The Relationship Between the Amount of Orthodontic Tooth Movement and the Effectiveness of Computer Assisted Treatment

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Abstract

Aim: To evaluate the effectiveness of SureSmile technology and determine if a correlation exists between discrepancy and overall movement throughout treatment.

Methods: Digital pre-treatment models, predicted final treatment models, and actual final treatment models of 30 patients were superimposed to determine both the overall movement each tooth completed throughout treatment, the amount of discrepancy between predicted and actual results, and if any correlation exists between these two findings.

Results: Statistically significant correlation between amount of overall tooth movement and discrepancy between predicted and actual final alignment was found in the following instances: Mesial-distal dimension in maxillary canines. Facial-lingual dimension of maxillary central incisors, and lateral incisors. Torque of maxillary central incisors, lateral incisors, 1st molars, and all mandibular teeth. Rotation of maxillary central incisors.

Conclusion: The effectiveness of SureSmile is highly variable and dependent on tooth type and dimension of movement.

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Introduction

Technology and innovation continue to enhance the practice of dentistry. Increased efficiency and reduced costs of production make modern technologies more affordable as well as more accessible to dental providers. For example, cone beam computed topography machines are becoming more affordable and now offer comparably less radiation dosage to capture a patient's entire cranium than what was once delivered with a single panorex film. Stereolithographic renderings and 3D models of the human dentoalveolar complex allow doctors to design treatment plans with respect to all three dimensions and further personalize their care to the patient.

Orthodontists inherently strive to personalize care for their patients. By studying archforms, cephalometrics, and a multitude of other factors, a treatment plan is developed for the individual. The orthodontic market is saturated with straight wire appliances that use aggregated data to create a generic prescription based on average tooth position. These preprogrammed appliances cannot take into account the subtletees of each patient's malocclusion and surrounding alveolus. Thus, companies have begun fabricating customizable appliances. For example, Invisalign and Insignia aim to optimize personalized treatment by creating custom aligners and brackets. Both aim to optimize patient care by providing more efficient and effective treatments customized to the individual.

SureSmile (Orametrix, Richardson, TX) entered the marketplace providing robotically bent, custom-fabricated archwires milled to the providers specifications. Currently holding more than 70 patents, SureSmile aims to "deliver better care through a proactive care model enabled by technology and processes." (Scholz 2010) In the years surrounding the release of SureSmile, publications were mainly composed of case reports and editorials by SureSmile's Cofounder and Chief Clinical Officer Dr. Sachdeva describing the process and philosophy of treatment. Sachdeva reported that SureSmile technology was designed to substantially reduce errors in treatment resulting from appliance management (Sachdeva 2005; Sachdeva et al. 2012). Sachdeva's philosophy was that contemporary orthodontics was a reactive process in which the provider, who typically uses a similar bracket for most patients, is constantly making minor adjustments and compensations for bracket placements and other prescription discrepancies that are built into the system (Scholz 2010; Sachdeva 2005, 2012).

Though limited amount of study has been completed on SureSmile Technologies, several authors have concluded that implementation of the system will increase clinical efficiency and decrease overall treatment time (Saxe et al, 2010; Alford et al, 2011; Sachdeva et al. 2012). Efficiency aside, additional studies have shown that treatment outcomes are acceptable despite some variability in effectiveness from tooth to tooth (Larson 2013; Hartwich 2007). SureSmile can be easily integrated into any practice as it allows the provider the autonomy to use bracket and band systems along with additional auxiliary appliances.

The SureSmile Process

Suresmile Technology can be implemented at any time during orthodontic treatment. The provider can choose to utilize a conventional bracket and band system of their choosing in conjunction with the technology. When planning SureSmile treatment, a Cone Beam CT image or a intra-oral scan, using the SureSmile OraScanner, is used to capture a 3D model of the patient's dentition and appliances on each individual tooth (Scholz 2010; Sachdeva 2005; Moles 2009). This 3D rendering is called the therapeutic model (figure 1). The therapeutic model can be manipulated by SureSmile's treatment planning software. Reports show that about half of users will start SureSmile treatment 4 to 6 months into the care cycle (Scholz 2010; Sachdeva 2005).

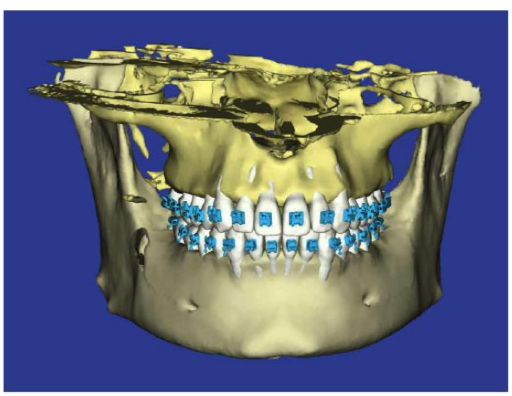

Figure 1. Therapeutic model

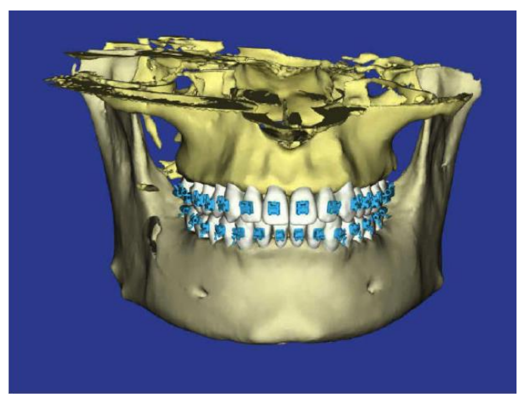

Figure 2. Treatment simulation showing final prescribed alignment

The operator can run multiple treatment scenarios and simulate different treatment plans until an optimal one is found (Mah 2001). When a final treatment plan is decided upon (see figure 2 and 3), robotic technology can accurately bend a stainless steel wire with less than 1 degree of variation (see figure 4)(Sachdeva 2001). This creates a system that overcomes the challenges of perfect bracket placement and instead places the prescription in the arch wire. (Moles, 2009)

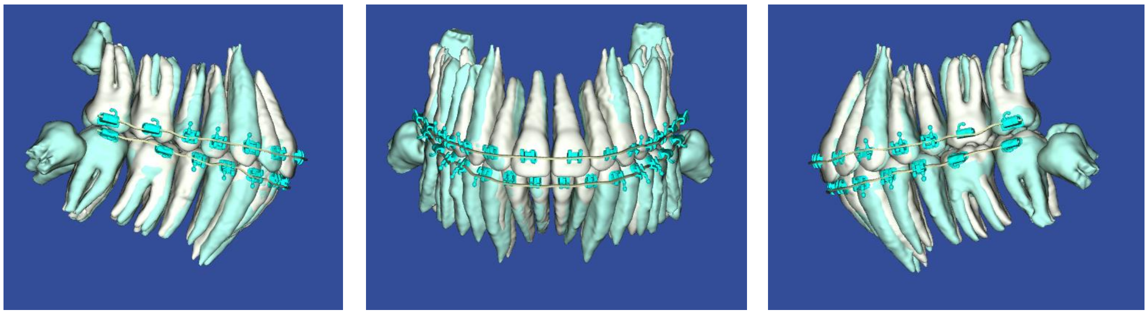

Figure 3. Teal teeth represent pre-treatment position. White teeth represent post-treatment position. SureSmile simulation provides individual tooth movement simulation throughout treatment.

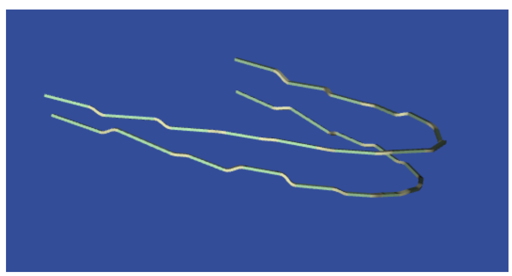

Figure 4. SureSmile milled arch wires for maxillary and mandibular arches

Providers can select from various sizes and types of archwires to sequence their prescribed movements. Providers are able to replicate similar mechanics as when using a conventional bracket system by selecting from a flexible, undersized, Copper NiTi, wire up to a more slot filling, rigid, finishing arch-wire. The treating orthodontist regulates wire placement, wire sequence, and time spent in treatment with each wire. The provider also maintains the autonomy to use any auxiliary mechanics such as elastic chains or anything else in his armamentarium that will aid him throughout treatment. Additional wires can be ordered at any point during SureSmile treatment.

