psychological or cognitive disability as reported by patient on medical history form
2. Significant congenital malformation of dentition
3. Significant decay or mutilated dentition

Figure 2. Inclusion and Exclusion Criteria Used in Patient Selection

Data Collection

Data collection took place within the premises of the Loma Linda University Graduate Orthodontic Clinic. Data was collected at two separate time points separated by a three month period- T1 (initial) and T2 (final). The three month duration was selected to produce movements of sufficient magnitude that would surpass the sensitivity threshold of the instruments involved, while minimizing noise and any associated sources of error. For each individual subject, the following four sets of data were collected at both T1 and T2:

- Maxillary and mandibular intraoral 3D scan using the designated 3M True Definition scanner
- First of two video scans taken by the subject using Dental Monitoring's™ proprietary system

- Second of two video scans taken by the subject using Dental Monitoring's™ proprietary system
- Single video scan taken by the operator using Dental Monitoring's™ proprietary system

All scans were performed by a single practitioner under standardized conditions. The isolation protocol was standardized to include a designated type of cheek retractor, vacuum suction, cotton rolls and sterile 2x2 gauze pads. More specifically for the mandibular arch, isolation was supplemented by lingual retraction using a patient mirror as deemed necessary. No other isolation methods were implemented in any case. Powder application was performed following complete isolation using the applicator supplied by the manufacturer and included in the unit. Each arch was scanned in a standard sequence recommended by the manufacturer (see Figure 3 below) and stored in the STL file format.

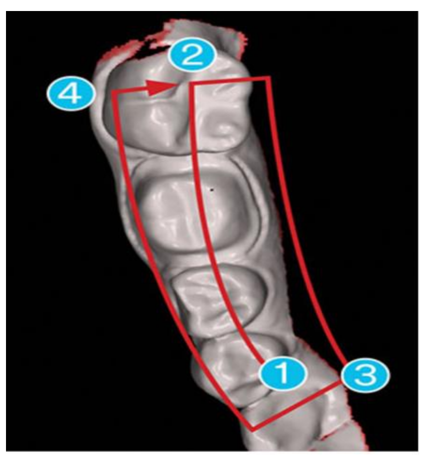

Figure 3. Intraoral Scanning Pattern for a Given Quadrant as Recommended by the Manufacturer

At T1, in addition to the four sets of data collected as outlined above, patient education and training were provided for the following purposes by the examiner:

- to register the patient within the Dental Monitoring™ smartphone based application
- to train the patient in the proper placement of the calibrated cheek retractors designed specifically for Dental Monitoring's™ patented tracking algorithm
- to train the patient to properly take the intraoral video scans in the systematic fashion explained/illustrated by the application
- to familiarize the patient with common preventable mistakes that can lead to poor intraoral video scans

Besides the initial guidance and training provided to the patient at T1, no other form of education/training was carried out by the practitioner at T2 in an attempt to mimic the actual intended conditions in which photos/video scans are taken by the subject without professional supervision. The video scans were taken in immediate succession following the intraoral scan in order to eliminate any temporal sources of error. A single designated smartphone (Apple iPhone 7™) was used by all subjects for the purposes of the study as a further means of standardization.

Data was collected and analyzed for the following six orthodontic parameters tracked by Dental Monitoring's™ patented algorithm:

- mesial/distal translation
- intrusion/extrusion
- retraction/advancement
- tip

- rotation
- torque

In order to homogenize the data collection technique, both the sequential STL files produced for the reference (True Definition Scanner™, 3M) and the sequential video scans for the test group (Dental Monitoring™, Rocky Mountain Orthodontics) were analyzed using Dental Monitoring's™ patented tracking algorithm. This process eliminated any potential metrologic sources of error associated with the use of secondary software.

Statistical Analysis

SPSS™ 23.0 (SPSS Inc., Chicago, IL, USA) and Microsoft® Excel were used for statistical analysis of the collected data. The overall dentition (non-stratified) results were analyzed using the non-parametric Friedman's analysis to determine whether statistically significant differences existed between movement tracked by the reference (3M True Definition scanner) and those tracked by Dental Monitoring's™ system. Post-hoc analysis was conducted using the Wilcoxon signed-rank test with the Bonferroni correction for all pairwise comparisons. The non-parametric Mann-Whitney U test was used to analyze the effect of upper vs lower and anterior vs posterior stratifications. The non-parametric Kruskal-Wallis test was used to analyze the effect of stratification by three representative teeth (central incisors, canines and first molars). Post-hoc analysis was conducted using the Mann-Whitney U test with the Bonferroni correction for all pairwise comparisons of the three representative teeth. For all statistical analyses the significance level was set at alpha ≤ 0.05.

Intra-user reliability of the Dental Monitoring™ system was assessed and expressed as the intraclass correlation coefficient (ICC). The ICC examined correlations between the data collected for the two sets of sequential video scans performed by a given study participant. In a similar manner, inter-user reliability was examined using the ICC which compared video scans taken by study participants to those taken by the operator.

Results

Pre-Clinical Calibration

Surface tolerance analysis was performed for evaluation of the global and local error associated with the reference intraoral scanner (3M True Definition scanner) utilized for the study via GOM™ Inspect software. The maximum mean global error associated with the sequential scans was 100 microns (Table 1), which represents overall deviation following whole arch alignment using the best-fit method as previously described. The maximum local error (Table 2) associated with each of the six parameters (three linear and three angular) were as follows: 0.27 mm (extrusion/intrusion); 0.29 mm (buccal-lingual translation); 0.14 mm (mesial-distal translation); 1.16° (mesial-distal rotation); 1.89° (mesial-distal angulation/tip); 2.12° (buccal-lingual torque).

Table 1. Global Error Assessment for Reference Intraoral Scanner. Units in millimeters.

Global Error		
Model #		**Mean+/- SD**
1	**Maxilla**	0.00 +/- 0.00
	Mandible	0.00 +/- 0.00
2	**Maxilla**	0.09 +/- 0.04
	Mandible	0.06 +/- 0.03
3	**Maxilla**	0.06 +/- 0.03
	Mandible	0.07 +/- 0.03
4	**Maxilla**	0.01 +/- 0.06
	Mandible	0.07 +/- 0.04
5	**Maxilla**	0.09 +/- 0.05
	Mandible	0.07 +/- 0.04
6	**Maxilla**	0.08 +/- 0.04
	Mandible	0.07 +/- 0.03
7	**Maxilla**	0.01 +/- 0.06
	Mandible	0.07 +/- 0.04
8	**Maxilla**	0.06 +/- 0.04
	Mandible	0.06 +/- 0.03
9	**Maxilla**	0.10 +/- 0.06
	Mandible	0.07 +/- 0.04
10	**Maxilla**	0.09 +/- 0.05
	Mandible	0.10 +/- 0.06

Table 2. Local Error Assessment for Reference Intraoral Scanner. Local error represented for three linear (mm) and three angular (degrees) parameters.