Review of Current Literature

Since SureSmile's global launch in 1999, only a limited number of publications have been released regarding the technology. From a case report published in 2001, Sachdeva defined the technology as being designed to substantially reduce errors in treatment resulting from appliance management (Sachdeva, 2001). The time spent in finishing a limited amount of cases was decreased from an average of 7 months using conventional appliances to 4 months when using SureSmile. However, the quality of treatment was not assessed so the overall conclusions are difficult to determine. No sampling methods were listed as to how patients were assigned to each treatment category leaving any conclusions questionable.

In 2007, Müller-Hartwich *et al*. published a retrospective study using SureSmile virtual setup models of 26 consecutively treated patients were compared to models of the actual final outcome. Superimposition of the final outcome with the virtual setup predicted outcomes were completed using GeoAnalyzer (Orametrix) software. Superimpositions of both models were completed based on the teeth without any adjacent structures as reference. Model superimposition was preceded with preliminary positioning based on 3-10 teeth distributed across the arch to triangulate a 3D relationship. A total of six values were calculated for each premolar, canine, and incisor. Deviations averaged between all teeth reached medians of 2.12 degrees for torque, 1.77 degrees for tip, and 3.04 degrees for rotation. Translational errors for all teeth reached medians of

0.19mm in the mesiodistal and orovestibular planes and 0.21mm in the vertical plane. The poorest precision was noted for the upper and lower canines, upper premolar rotation, and lower premolar inclination. The author concluded that the highest precision should be expected for all translational and rotational components of incisor movement.

In a trial from 2010, Saxe et al. examined the efficiency and effectiveness of SureSmile by comparing both treatment times and case quality using the American Board of Orthodontics Objective Grading System (ABO-OGS) and the case difficulty using the Discrepancy Index (DI). Two groups of subjects were established. 24 patients that were being treated with conventional fixed appliances and 38 patients who were being treated using SureSmile. The study did not specify how the patient sample from three orthodontic practices was accrued and what selection criteria were implemented to divide the patient groupings. When comparing the quality of the finished cases, the American Board of Orthodontics Objective Grading System (ABO-OGS) showed a 4.4 point reduction in cases treated with SureSmile compared to conventional appliances alone. A lower Objective Grading Scale (OGS) score indicates a higher quality treatment outcome (American Board of Orthodontics, 2012). Overall treatment time for the SureSmile group was decreased by approximately 25% compared to the conventional group (average 14.7 months versus 20 months). Using the Discrepancy Index (DI), the author was able to compare treatment outcomes and case difficulty. No correlation was found between these two variables. Results show a statistical difference between overjet on the right as well as interproximal contacts on the left. However, a rationale for the asymmetric results is difficult to formulate and the author offers no explanation for these unilateral discrepancies. Potential flaws in the study include the author referencing 14 components of the American Board of Orthodontics Objective Grading System (ABO-OGS) system when only 7 were used since radiographs were not included (American Board of Orthodontics, 2012). Another possible flaw is that the comparison did not use randomized-case distribution. Lastly, it is not clearly stated that the same guidelines for optimal results were used for both groups of patients.

In 2011 *Alford et al*. published a study similar to *Saxe et al*. The study investigated treatment duration and outcomes of SureSmile subjects compared to conventional fixed appliance subjects using Cast-Radiograph Evaluation (CRE) and Discrepancy Index (DI). The sample size consisted of 132 consecutively treated cases. 63 patients were treated with conventional appliances and 69 patients were treated with SureSmile. The same orthodontist treated all patients. To be eligible to participate in the study subjects must have had second molars in occlusion, no congenitally missing teeth, and no documented compliance problems. Final case records were scored numerically based on the 8 categories compromising the ABO-CRE (American Board of Orthodontics Cast Radiograph Evaluation) score. The investigator was blinded during all parts of the scoring. The author concluded that SureSmile treatment produced a significantly lower ABO-CRE (American Board of Orthodontics Cast-

Radiograph Evaluation) score in the first order alignment, rotation, and interproximal space closure categories. Again, a lower OGS (Objective Grading Scale) score indicates a higher quality treatment outcome. However, conventional cases showed a better score for second-order tooth movement. The author concluded that this trend in poor axial inclination might be due to the comparatively lighter forces delivered when finishing in NiTi wires while using the SureSmile system. A second explanation is that providers are not allowing sufficient time for wires to fully express their prescribed movements and instead focusing on treatment duration. The SureSmile cases averaged 7 months less in treatment time compared with patients who were treated with just conventional braces. The SureSmile group did start with less complex malocclusions (mean DI=13.2) when comparing the DI (Discrepancy Index) scores with conventional cases (mean DI=15.8).

In 2012, Sachdeva published a study that was created to expand on the previous work completed by *Saxe et al.* and *Alford et al.* by using a much larger sample size. In 2003, Orametrix (Richardson, TX) created an ongoing system for providers to submit completed treatment records for both Suresmile and conventional patients. The patient database was composed of 12,335 patients accrued from the years 2003-2008 from 142 practices using SureSmile. The SureSmile group comprised 9,390 patients and the conventional group comprised 2,945 patients. Results showed the median SureSmile treatment length was 15 months and the median conventional treatment length was 23 months. The shorter treatment time was evident for Class I, II and III cases. SureSmile patients finished an average of 8 months faster and experienced four visits less than conventional patients. The shortcomings of this study are that there are no selection criteria for the records submitted, nor rationale for how cases were chosen to receive conventional versus SureSmile treatment. Unlike *Alford et al. (2011)* and *Sax et al. (2010)*, there was no standardized grading system to measure the effectiveness of treatment.

Larson et al (2013) published an objective, retrospective, study to assess the effectiveness of SureSmile by measuring the discrepancies between actual final dental alignment using conventional treatment versus the SureSmile virtual treatment plan. A total of 23 patients consecutively treated with SureSmile from two orthodontic practices were included. 18 patients were treated non-extraction and 5 were treated with extractions. Initial severity of malocclusion was not considered. Patient selection was based on the treatment protocols established in each orthodontic office. The treatment time and duration of time using each archwire was left to the clinical judgment of the treating orthodontist. Post-treatment models were digitized as sterolithography files to allow manipulation with their corresponding virtual treatment plan set up in the SureSmile software. Stereolithographs of the actual final outcome were superimposed over the predicted SureSmile virtual treatment plan using Compare (GeoDigm Corporation, Falcon Heights, MN) software. Threshold values for equivalence testing were taken from the ABO-OGS (American Board of Orthodontics

Objective Grading System) and set at +/-2 degrees of accepted discrepancy in tip, torque, and rotation. Threshold values for mesial-distal, facial-lingual, and vertical discrepancies were set at +/-0.5mm. Mesial-distal discrepancy values exceeded 0.5mmm for maxillary lateral incisors and second molars. Facial-lingual final tooth positions were outside of the accepted 0.5mm for maxillary central incisors, first and second premolars, and first and second molars. Facial lingual deviations for the mandible surpassed 0.5mm for central incisors, lateral incisors, and second molars. Vertical final tooth positions were clinically acceptable for all tooth types except maxillary second molars. Torque discrepancy exceeded the threshold of 2 degrees for all tooth types except mandibular second premolars. All tooth types with the exception of mandibular second premolars and first molars exceeded 2 degrees of tip discrepancy. Rotational discrepancy exceeded 2 degrees for all tooth types. The study concluded that the effectiveness of SureSmile treatment to achieve the prescribed tooth movements varies with tooth type and dimension of movement.

The Present Work

The present work is a follow up study based on the above-study by *Larson et al*. 2013, that examined the amount of discrepancy found when using SureSmile Technology as an adjunctive tool in fixed orthodontic treatment. As previously noted, *Larson et al.* (2013) concluded that discrepancy in individual tooth movement varies with which tooth type and dimension of movement. The present work was designed to evaluate if any correlation exists between the amount of discrepancy found in achieving the predicted tooth movement and the amount of total tooth movement that was completed throughout treatment. Digital models were superimposed from time points both pre-treatment to post-treatment to quantify overall tooth movement. Similarly, post-treatment models were superimposed with the SureSmile predicted treatment models to determine the amount of discrepancy between the actual and predicted finish. These quantitative measurements (millimeters and degrees depending on the type of movement) were obtained using eModel Compare (Geodigm Corporation, Chanhassen, MN) software. Discrepancies between predicted and actual treatment outcomes were then compared to amount of overall movement completed from pre-treatment to the time of post-treatment to determine if any significant correlations exist.