		Local Error					
Model #		**Extrusion/Intrusion**	**Bucco-lingual**	**Mesio-distal**	**Rotation**	**Tip**	**Torque**
1	**Mean +/- SD**	0.00 +/- 0.00	0.00 +/- 0.00	0.00 +/- 0.00	0.00 +/- 0.00	0.00 +/- 0.00	0.00 +/- 0.00
	Max	0.00	0.00	0.00	0.00	0.00	0.00
2	**Mean +/- SD**	0.00 +/- 0.00	-0.04 +/- 0.08	0.01 +/- 0.42	-0.16 +/- 0.50	-0.06 +/- 0.35	-0.34 +/- 0.71
	Max	0	0.1	0.08	0.86	0.53	0.99
3	**Mean +/- SD**	0.01 +/-0.39	-0.01 +/- 0.05	0.01 +/- 0.05	-0.10 +/- 0.53	0.04 +/- 0.37	-0.05 +/- 0.49
	Max	0.09	0.08	0.1	0.58	0.96	0.84
4	**Mean +/- SD**	0.01 +/- 0.09	0.03 +/- 0.08	0.01 +/- 0.06	0.09 +/- 0.53	0.12 +/- 0.58	-0.11 +/- 0.72
	Max	0.27	0.22	0.14	0.96	1.89	2.12
5	**Mean +/- SD**	0.02 +/- 0.08	0.00 +/- 0.09	-0.01 +/- 0.07	-0.13 +/- 0.55	0.05 +/- 0.59	-0.23 +/- 0.59
	Max	0.18	0.14	0.09	1.1	1.54	1.03
6	**Mean +/- SD**	-0.01 +/- 0.09	-0.03 +/- 0.06	0.01 +/- 0.07	-0.19 +/- 0.53	0.01 +/- 0.56	-0.09 +/- 0.58
	Max	0.17	0.06	0.09	0.65	0.81	1.08
7	**Mean +/- SD**	-0.00 +/- 0.15	0.00 +/- 0.06	-0.00 +/- 0.06	-0.01 +/- 0.41	0.10 +/- 0.70	-0.16 +/- 0.90
	Max	0.23	0.13	0.14	0.73	1.69	1.12
8	**Mean +/- SD**	-0.01 +/- 0.04	-0.00 +/- 0.05	0.00 +/- 0.04	-0.07 +/- 0.47	-0.01 +/- 0.36	0.08 +/- 0.48
	Max	0.06	0.17	0.07	0.94	0.92	0.97
9	**Mean +/- SD**	-0.02 +/- 0.07	-0.04 +/- 0.13	0.01 +/- 0.04	-0.11 +/- 0.57	0.03 +/- 0.43	-0.28 +/- 0.74
	Max	0.19	0.22	0.11	0.86	1.28	0.94
10	**Mean +/- SD**	-0.03 +/- 0.06	-0.01 +/- 0.14	0.00 +/- 0.07	-0.19 +/- 0.69	-0.03 +/- 0.40	-0.30 +/- 0.64
	Max	0.12	0.29	0.11	1.16	0.65	0.8

Clinical Assessment

The study involved a final sample size of thirty participants who successfully completed data collection over a three month time frame from T1 to T2. Three additional participants began data collection at T1 but dropped out of the study prior to data collection at T2. Study participants ranged in age, gender, type of malocclusion and treatment modality as illustrated by Table 3 below:

Table 3. Categorization of Study Participants by Various Factors

Age	Gender	Type of Malocclusion	Treatment Modality
Range: 8-56 yrs	21 Females / 9 Males	Class 1 Crowding: 18 Class 2 Malocclusion: 9 Class 3 Malocclusion: 3	Traditional Fixed: 26 Removable Aligners: 4

Tables 4-7 describe the means and standard deviations of all six measured parameters and the results of the statistical analyses. When comparing movements tracked between the reference and Dental Monitoring's[TM] system for overall dentition using the Friedman's analysis, no statistically significant differences were observed amongst the linear parameters (p >.05 for T_x, T_y, T_z; Table 4), while the angular parameters showed significant differences (p < .001 for R_x, R_y, R_z; Table 4). Post-hoc analysis for pairwise comparisons using the Wilcoxon signed-rank test showed no statistically significant differences when comparing sequential video scans taken by study participants for any of the angular parameters (p > .05; Table 4). Similarly, pairwise comparisons showed no statistically significant differences when comparing video scans taken by study participants to those taken by the operator for any of the angular parameters (p > .05; Table 4).

Table 4. Non-Stratified Friedman's Analysis- Overall Dentition. Superscripts (a, b, etc.) represent statistically significant differences ($p < .05$)

ACCURACY: OVERALL DENTITION						
Parameter	**Definition**	**TRUE**	**$Pt_1/T2$**	**$Pt_2/T2$**	**Op/T2**	**p-Value**
		Mean +/- SD	**Mean +/- SD**	**Mean +/- SD**	**Mean +/- SD**	
Tx	Mesial/ Distal Translation	-0.028 +/- 0.012	-0.026 +/- 0.011	-0.031 +/- 0.012	-0.029 +/- 0.012	0.169
Ty	Buccal/ Lingual Translation	0.014 +/- 0.008	0.013 +/- 0.008	0.013 +/- 0.008	0.013 +/- 0.008	0.129
Tz	Extrusion/ Intrusion	-0.097 +/- 0.016	-0.099 +/- 0.016	-0.099 +/- 0.016	-0.100 +/- 0.016	0.659
Rx	Buccal/ Lingual Torque	0.479^{a} +/- 0.078	0.335^{b} +/- 0.076	0.339^{b} +/- 0.076	0.322^{b} +/- 0.078	<0.001
Ry	Mesial/ Distal Rotation	0.118^{a} +/- 0.112	-0.082^{b} +/- 0.102	-0.095^{b} +/- 0.102	-0.040^{b} +/- 0.112	<0.001
Rz	Mesial/ Distal Angulation	0.029^{a} +/- 0.093	-0.157^{b} +/- 0.066	-0.211^{b} +/- 0.089	-0.191^{b} +/- 0.093	<0.001

When comparing upper vs lower dentition and anterior vs posterior dentition using the Mann-Whitney U analysis, deviations between the reference and Dental Monitoring's^{TM} system demonstrated no statistically significant differences for any of the linear or angular parameters regardless of type of video scan (*p* >.05; Tables 5,6).

Table 5. Stratified Friedman's Analysis- Upper vs Lower Dentition ($p < .05$)

ACCURACY: UPPER VS. LOWER					
Parameter	**Definition**	**Upper vs. Lower**	**TRUE-Pt$_1$/T2**	**True-Pt$_2$/T2**	**True-Op/T2**
			Mean +/- SD	**Mean +/- SD**	**Mean +/- SD**
Tx	Mesial/ Distal Translation	Upper	0.028 +/- 0.011	0.018 +/- 0.002	0.016 +/- 0.002
		Lower	0.019 +/- 0.007	0.020 +/- 0.007	0.013 +/- 0.001
		p-value	0.780	0.434	0.055
Ty	Buccal/ Lingual Translation	Upper	0.018 +/- 0.003	0.015 +/- 0.001	0.015 +/- 0.001
		Lower	0.014 +/- 0.001	0.014 +/- 0.001	0.013 +/- 0.006
		p-value	0.056	0.065	0.056
Tz	Extrusion/ Intrusion	Upper	0.020 +/- 0.003	0.019 +/- 0.003	0.018 +/- 0.003
		Lower	0.019 +/- 0.004	0.018 +/- 0.004	0.014 +/- 0.004
		p-value	0.358	0.141	0.833
Rx	Buccal/ Lingual Torque	Upper	0.190 +/- 0.018	0.178 +/- 0.011	0.183 +/- 0.011
		Lower	0.201 +/- 0.033	0.206 +/- 0.033	0.168 +/- 0.006
		p-value	0.099	0.069	0.397
Ry	Mesial/ Distal Rotation	Upper	0.173 +/- 0.011	0.178 +/- 0.009	0.175 +/- 0.009
		Lower	0.269 +/- 0.096	0.273 +/- 0.096	0.164 +/- 0.009
		p-value	0.097	0.260	0.861
Rz	Mesial/ Distal Angulation	Upper	0.303 +/- 0.116	0.186 +/- 0.014	0.189 +/- 0.014
		Lower	0.225 +/- 0.051	0.221 +/- 0.051	0.177 +/- 0.006
		p-value	0.147	0.116	0.070

Table 6. Stratified Friedman's Analysis- Anterior vs Posterior Dentition ($p < .05$)