Specific Aims

The aims of this study were:

1. To revaluate SureSmile treatment effectiveness to achieve final tooth positions that are within 0.5 mm mesial-distally, facial-lingually, and vertically of the final tooth position predicted in the SureSmile virtual treatment plan,

2. To revaluate SureSmile treatment effectiveness to achieve buccal-lingual crown torque, mesial-distal crown tip, and crown rotation of final tooth position that are within 2 degrees of the final tooth position predicted by the SureSmile virtual treatment plan, and,

3. To evaluate for any correlation between a discrepancy in movement to the overall amount of movement throughout treatment in six-dimensions.

Hypothesis

The hypothesis were:

1. Discrepancy between mesial-distal, facial-lingual, and vertical position between predicted and final tooth position, based on the SureSmile treatment plan, and actual final tooth position obtained following orthodontic treatment will not be significantly different than threshold values of 0.5mm set by the American Board of Orthodontics.

2. Discrepancy of buccal-lingual crown torque, mesial-distal crown tip, and crown rotation between predicted final tooth position, based on the SureSmile treatment plan, and actual final tooth position obtained following orthodontic treatment will not be significantly different than threshold values of 2 degrees set by the American Board of Orthodontics.

3. Any noted discrepancies over 2 degrees or 0.5mm of tooth movement will correlate to a greater overall tooth movement in the respective dimension.

Materials and Methods

This retrospective cohort study involved review of post-treatment patient records, for which the Institutional Review Board at the University of Minnesota granted approval (Study Number 1512E81622). The sample data was collected from one orthodontic office trained by Orametrix (Richardson, TX) to use SureSmile Technologies. A total of 32 patients were included in the study (14 male and 18 female, average age 13 years 9 months). All comprehensive cases in this office are treated using SureSmile. SureSmile archwires were fabricated to the digital setup specifications prescribed by the treating orthodontist. Leveling and alignment was completed in all patients prior to initiation of SureSmile treatment. The time of wire placement and time spent in the SureSmile wires was determined by the clinical judgment of the treating orthodontist. Exclusion criteria for subjects were if dental casts from pre or post treatment were missing, if patient was treated in the mixed dentition phase, or if extractions were a part of the treatment plan. Initial severity of malocclusion was not considered.

The SureSmile predicted treatment plans, from which the final archwires were fabricated, were exported from the SureSmile software as stereolithography (.stl) files. All iTero scans and SureSmile plans for each individual were converted to the eModel format using eModel 9.0 digital model software (Geodigm Corporation, Chanhassen MN) for further analysis. Patient identification from digital models was removed prior to processing. Models were trimmed using Compare Software (Geodigm Corporation, Chanhassen MN). To ensure tooth position analysis was based solely on surface features, landmarks such as soft tissues, papillae, positive defects, bonded-retainers, and any residual dental material were removed from models prior to superimposition (see figure 5).

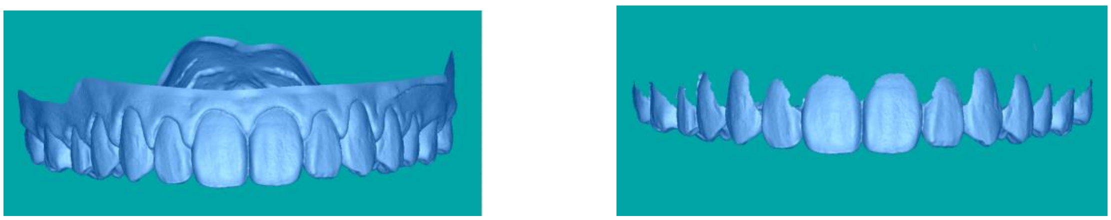

Figure 5. Before and after trimming gingival tissues and isolating hard dentition that will be superimposed.

Arch Registration

A single calibrated operator completed all registration and data collection on the subjects. Post-treatment models were segmented to isolate each tooth as a separate object so teeth could be analyzed individually. Following segmentation of the model, individual reference coordinates were placed on each tooth. The center of resistance is estimated to be halfway between the alveolar crest and apex of a tooth. (Proffit et al. 2012) Factors such as root length, root morphology, and alveolar bone height can all affect the center of resistance. (Smith and Burstone, 1984). For simplicity, root lengths from the cement enamel junction minus 2mm to accommodate the biologic width were averaged to reach a standardized position for the center of resistance. (Nelson and Ash, 2010; Tai,

2017) The center of resistance was placed 8mm apical to the cemento-enamel-junction on each tooth (see figure 6).

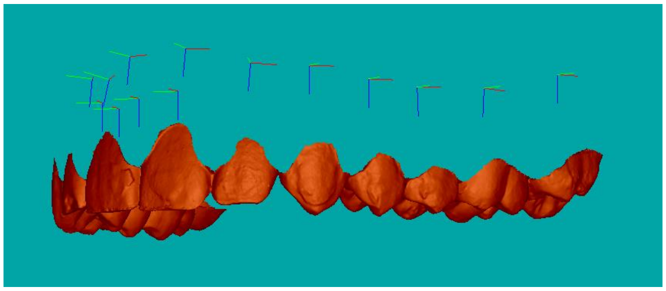

Figure 6. Assignment of axes and adjusted center of resistance 8mm apical to cemento enamel junction

Segmented Post-treatment models with coordinate axes placed were superimposed on the SureSmile virtual plan model using a best-fit surface based registration. The software compares a segmented arches position relative to an unsegmented arch. Upper and lower arches are analyzed separately. The following protocol developed by Chris Vaubel (2011) for arch registration was replicated for consistency:

Initial registration was completed by a three-point match based on the mesial-buccal cusps of 1st molars and the incisal contact point between central incisors. The same landmarks were used in both the maxillary and mandibular arches. Alignment of the post-treatment model to the virtual-plan model was completed by 50 iterations of a closest point algorithm in the Compare Software (Geodigm

Corporation, Chanhassen MN) to achieve a best fit on the occlusal surfaces. Following this global alignment, individual segmented teeth are superimposed with their analogous teeth in the unsegmented model so that individual positional discrepancies can be measured (See figure 7).

Figure 7. Left: 3-point match based registration on mesial-buccal cusps of maxillary first molars and contact point of central incisors completed on both analogous arches being superimposed. Center: Post global superimposition via 50 transformations using the iterative closest point algorithm of post-treatment model (orange) and virtual plan (white). Right: Individual teeth from post-treatment outcome (green) shifted in 6-dimensions to superimpose upon their analogous tooth from the virtual plan (white).

A similar registration protocol was used to align the pre-treatment model to the post-treatment model. Initial registration was completed using a three-point match based on the mesial-buccal cusps of 1st molars and the incisal contact point between central incisors. The same landmarks were used in both the maxillary and mandibular arches. Due to the amount of alignment change between pre-treatment to post-treatment movement, the Compare Software(Geodigm Corporation, Chanhassen, MN) calculated an unrealistic superimposition on select cases when registration was executed. Since no auxiliary fixed functional appliances or headgear were used during SureSmile treatment, cases with anterior crowding were assumed to gain arch-length through proclination of incisors and uprighting of posterior teeth. Compare (Geodigm Corporation, Chanhassen, MN) Software split the difference when arch-length was gained in the anteroposterior direction showing both molar distalization and incisor proclination. The operator reoriented the superimposition in the sagittal dimension using 3D controls if arch-based registration displayed molar distalization in a case of anterior crowding (See figure 8).

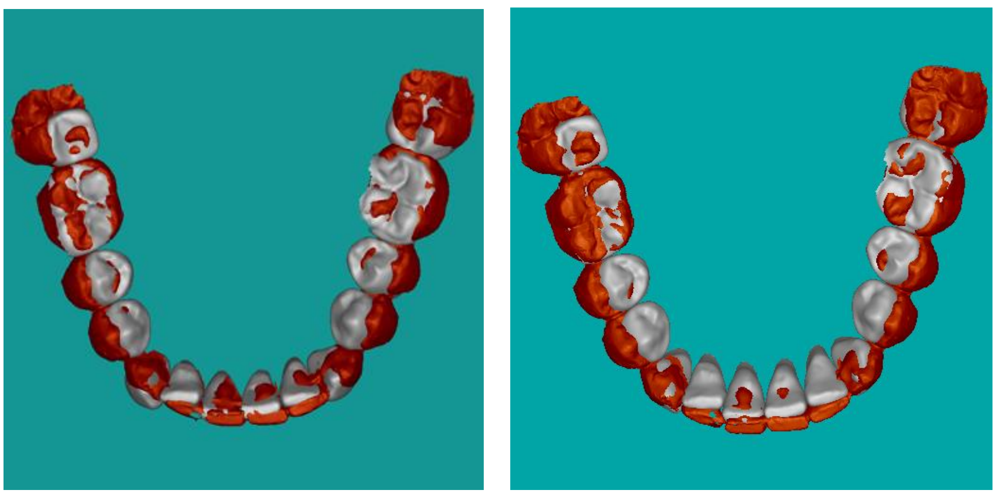

Figure 8. Left photo: Superimposition via 50 transformations using the iterative closest point algorithm. Note lower left 2nd molar distalized approximately 1mm. Right photo: Manual adjustment of sagittal plane to remove distalization of posterior teeth and more realistically represent treatment mechanics through proclination of lower incisors.