ACCURACY: ANTERIOR VS. POSTERIOR					
Parameter	**Definition**	**Anterior vs Posterior**	**TRUE-Pt$_1$/T2**	**True-Pt$_2$/T2**	**True-Op/T2**
			Mean +/- SD	**Mean +/- SD**	**Mean +/- SD**
Tx	Mesial/ Distal Translation	Anterior	0.012 +/- 0.001	0.012 +/- 0.001	0.012 +/- 0.001
		Posterior	0.031 +/- 0.010	0.023 +/- 0.006	0.017 +/- 0.002
		p-value	0.127	0.662	0.725
Ty	Buccal/ Lingual Translation	Anterior	0.012 +/- 0.001	0.012 +/- 0.001	0.011 +/- 0.001
		Posterior	0.018 +/- 0.003	0.016 +/- 0.001	0.016 +/- 0.001
		p-value	0.745	0.720	0.335
Tz	Extrusion/ Intrusion	Anterior	0.012 +/- 0.001	0.012 +/- 0.001	0.012 +/- 0.001
		Posterior	0.024 +/- 0.004	0.023 +/- 0.004	0.019 +/- 0.003
		p-value	0.412	0.842	0.516
Rx	Buccal/ Lingual Torque	Anterior	0.149 +/- 0.005	0.151 +/- 0.006	0.160 +/- 0.005
		Posterior	0.224 +/- 0.030	0.217 +/- 0.028	0.185 +/- 0.010
		p-value	0.863	0.551	0.307
Ry	Mesial/ Distal Rotation	Anterior	0.150 +/- 0.005	0.160 +/- 0/006	0.155 +/- 0.005
		Posterior	0.264 +/- 0.076	0.265 +/- 0.076	0.179 +/- 0.010
		p-value	0.898	0.916	0.350
Rz	Mesial/ Distal Angulation	Anterior	0.158 +/- 0.006	0.159 +/- 0.006	0.160 +/- 0.006
		Posterior	0.334 +/- 0.106	0.230 +/- 0.042	0.198 +/- 0.012
		p-value	0.779	0.414	0.843

When comparing representative teeth (central incisors, canines and first molars) using the Kruskal-Wallis analysis, deviations between the reference and Dental Monitoring's^{TM} system revealed statistically significant differences for the three linear and three angular parameters ($p < .05$; Table 7). Post-hoc analysis for pairwise comparisons using the Mann-Whitney U test showed statistically significantly greater deviation amongst first molars when compared to both central incisors and canines ($p < .05$; Table 7). Pairwise comparisons showed no statistically significant difference when comparing the deviation for central incisors and canines ($p > .05$; Table 7).

Table 7. Stratified Friedman's Analysis- Representative Teeth. Superscripts (a, b, etc.) represent statistically significant differences ($p < .05$)

ACCURACY: REPRESENTATIVE TEETH					
Parameter	**Definition**	**Central Incisor vs. Canine vs. First Molar**	**TRUE-Pt_1/T2 Mean +/- SD**	**True-Pt_2/T2 Mean +/- SD**	**True-Op/T2 Mean +/- SD**
Tx	Mesial/ Distal Translation	Central Incisor	0.012^{a} +/- 0.001	0.012^{a} +/- 0.001	0.012^{a} +/- 0.001
		Canine	0.012^{a} +/- 0.001	0.013^{a} +/- 0.001	0.012^{a} +/- 0.001
		First Molar	0.015^{b} +/- 0.001	0.016^{b} +/- 0.001	0.016^{b} +/- 0.001
		p-value	0.036	< 0.001	< 0.001
Ty	Buccal/ Lingual Translation	Central Incisor	0.013 +/- 0.001	0.012^{a} +/- 0.001	0.010^{a} +/- 0.001
		Canine	0.014 +/- 0.001	0.013^{a} +/- 0.001	0.012^{a} +/- 0.001
		First Molar	0.015 +/- 0.001	0.017^{b} +/- 0.001	0.016^{b} +/- 0.001
		p-value	0.077	< 0.001	< 0.001
Tz	Extrusion/ Intrusion	Central Incisor	0.012^{a} +/- 0.001	0.012^{a} +/- 0.001	0.012 +/- 0.001
		Canine	0.012^{a} +/- 0.001	0.012^{a} +/- 0.001	0.012 +/- 0.001
		First Molar	0.017^{b} +/- 0.001	0.016^{b} +/- 0.001	0.012 +/- 0.001
		p-value	< 0.001	0.011	0.872
Rx	Buccal/ Lingual Torque	Central Incisor	0.126^{a} +/- 0.008	0.143^{a} +/- 0.009	0.151^{a} +/- 0.008
		Canine	0.117^{a} +/- 0.009	0.133^{a} +/- 0.009	0.153^{a} +/- 0.009
		First Molar	0.201^{b} +/- 0.013	0.216^{b} +/- 0.012	0.218^{b} +/- 0.013
		p-value	< 0.001	< 0.001	< 0.001
Ry	Mesial/ Distal Rotation	Central Incisor	0.145^{a} +/- 0.009	0.144^{a} +/- 0.009	0.149^{a} +/- 0.009
		Canine	0.145^{a} +/- 0.009	0.152^{a} +/- 0.009	0.145^{a} +/- 0.009
		First Molar	0.202^{b} +/- 0.012	0.224^{b} +/- 0.012	0.202^{b} +/- 0.012
		p-value	0.002	< 0.001	< 0.001
Rz	Mesial/ Distal Angulation	Central Incisor	0.137^{a} +/- 0.008	0.146^{a} +/- 0.008	0.146^{a} +/- 0.008
		Canine	0.168^{a} +/- 0.009	0.152^{a} +/- 0.010	0.160^{a} +/- 0.009
		First Molar	0.216^{b} +/- 0.012	0.209^{b} +/- 0.013	0.191^{b} +/- 0.011
		p-value	< 0.001	< 0.001	0.021