Compare Software (Geodigm Corporation, Chanhassen, MN) does not account for which orthodontic mechanics are being used when leveling the mandibular Curve of Spee and showed superimpositions that reflected absolute intrusion of the anterior dentition. Leveling the mandibular Curve of Spee was done through relative intrusion and not absolute intrusion.   Taking these biomechanical principles into mind the operator manually repositioned the pre-treatment and post-treatment cast superimpositions in only the vertical dimension if incisors showed absolute intrusion with no extrusion of the premolar segments.

Tooth Position Analysis

The direction and magnitude of transformation to achieve the best-fit superimposition was calculated to determine the discrepancy between the expected tooth position dictated by the SureSmile virtual plan and the post-treatment outcome. The total movement throughout between the pre-treatment model and the post-treatment model that represented overall tooth movement was also recorded. Transformation with respect to six dimensions of tooth movement, including bodily movement mesial-distally, facial-lingually, and occlusal-gingivally; crown rotation; mesial-distal crown tip; and facial-lingual crown torque, was calculated in reference to a coordinate system approximating the center resistance for each individual tooth. In the discrepancy between post-treatment and virtually planned treatment, positive numbers indicated that the predicted tooth position was different than the achieved tooth position in the following directions: more mesial, more buccal, more occlusal, had more mesial crown tip, more labial crown torque, and more mesial rotation whereas negative numbers indicated differences in the respective opposite directions. In the distance travelled throughout treatment, positive values indicated a tooth moved in this direction throughout treatment: mesial, buccal, occlusal, mesial crown tip, labial crown torque, and mesial rotation whereas negative numbers indicated differences in the respective opposite directions.

Compare Software (Geodigm Corporation, Chanhassen, MN) detects differences up to the thousandth digit, which is far beyond clinically relevant standards. Threshold values for clinical relevance were set following the American Board of Orthodontics (ABO) model grading system (MGS) for case evaluation, which is representative of acceptable professional standards (American Board of Orthodontics, 2012).

Based on the model grading system criteria, only discrepancies beyond 0.5mm in the mesial-distal, facial-lingual, and occlusal gingival were considered clinically relevant. Again, following the model grading system (MGS) criteria, only discrepancies beyond 2 degrees in torque, tip, and rotation were considered clinically relevant.

Statistics

Part 1: To establish discrepancy values between actual post-treatment outcome and the predicted post treatment outcome from the virtual SureSmile plan

Data from each tooth type was pooled by analogous tooth for analysis. A comparison between left and right analogous teeth was completed using a linear mixed model to ensure no statistically significant discrepancies existed between the left and right. To assess whether the differences between predicted and achieved tooth positions were large enough to be clinically relevant, equivalence testing was used. Due to the possibility that positive and negative numbers representing tooth movements in opposite directions could average out inappropriately to near 0, a one-sided equivalence test was completed. Threshold values for equivalence were defined as 0.5 mm for mesial-distal, facial-lingual, and vertical discrepancies, and 2 degrees for crown torque, crown tip, and crown rotation. Since the distribution of absolute values is skewed a log10 transformation was applied. For the analysis using log10 transformation, the zeros are removed. All the teeth are treated as independent from each other. One-sided equivalence test is based on log transformed data. Log scale data was transferred back to original scale.

Absolute value equivalence testing was able to show which teeth showed clinically significant discrepancies; however, it does not specify any trends in directionality. Descriptive statistics were computed for the differences between predicted and achieved tooth positions with respect to each of the six directions. For each mean difference, the linear mixed model was applied to calculate the corresponding 95% confidence interval. The null hypothesis was set to 0 millimeters or degrees depending on what dimension of movement was being assessed To assess whether the results were statistically significant, P-values were calculated using a false discovery rate method to adjust for the multiple comparisons performed.

To rule out intra-operator error an Altman-Blend method was used. To eliminate bias, a random number generator was used to select 16 cases that would be processed using the using the same study protocol for superimposition, evaluation, and to then compare results.

Part 2: To compare discrepancy values from Statistics Part 1 above to overall tooth movement throughout treatment.

Discrepancy values from Part 1 in all six dimensions were correlated to each analogous dimension of total tooth movement that was completed throughout treatment. The Pearson correlation coefficient, slope estimates, and p-values were calculated from linear regression with GEE (generalized estimating equation) to account for within-subject correlation to determine if any significant correlations exist.

Results

Intraexaminer Agreement

Intraexaminer agreement was confirmed using the Altman-Bland method. Half of the subjects were selected via a random number generator to be reanalyzed a second time. The same methodology was used to prepare and register the subjects' casts and determine discrepancy values. The mean difference between discrepancy values of the first and second data set is compared below in table 1.

Parameter	Mean Difference	95% CI
Mesial-Distal	-0.0109	(-0.3294, 0.3076)
Buccal-Lingual	-0.0133	(-0.3604, 0.3338)
Occlusal-Gingival	-0.0021	(-0.1584, 0.1541)
Tip	0.0285	(-1.2809, 1.3378)
Torque	-0.0158	(-0.7846, 0.7530)
Rotate	0.0054	(-0.9540, 0.9649)

Table 1. Altman-Bland method to determine agreement between rater at two time points.

The Altman-Bland plots illustrate good agreement between the two iterations of the comparison process for the 15 cases that were analyzed in duplicate. (See Fig. 9)

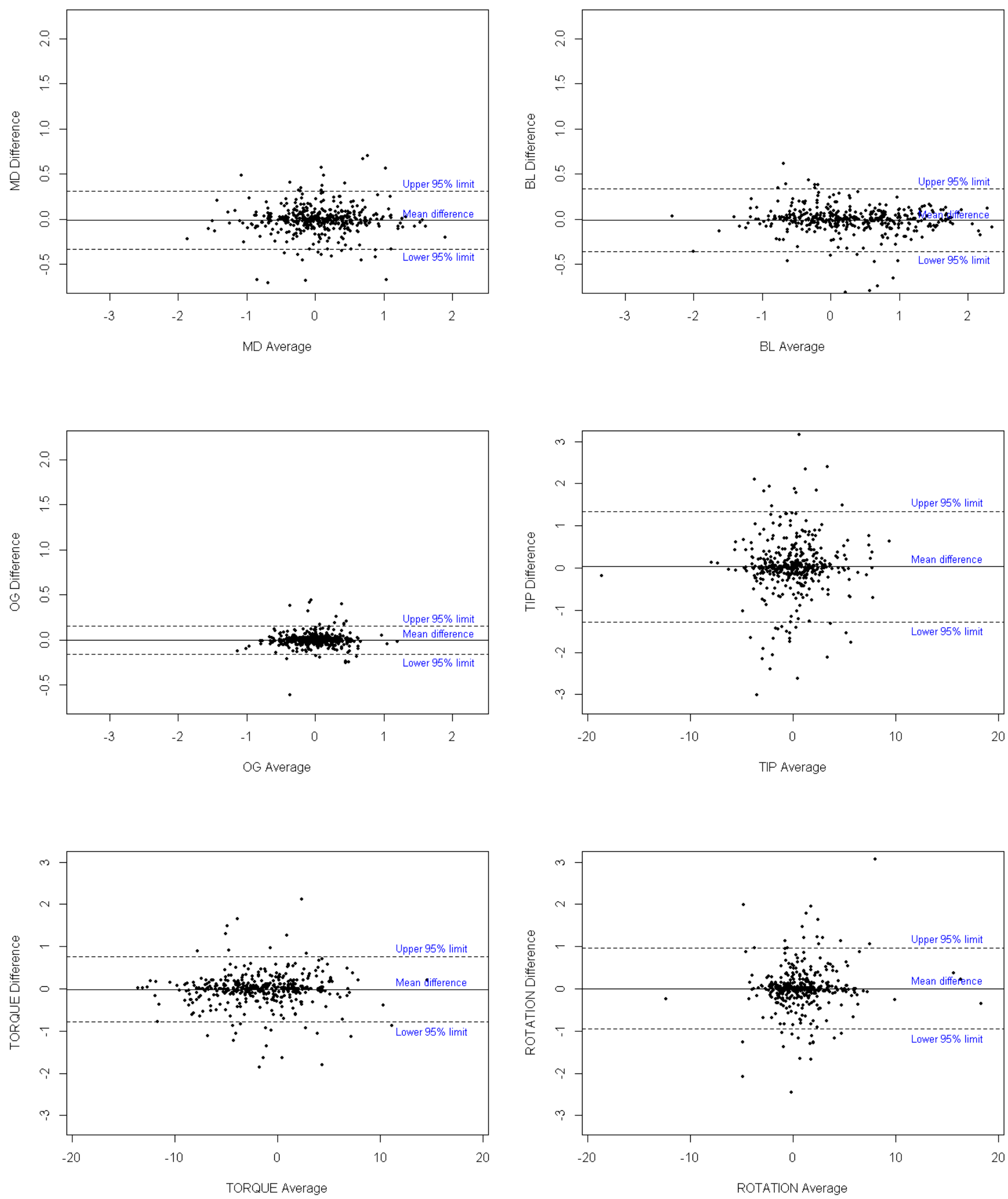

Figure 9. Altman-Bland plots illustrating intra-examiner agreement.

Comparison Right Versus Left Side

To determine if any alignment errors or outstanding asymmetric deviations occurred during the registration process mean discrepancy values were calculated between analogous teeth from the right and left quadrants of both arches (see table 2). Right and left values displayed statistically insignificant differences outside of the rotation category. Despite being statistically significant (alpha < 0.05) the rotational discrepancy was not deemed clinically significant to the results of this study.

Dimension	Difference	SE	P-Value
Mesial-Distal	-0.015	0.0411	0.7167
Buccal-Lingual	-0.0066	0.0408	0.872
Occlusal-Gingival	0.0304	0.0263	0.2535
Tip	0.0124	0.1655	0.9407
Torque	0.0466	0.2247	0.8362
Rotate	0.4764	0.1565	0.0029*

Table 2. Mean discrepancy between right vs. left side. Statistically significant difference (alpha 0.05) indicated by *.

Part 1: Discrepancy: Predicted versus Final Result

Data sets from analogous tooth types were aggregated together to provide a greater sample size when determining further statistics. Table 3 reflects the total sample size when comparing predicted results to actual treatment results after analogous tooth pairs were combined. Variation in sample size for each tooth pair reflects several teeth that Compare (Geodigm Corporation, Chanhassen, MN) was unable to superimpose. When the operator reviewed the final Compare (Geodigm Corporation, Chanhassen, MN) superimpositions for accuracy, certain teeth with less than full crown captured on the 3D models were unable to be properly superimpose with their corresponding tooth. In these few cases this applied to, it was visually evident as the partial crown was considerably misaligned during individual tooth registration. Manual reposition was not trusted, as a human operator could not replicate the accuracy of the Compare (Geodigm Corporation, Chanhassen, MN). The second molars were most affected as complete scanning could is impaired by limited mouth opening and interference with the hand-held scanning device (see table 3).

Tooth Pairs	n=
Upper Centrals	60
Upper Laterals	60
Upper Canines	60
Upper First Bicuspids	60
Upper Second Bicuspids	60
Upper First Molars	60
Upper Second Molars	56
Lower Centrals	58
Lower Laterals	57
Lower Canines	58
Lower First Bicuspids	58
Lower Second Bicuspids	58
Lower First Molars	58
Lower Second Molars	58

Table 3. Grouping and sample size of Actual Post-Treatment tooth pairs that were accurately superimposed on Predicted Post-Treatment tooth pairs.

The absolute value was first used to evaluate if any discrepancy exists between post-treatment results and predicted SureSmile treatment results (see table 4a and 4b below). Since the distribution of absolute values is skewed, log10 transformation is applied. One-sided equivalence test is based on log transformed data. log10(0.5) and log10(2) are equivalence bounds for distance and angle, respectively. The data then underwent Back transformation to convert log scale data to original scale.

Upper Arch Absolute Discrepancy Mean and p-value

Tooth Pair	M-D (mm)		Fa-Li (mm)		Vertical (mm)	
	mean	p-value	mean	p-value	mean	p-value
central incisors	0.28	<0.0002*	0.80	1.000	0.15	<0.0001*
lateral incisors	0.33	0.0046*	0.39	0.068	0.11	<0.0001*
canines	0.43	0.108	0.63	0.976	0.20	<0.0001*
1st premolars	0.36	0.007*	0.25	<0.0001*	0.20	<0.0001*
2nd premolars	0.27	0.0001*	0.33	0.0023*	0.13	<0.0001*
1st molars	0.23	<0.0001*	0.50	0.459	0.14	<0.0001*
2nd molars	0.58	0.871	0.53	0.642	0.14	<0.0001*

Tooth Pair	Tip (deg)		Torque (deg)		Rotate (deg)	
	mean	p-value	mean	p-value	mean	p-value
central incisors	0.92	<0.0001*	3.65	>0.9999	1.01	<0.0001*
lateral incisors	1.28	0.0002*	2.04	0.559	1.33	0.0004*
canines	1.29	0.0006*	3.03	0.999	1.09	<0.0001*
1st premolars	1.11	0.0005*	1.58	0.050	0.87	<0.0001*
2nd premolars	0.99	<0.0001*	1.23	0.001	0.90	<0.0001*
1st molars	1.07	<0.0001*	1.71	0.161	2.49	0.926
2nd molars	2.31	0.877	3.10	>0.9999	1.93	0.391

Table 4a. Absolute discrepancy means and p-values for each tooth pair in the upper arch. Values indicate discrepancy between final tooth position and the predicted SureSmile plan. p-value of less than 0.05 indicates final tooth position is within clinically acceptable limits and is indicated by *. M-D (mesial-distal), Fa-Li (facial-lingual).

Lower Arch Absolute Discrepancy Mean and p-value

Tooth Pair	M-D (mm) mean	M-D (mm) p-value	Fa-Li (mm) mean	Fa-Li (mm) p-value	Vertical (mm) mean	Vertical (mm) p-value
central incisors	0.16	<0.0001*	0.400	0.050	0.17	<0.0001*
lateral incisors	0.21	<0.0001*	0.32	0.0005*	0.15	<0.0001*
canines	0.24	<0.0001*	0.42	0.097	0.13	<0.0001*
1st premolars	0.26	<0.0001*	0.37	0.0145*	0.23	<0.0001*
2nd premolars	0.23	<0.0001*	0.57	0.822	0.19	<0.0001*
1st molars	0.23	<0.0001*	0.44	0.185	0.21	<0.0001*
2nd molars	0.37	0.0114*	0.61	0.863	0.17	<0.0001*

Tooth Pair	Tip (deg) mean	Tip (deg) p-value	Torque (deg) mean	Torque (deg) p-value	Rotate (deg) mean	Rotate (deg) p-value
central incisors	0.70	<0.0001*	1.81	0.262	1.04	<0.0001*
lateral incisors	1.02	<0.0001*	1.97	0.451	0.85	<0.0001*
canines	1.18	0.0002*	2.56	0.967	0.92	0.0002*
1st premolars	1.00	<0.0001*	1.70	0.109	0.70	<0.0001*
2nd premolars	1.03	0.0007*	2.90	0.999	0.48	<0.0001*
1st molars	1.63	0.069	2.00	0.512	1.45	0.0232*
2nd molars	2.43	0.915	3.89	>0.9999	1.36	0.0046*

Table 4b. Absolute discrepancy means and p-values for each tooth pair in the lower arch. Values indicate discrepancy between final tooth position and the predicted SureSmile plan. p-value of less than 0.05 indicates final tooth position is within clinically acceptable limits and is indicated by *. M-D (mesial-distal), Fa-Li (facial-lingual).

Absolute values show which discrepancies fall outside of our accepted parameters of 0.5mm or 2 degrees. However, they do not show directionality to whether the teeth consistently undershot or overshot their target position.

Sign values were set in reference to tooth movement throughout treatment relative to the SureSmile plan. Positive values represented a tooth finishing more mesial, facial, or occlusal than the SureSmile plan and finishing in the converse direction was represented with a negative sign. Positive values also represented a tooth positioned with buccal crown torque, mesial crown tip, or mesial rotation relative to the SureSmile plan. Again the converse direction of the previous movements would be represented with a negative sign (see table 5).