The intraclass correlation coefficient (ICC) used to assess intra-user reliability demonstrated excellent correlation (>0.90) between sequential videos scans taken by study participants at T1 for all linear and angular parameters (Table 8).

Table 8. Intraclass Correlation Coefficient and 95% Confidence Interval- Pt_1/T1 correlated with Pt_2/T1.

Parameter		Intraclass Correlation	95% Confidence Interval	
			Lower Bound	Upper Bound
R	**X**	0.937	0.928	0.944
	Y	0.937	0.928	0.944
	Z	0.938	0.930	0.946
T	**X**	0.956	0.949	0.961
	Y	0.951	0.945	0.957
	Z	0.951	0.944	0.957

The intraclass correlation coefficient (ICC) used to assess inter-user reliability demonstrated excellent correlation (>0.90) when comparing videos scans taken by study participants and those taken by the operator for all linear and angular parameters (Table 9 and 10).

Table 9. Intraclass Correlation Coefficient and 95% Confidence Interval; Pt_1/T1 correlated with Op/T1.

Parameter		Intraclass Correlation	95% Confidence Interval	
			Lower Bound	Upper Bound
R	**X**	0.908	0.896	0.919
	Y	0.913	0.900	0.923
	Z	0.904	0.890	0.915
T	**X**	0.905	0.892	0.917
	Y	0.913	0.901	0.924
	Z	0.903	0.889	0.915

Table 10. Intraclass Correlation Coefficient and 95% Confidence Interval- Pt_2/T1 correlated with Op/T1.

Parameter		Intraclass Correlation	95% Confidence Interval	
			Lower Bound	Upper Bound
R	**X**	0.935	0.926	0.943
	Y	0.930	0.921	0.939
	Z	0.931	0.922	0.94
T	**X**	0.946	0.939	0.953
	Y	0.952	0.945	0.958
	Z	0.949	0.942	0.955

Discussion

The application of photogrammetric techniques in the field of orthodontics has the potential to significantly alter the means by which treatment planning, case monitoring and intervention take place. Initial attempts at employing digital macro-photogrammetry (DMP) for tracking orthodontic tooth movement have demonstrated the feasibility of the concept through various laboratory and clinical simulations.[2,8,9] Toodehzaeim et. al established an initial clinical framework for pursuing such techniques by demonstrating the accuracy and reliability of digital photographic analysis via the implementation of AutoCAD software as a means of evaluating clinical tooth movement.[11] This study intended to assess the accuracy and reliability associated with a commercially available remote photogrammetric monitoring system developed by Dental Monitoring™ for use by providers of orthodontic services. To our knowledge, this is the first study to evaluate the accuracy and reliability of a commercially available remote orthodontic monitoring system.

The first null hypothesis regarding the accuracy of the system under investigation was partially rejected. The overall dentition analysis comparing movements tracked by the reference and those tracked by Dental Monitoring's™ proprietary system demonstrated no statistically significant difference for any of the three linear parameters: extrusion/intrusion, mesial/distal translation and buccal/lingual translation (Table 4). On the contrary, the analysis showed statistically significant differences for the three angular parameters: rotation, angulation and torque (Table 4). With that said, the statistically significant differences in the angular measurements need to be adjusted to account for the inherent error associated with the reference when interpreting such results (3M true definition scanner).

The accuracy and reliability of intraoral scanners has been shown to closely resemble that of more traditional registration techniques in terms of clinical applicability.[1,5] However, the inherent error associated with such digital systems must be taken into consideration when using intraoral scanners as a reference for the assessment of other technologies. Pre-clinical calibration studies were performed to assess such error. This analysis produced a maximum mean global error of approximately 100 microns (Table 2) and maximum local errors of approximately 0.2-0.3mm for linear parameters and 1-2° for angular parameters (Table 3). These findings are similar to those of previous studies investigating the trueness and precision of various commercially available digital intraoral scanners.[6,14 15] In particular, when considering the digital scanner used as a reference for this study (3M True Definition) these results align with those of Sevcik et al. who reported a maximum error of approximately 93 microns.[2] The aforementioned results should be interpreted with a consideration of the above mentioned sources of error associated with the reference.

In a similar manner, the differences found for the angular parameters warrant an evaluation for clinical relevance. Regarding the three angular parameters, the mean differences between movement tracked by the reference and Dental Monitoring's™ system ranged from 0.10°- 0.25° (Table 4). In order to evaluate the clinical applicability of such statistically significant differences, the Objective Grading System set forth by the American Board of Orthodontics may be used as a benchmark for comparison.[16] In the context of these established standards, one can safely conclude that the magnitude of the aforementioned differences may be deemed clinically insignificant.[16]

The results demonstrated no difference in the level of deviation between the reference and Dental Monitoring's™ system when comparing upper vs lower dentition and anterior vs posterior dentition (Tables 5,6). Considering that the system under investigation is based largely on the application of machine learning to photogrammetry, it is susceptible to the sources of error that are commonly associated with such computational endeavors. Common photogrammetric sources of error include those due to uneven surfaces, tilt, parallax, focal-plane flatness and lens distortion.[17] In addition, the intraoral environment poses specific challenges for photogrammetry largely from the optical characteristics of tooth enamel. Tooth enamel poses a large challenge as a photogrammetric surface since it is relatively featureless.[18] In addition, enamel is highly reflective resulting in the production of glare.[18] Furthermore, the presence of saliva within the intraoral environment adds another challenge due to its associated optical properties.[18] Therefore, a common concern among users of the novel system is its ability to accurately capture and track teeth located in areas that are more prone to such sources of distortion and error. In particular, the upper arch and the posterior quadrants are two areas of greatest concern when considering accessibility and general photographic difficulty. Despite the photogrammetric challenges posed above, the results of this investigation demonstrate the consistency of the system's performance when evaluated at the macro-level in regards to posterior vs anterior sextants and upper vs lower arches.

On the contrary, at the micro-level the results revealed statistically significant differences when comparing deviations associated with representative teeth (Table 7). More specifically, first molars consistently showed greater deviation than both central incisors and canines (Table 7). Such differences may stem from stereo-photogrammetric principles and how they apply to the intraoral environment. Such technology applies triangulation algorithms that utilize specific surface landmarks in order to stitch together sequential images to re-create three dimensional models.[19] This largely depends on a given system's ability to resolve details associated with anatomical features of the teeth.[19] Furthermore, the difference may be attributed to the challenge associated with obtaining an appropriate angle between the camera lens and the surfaces of first molar teeth as opposed to those of central incisors and canines. The optical challenges associated with the posterior positioning of first molars may partially explain the greater error associated with such measurements.

With regard to the intra-user reliability of Dental Monitoring's™ tracking system, the results of the ICC and post-hoc Friedman's analyses failed to reject the second null hypothesis (post-hoc: Tables 4-7, ICC: Table 8). The results demonstrate a high level of intra-user reliability when comparing the results of sequential video scans taken by a given study participant. Such results may be interpreted to demonstrate the lack of dependency of Dental Monitoring's™ system upon the proficiency of the specific user. Such findings are of critical importance for assessing the user-friendly nature of the system under investigation. Therefore, it may be concluded that these results highlight the ability of the system to produce accurate measurements independent of the level of proficiency of the user.