Dimension	Positive Value	Negative Value
M-D (mm)	more mesial	more distal
Fa-Li (mm)	more facial	more lingual
Vertical (mm)	more occlusal/incisal	more gingival
Torque (°)	more buccal crown torque	more lingual crown torque
Tip (°)	more mesial crown tip	more distal crown tip
Rotation (°)	facial surface rotated more mesially	facial surface rotated more distally

Table 5. Sign convention for discrepancy values with respect to six dimensions of tooth movement: Final treatment position relative to predicted setup. (M-D: mesial-distal, F-A: facial-lingual)

To assess in which direction the tooth was consistently positioned absolute values were negated and traditional means were calculated. Table's 6a and 6b show the mean with standard deviation and corresponding p-value for all six measures of tooth movement. The Null Hypothesis = 0. For all p-values less than 0.5 the null hypothesis is rejected and a statistically significant discrepancy is observed.

Upper Arch Mean Discrepancy

Tooth Pair	Mesial-Distal (mm) mean (SD)	Mesial-Distal (mm) p-value	Facial-Lingual (mm) mean (SD)	Facial-Lingual (mm) p-value	Vertical (mm) mean (SD)	Vertical (mm) p-value
central incisors	0.17 (0.48)	0.044	1.11 (0.94)	<0.0001	-.04 (0.29)	0.4227*
lateral incisors	0.35 (0.58)	<0.0001	0.34 (0.85)	0.002	0.05 (0.27)	0.2587*
canines	0.43 (0.58)	<0.0001	0.62 (0.82)	<0.0001	-.14 (0.32)	0.001
1st premolars	0.37 (0.53)	<0.0001	0.02 (0.58)	0.8624*	-.12 (0.33)	0.002
2nd premolars	0.24 (0.50)	0.001	-.35 (0.58)	0.001	0.06 (0.24)	0.1653*
1st molars	0.21 (0.40)	0.003	-.42 (0.76)	<0.0001	0.04 (0.23)	0.3595*
2nd molars	0.62 (0.79)	<0.0001	-.43 (0.92)	<0.0001	-.01 (0.33)	0.7499*

Tooth Pair	Tip (deg) mean (SD)	Tip (deg) p-value	Torque (deg) mean (SD)	Torque (deg) p-value	Rotate (deg) mean (SD)	Rotate (deg) p-value
central incisors	-.55 (1.76)	0.1264*	-4.93 (3.89)	<0.0001	-.32 (1.69)	0.4312*
lateral incisors	-1.17 (1.93)	0.000	-2.25 (3.78)	<0.0001	0.27 (2.18)	0.4312*
canines	-1.14 (1.99)	0.000	-3.69 (3.53)	<0.0001	-.44 (2.27)	0.3047*
1st premolars	-1.31 (1.94)	<0.0001	-1.05 (2.75)	0.027	-.44 (1.57)	0.3047*
2nd premolars	-.92 (1.96)	0.004	1.24 (2.47)	0.009	0.91 (1.71)	0.011
1st molars	-.67 (2.07)	0.038	1.75 (3.19)	0.000	3.68 (3.48)	<0.0001
2nd molars	-2.32 (3.94)	<0.0001	3.64 (3.84)	<0.0001	2.46 (3.65)	<0.0001

Table 6a. *SD = standard deviation.* Mean discrepancy for each tooth pair in the upper arch. Final values indicate actual tooth position in relation to SureSmile plan. Positive values indicate increased mesial, facial, or occlusal position; increased buccal crown torque, mesial crown tip, and mesial-lingual crown rotation of final tooth position relative to SureSmile plan. M-D (mesial-distal), Fa-Li (facial- lingual). An * was placed next to any value falling within acceptable limits.

Lower Arch Mean Discrepancy

Tooth Pair	Mesial-Distal (mm)		Facial-Lngual (mm)		Vertical (mm)	
	mean (SD)	p-value	mean (SD)	p-value	mean (SD)	p-value
central incisors	-.05 (0.44)	0.4912*	-.17 (0.77)	0.2079*	0.26 (0.29)	<0.0001
lateral incisors	-.08 (0.42)	0.2683*	0.01 (0.60)	0.8624*	0.16 (0.23)	<0.0001
canines	-.19 (0.41)	0.007	0.39 (0.61)	0.000	0.05 (0.26)	0.2234*
1st premolars	-.06 (0.42)	0.3889*	0.34 (0.58)	0.001	-.16 (0.36)	<0.0001
2nd premolars	-.27 (0.43)	0.000	0.79 (0.60)	<0.0001	-.30 (0.32)	<0.0001
1st molars	-0.24	0.000	0.64	<0.0001	-0.25	<0.0001
2nd molars	-.21 (0.67)	0.004	0.81 (0.85)	<0.0001	0.23 (0.27)	<0.0001

Tooth Pair	Tip (deg)		Torque (deg)		Rotate (deg)	
	mean (SD)	p-value	mean (SD)	p-value	mean (SD)	p-value
central incisors	0.06 (2.09)	0.8687*	0.12 (3.73)	0.8342*	0.29 (2.07)	0.4312*
lateral incisors	0.11 (2.13)	0.7878*	-.58 (3.03)	0.2063*	0.24 (2.25)	0.4602*
canines	0.91 (1.93)	0.005	-2.61 (3.42)	<0.0001	-.36 (2.75)	0.3602*
1st premolars	0.17 (1.69)	0.6793*	-1.46 (2.77)	0.003	0.63 (1.49)	0.1282*
2nd premolars	1.59 (2.28)	<0.0001	-3.36 (3.22)	<0.0001	0.36 (1.23)	0.3602*
1st molars	1.98	<0.0001	-2.12	<0.0001	1.70	<0.0001
2nd molars	2.33 (3.52)	<0.0001	-2.47 (4.95)	<0.0001	0.40 (3.35)	0.3567*

Table 6b. *SD = standard deviation.* Mean discrepancy for each tooth pair in the lower arch. Final values indicate actual tooth position in relation to SureSmile plan. Positive values indicate increased mesial, facial, or occlusal position; increased buccal crown torque, mesial crown tip, and mesial-lingual crown rotation of final tooth position relative to SureSmile plan. M-D (mesial-distal), Fa-Li (facial- lingual). An * was placed next to any value falling within acceptable limits.

Mean discrepancy 95% confidence intervals were also calculated for each tooth pair with respect to each dimension (see table 7). Figure 10 and 11 show each confidence interval in conjunction with the range of discrepancy.

Mean Discrepancies with 95% Confidence Intervals

Tooth Category	Mesial-Distal	Buccal-Lingual	Occlusal-Gingival
U1	0.17 (0.01, 0.32)	1.11 (0.87, 1.34)	-0.04 (-0.12, 0.05)
U2	0.35 (0.22, 0.49)	0.34 (0.14, 0.55)	0.05 (-0.03, 0.12)
U3	0.43 (0.30, 0.57)	0.62 (0.43, 0.82)	-0.14 (-0.21, -0.06)
U4	0.37 (0.23, 0.50)	0.02 (-0.17, 0.21)	-0.12 (-0.20, -0.05)
U5	0.24 (0.11, 0.37)	-0.35 (-0.54, -0.16)	0.06 (-0.01, 0.13)
U6	0.21 (0.08, 0.34)	-0.42 (-0.61, -0.23)	0.04 (-0.04, 0.11)
U7	0.61 (0.48, 0.75)	-0.42 (-0.61, -0.23)	-0.01 (-0.09, 0.06)
L1	-0.05 (-0.21, 0.10)	-0.17 (-0.41, 0.08)	0.26 (0.18, 0.35)
L2	-0.08 (-0.22, 0.05)	0.02 (-0.19, 0.23)	0.16 (0.09, 0.24)
L3	-0.19 (-0.33, -0.06)	0.39 (0.19, 0.59)	0.05 (-0.02, 0.13)
L4	-0.06 (-0.20, 0.07)	0.34 (0.15, 0.54)	-0.16 (-0.24, -0.09)
L5	-0.27 (-0.41, -0.14)	0.79 (0.60, 0.98)	-0.30 (-0.38, -0.23)
L6	-0.27 (-0.41, -0.14)	0.59 (0.39, 0.78)	-0.26 (-0.34, -0.19)
L7	-0.21 (-0.34, -0.07)	0.81 (0.62, 1.00)	0.23 (0.16, 0.31)