Likewise, the results of the ICC and post-hoc Friedman's analyses failed to reject the third null hypothesis (post-hoc: Tables 4-7, ICC: Tables 9,10). These findings represent a high level of inter-user reliability when comparing video scans taken by study participants to those taken by the designated study examiner. Such findings shed light on the effect of operator skill level upon the accuracy of Dental Monitoring's™ system. Thus, it may be concluded from the aforementioned results that the performance of the system is relatively independent of the skill level of the operator.

Overall, the results of this study provide a scientific basis for the accuracy and reliability of a novel photogrammetric system intended to remotely monitor the progress of orthodontic patients. When considering the practical implications of such results within the scope of modern orthodontics, one must consider the potential impact of such technology upon clinical efficiency and economics. The ability to remotely acquire updated information on the precise status of a given patient has the potential to alter the nature of orthodontic treatment from a largely reactive experience to a more pro-active sequence of events. Movement monitoring metrics have the potential to optimize the efficiency and effectiveness of various orthodontic mechanics by providing more continuous feedback to the clinician. Such feedback allows the clinician to make decisions regarding care on an ongoing basis as opposed to restricting decision making to the intermittent pattern of conventional appointments. Similarly, such data streams have the ability to optimize the efficiency of the mechanics employed to treat a large variety of cases thus expanding our knowledge as a profession. From the perspective of practice management, remote monitoring has the potential to create lean operational systems that maximize productivity and minimize overhead costs while improving the quality of care provided to patients.

Conclusions

1. No statistically significant differences were found for movements tracked between the reference intraoral scanner and Dental Monitoring's™ system for all three linear parameters ($p>.05$).
2. Statistically significant differences were found for movements tracked between the reference intraoral scanner and Dental Monitoring's™ system for all three

angular parameters ($p<.05$); however, these differences were considered clinically insignificant.

3. No statistically significant differences were noted when comparing upper vs lower or anterior vs posterior dentition ($p>.05$).
4. Statistically significantly greater deviation between the reference and Dental Monitoring's™ system was found for first molars as compared to central incisors and canines; however, these differences were considered clinically insignificant.
5. High level of intra-user reliability was supported by the results.
6. High level of inter-user reliability was supported by the results.

CHAPTER THREE

EXTENDED DISCUSSION

Study Limitations

Examination of the methodology of the investigation reveals various parameters that were not strictly controlled for during data collection. First of all, the proprietary system is intended to be used by a given patient in a remote location outside the clinic setting in the absence of the orthodontist. The study at hand conducted all data collection in the same clinic with video scans being taken in the presence of the operator. Although participant training was only conducted at T1 and the operator provided no further instruction at T2, actual settings did not properly mimic the intended use of the system. In a similar fashion, all video scans were taken using a single designated smartphone (Apple iPhone 7™), while the system is intended to be used on various types of smartphones operating on different platforms. All of the above considerations may have potentially introduced systematic bias into the methodological approach taken by the investigation.[20]

From the perspective of patient selection, the study sample did not control for treatment modality or specific stage in treatment. Such variables may play a role in differentially influencing the system's ability to accurately capture and track movements. Similarly, the study sample did not control for age, proficiency with photography or comfort level with technology. Such participant-specific considerations may have affected the outcomes of both the intra-user and inter-user reliability measures associated with the study.[20]

Future Study Direction

A sample size of thirty participants were followed during the course of this investigation for a duration of three months with data collection occurring at two time points (initial and final). Future studies could not only expand upon the sample size but also increase the frequency of data collection. This would allow investigators to examine smaller magnitudes of movement (weekly or monthly) which would more closely simulate the intended use of the proprietary system.

Similarly, a future study could incorporate video scans taken remotely by study participants outside the clinic setting to account for variables associated with the remote use of the system. Given that the intended use of the commercial system entails patient compliance and autonomous operation of the technology, this could provide more representative results.

Furthermore, more specialized studies could stratify the investigation by comparing results for fixed appliances against those of clear aligners. Given the inherent nature of clear aligner therapy, the application of such technology may play a large role in the expansion of such treatment modalities. Finally, by incorporation of CBCT data, a future study can examine the proprietary system's ability to track movements associated with tooth roots and potentially even changes in alveolar parameters.

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