Tooth Category	Tip	Torque	Rotate
U1	-0.55 (-1.21, 0.11)	-4.93 (-6.06, -3.81)	-0.32 (-0.99, 0.35)
U2	-1.17 (-1.77, -0.58)	-2.25 (-3.22, -1.28)	0.27 (-0.34, 0.88)
U3	-1.14 (-1.73, -0.54)	-3.69 (-4.61, -2.77)	-0.44 (-1.05, 0.16)
U4	-1.31 (-1.90, -0.72)	-1.05 (-1.96, -0.15)	-0.44 (-1.05, 0.16)
U5	-0.92 (-1.52, -0.33)	1.24 (0.33, 2.14)	0.91 (0.31, 1.52)
U6	-0.67 (-1.26, -0.07)	1.75 (0.85, 2.65)	3.68 (3.08, 4.29)
U7	-2.30 (-2.92, -1.69)	3.71 (2.79, 4.63)	2.45 (1.82, 3.07)
L1	0.06 (-0.61, 0.73)	0.12 (-1.02, 1.26)	0.29 (-0.39, 0.97)
L2	0.11 (-0.50, 0.72)	-0.66 (-1.65, 0.33)	0.23 (-0.39, 0.86)
L3	0.91 (0.31, 1.51)	-2.61 (-3.55, -1.67)	-0.36 (-0.98, 0.26)
L4	0.17 (-0.43, 0.77)	-1.46 (-2.38, -0.54)	0.63 (0.01, 1.24)
L5	1.59 (0.98, 2.19)	-3.36 (-4.27, -2.44)	0.36 (-0.26, 0.97)
L6	1.88 (1.27, 2.48)	-2.04 (-2.96, -1.13)	2.13 (1.51, 2.74)
L7	2.33 (1.72, 2.93)	-2.47 (-3.39, -1.56)	0.40 (-0.22, 1.01)

Table 7. Estimated mean and its 95% confidence interval for each tooth pair.

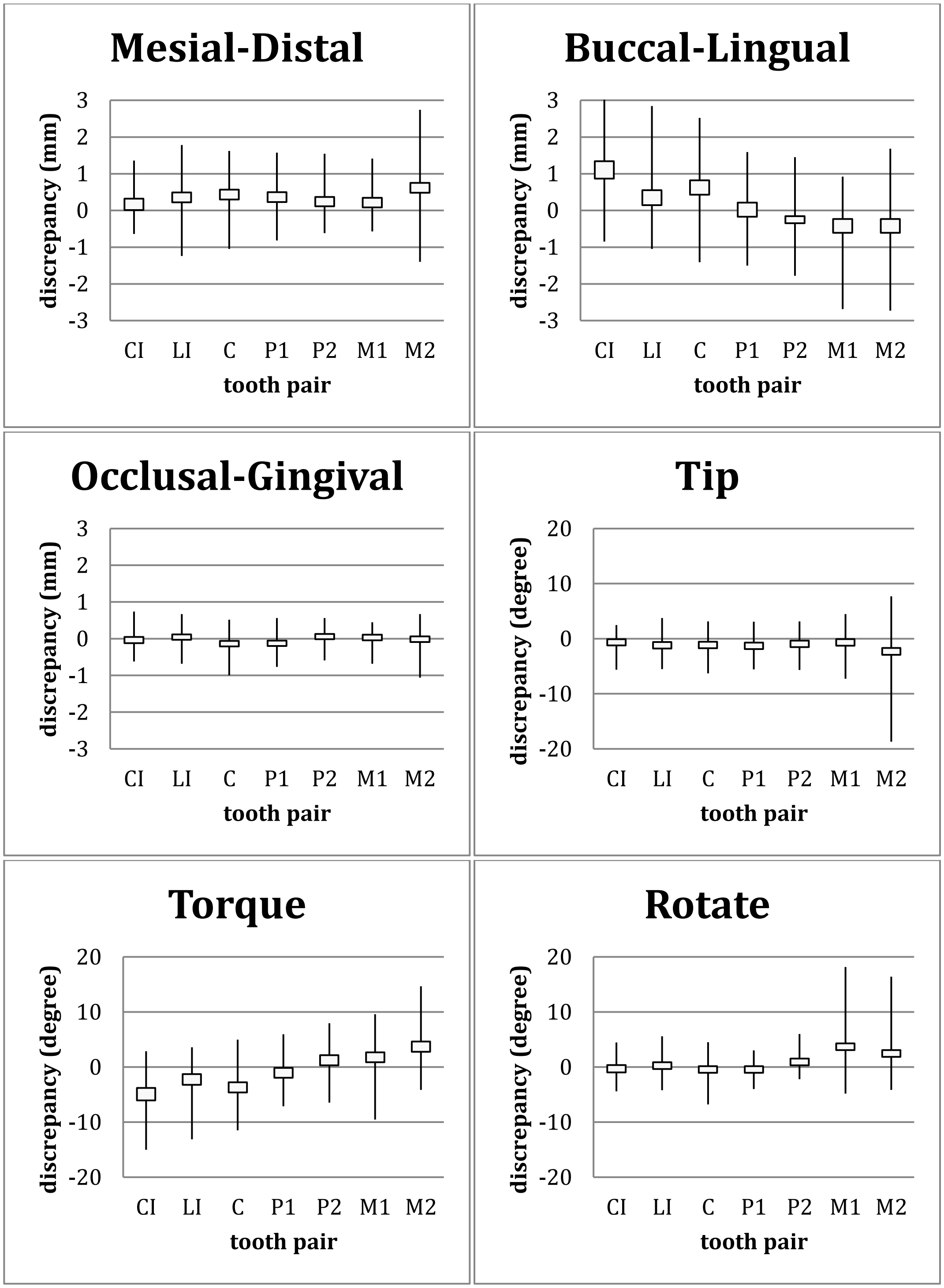

Figure 10. Upper arch 95% confidence intervals for mean tooth position discrepancy. Boxes indicate 95% confidence intervals, solid vertical lines indicate range of individual discrepancy values. Positive values indicate increased mesial, facial, or occlusal position; increased buccal crown torque, mesial crown tip, and mesial-lingual crown rotation of final tooth position relative to SureSmile plan.

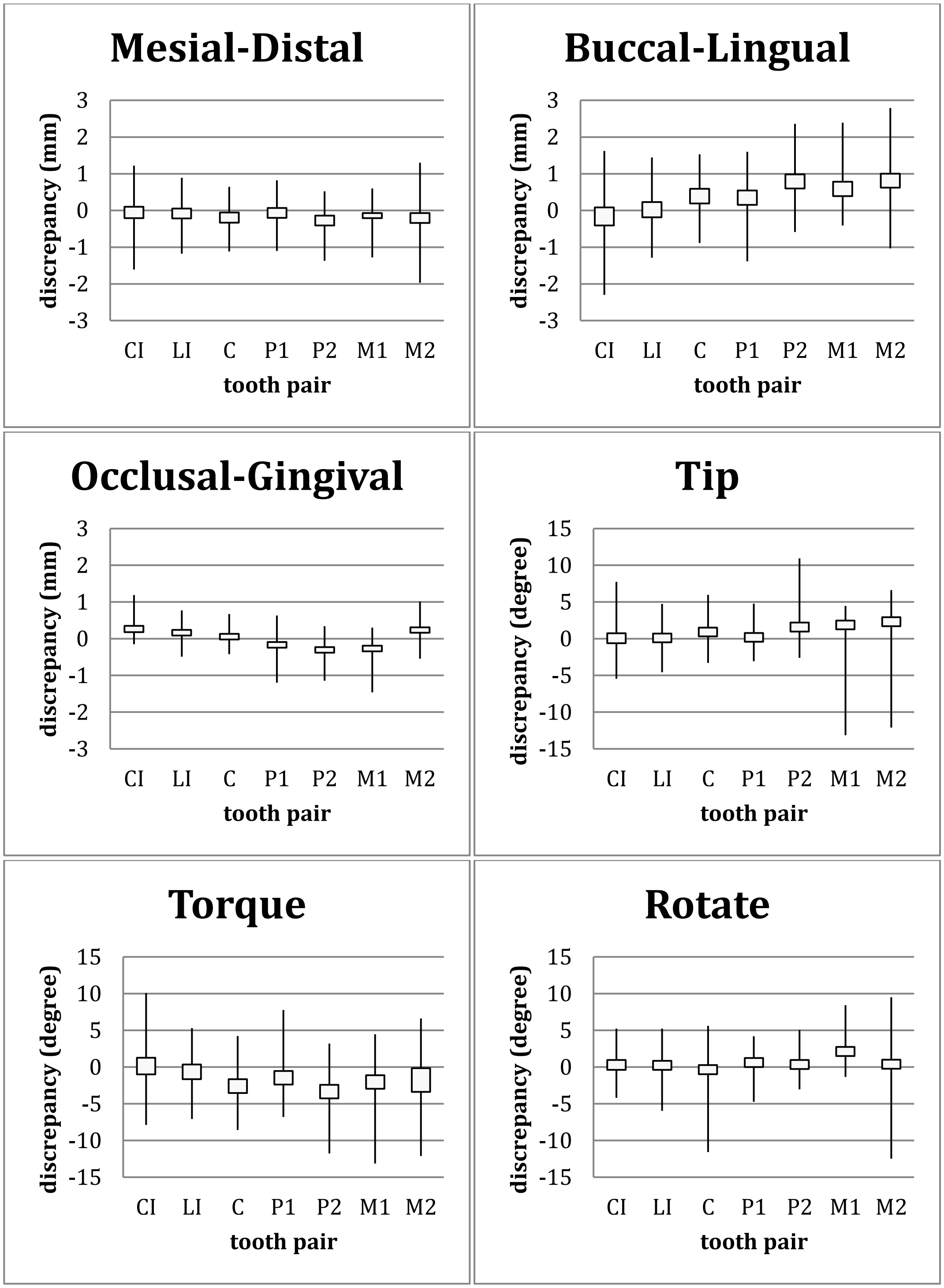

Figure 11. Lower arch 95% confidence intervals for mean tooth position discrepancy. Boxes indicate 95% confidence intervals, solid vertical lines indicate range of individual discrepancy values. Positive values indicate increased mesial, facial, or occlusal position; increased buccal crown torque, mesial crown tip, and mesial-lingual crown rotation of final tooth position relative to SureSmile plan.

Part 2: Correlation between overall tooth movement and discrepancy in predicted SureSmile movement:

Post-Treatment and Pre-Treatment models were superimposed to establish the overall movement each tooth completed throughout treatment. Similar to Table 3, Table 8 below shows the aggregated values of analogous tooth pairs that were combined to give the overall sample size. Just as with Table 3, a decreased n-value represents either a pre-treatment or post-treatment model that was either missing a tooth or a portion of the tooth causing the Compare Software to inaccurately register the tooth properly.

Tooth Pairs	n
Upper Centrals	60
Upper Laterals	60
Upper Canines	59
Upper First Bicuspids	60
Upper Second Bicuspids	59
Upper First Molars	60
Upper Second Molars	43
Lower Centrals	58
Lower Laterals	57
Lower Canines	58
Lower First Bicuspids	58
Lower Second Bicuspids	58
Lower First Molars	58
Lower Second Molars	53

Table 8. Grouping of Final-Treatment tooth pairs that were accurately superimposed on Pre-Treatment Models

Pre-treatment records were superimposed on the post-treatment finish to determine how much movement each tooth underwent with respect to six dimensions of tooth movement relative to its starting position. Similar to Part 1, directionality of movements were assigned + and – values (see table 9 below).

Dimension	Positive Value	Negative Value
M-D (mm)	tooth moved mesial	tooth moved distal
Fa-Li (mm)	tooth moved facial	tooth moved lingual
Vertical (mm)	tooth moved occlusal/incisal	tooth moved gingival
Torque (°)	tooth received buccal crown torque	tooth received lingual crown torque
Tip(°)	tooth received mesial crown tip	tooth received distal crown tip
Rotation (°)	facial surface of tooth rotated mesially	facial surface of tooth rotated distal

Table 9. Sign convention for overall treatment directionality with respect to six dimensions of tooth movement. M-D (mesial-distal), F-A (facial-lingual).

The following tables (10 and 11) display average tooth movements with their relevant statistical data in each of six-dimensions.

Overall Averages for tooth movement throughout treatment

Variable	N	Mean	Median	Std Dev	Minimum	Maximum
Mesial-Distal (mm)	801	0.25	0.25	1.02	-5.20	4.33
Buccal-Lingual (mm)	801	-0.07	-0.06	1.02	-3.63	5.72
Occlusal-Gingival (mm)	801	0.13	0.09	0.72	-3.44	4.43
Tip(°)	801	-1.09	-1.04	4.95	-28.67	20.89
Torque(°)	801	2.39	2.47	5.13	-31.68	17.43
Rotation(°)	801	1.04	0.54	7.12	-23.05	36.41

Table 10. Overall tooth movement throughout treatment

Maxillary mean movement throughout treatment

	M-D	F-L	OG	Tip	Torque	Rotation
central incisors	0.4	-0.53	-0.2	-2.09	1.94	1.26
lateral incisors	0.12	0.08	0.28	-0.71	1.19	1.75
canine	0.57	-0.11	0.61	-4.02	0.15	6.08
1st premolars	0.49	-0.2	0.08	-1.97	3.87	3.55
2nd premolars	0.74	-0.09	0	-2.99	3.37	0.08
1st molars	0.58	0.29	-0.03	-1.99	0.24	-0.76
2nd molars	0.65	0.64	0.75	2.88	-1.06	-1.65

Mandibular mean movement throughout treatment

	M-D	F-L	OG	Tip	Torque	Rotation
central incisors	0.1	-0.54	-0.31	-0.4	4.7	0.46
lateral incisors	0.19	-0.4	-0.44	1.21	5.61	0.09
canine	-0.2	-0.31	-0.05	0.54	2.89	4.78
1st premolars	-0.06	0.05	0.42	1.08	2.96	1.68
2nd premolars	0.61	0.35	0.51	-1.45	2.5	-2.73
1st molars	0.61	-0.06	0.12	-1.63	2.62	0.43
2nd molars	0.16	-0.01	0.29	-2.55	1.7	-1.57

Table 11. Tooth movement within each arch completed throughout treatment.

The amount of discrepancy determined in each of the six-dimensions of movement in Part 1 was compared with the overall tooth movement that occurred throughout treatment in the corresponding dimension is displayed below in tables 12a and 12b.

Upper Arch Tooth Movement Correlated with Amount of Discrepancy

	Mesial-Distal (mm)			Facial-Lingual (mm)			Vertical (mm)		
Tooth Pair	CC	SE	p-value	CC	SE	p-value	CC	SE	p-value
central incisors	0.319	0.18 (0.07)	0.0085*	0.423	0.29 (0.10)	0.0062*	0.143	0.07 (0.07)	0.297
lateral incisors	0.244	0.13 (0.07)	0.083	0.343	0.24 (0.11)	0.03*	0.236	0.11 (0.07)	0.106
canine	0.334	0.25 (0.10)	0.0137*	0.097	-0.02 (0.06)	0.699	0.227	0.07 (0.03)	0.0087*
1st premolars	0.217	0.18 (0.06)	0.0037*	0.193	0.02 (0.06)	0.815	0.260	0.17 (0.10)	0.071
2nd premolars	0.211	0.09 (0.08)	0.260	0.138	0.19 (0.08)	0.0178*	0.251	0.14 (0.05)	0.0106*
1st molars	0.086	0.05 (0.09)	0.531	0.024	0.07 (0.10)	0.509	-0.006	-0.08 (0.06)	0.219
2nd molars	0.044	0.05 (0.05)	0.311	0.077	-0.00 (0.15)	0.997	0.374	0.11 (0.03)	0.001*

	Tip (deg)			Torque (deg)			Rotate (deg)		
Tooth Pair	CC	SE	p-value	CC	SE	p-value	CC	SE	p-value
central incisors	0.364	0.18 (0.06)	0.0015*	0.367	0.28 (0.09)	0.0021*	0.208	0.04 (0.03)	0.184
lateral incisors	0.238	0.08 (0.04)	0.042*	0.358	0.38 (0.09)	<0.0001*	-0.097	-0.01 (0.04)	0.878
canine	0.362	0.17 (0.07)	0.0099*	0.323	0.11 (0.08)	0.147	0.178	0.04 (0.04)	0.263
1st premolars	0.212	0.13 (0.06)	0.0345*	0.015	-0.00 (0.07)	0.956	-0.133	-0.03 (0.04)	0.429
2nd premolars	0.217	0.09 (0.07)	0.194	0.196	0.11 (0.06)	0.063	-0.152	-0.08 (0.04)	0.055
1st molars	0.090	0.05 (0.08)	0.489	0.346	0.40 (0.12)	0.0006*	0.508	0.39 (0.10)	<0.0001*
2nd molars	0.090	0.06 (0.07)	0.419	-0.191	-0.12 (0.11)	0.281	-0.023	-0.04 (0.13)	0.749

Table 12a. *CC = correlation coefficient*. *SE= slope estimate with standard error in parenthesis.* Overall discrepancy between predicted and actual finished treatment was correlated to the overall amount of tooth movement throughout treatment in the upper arch. The null hypothesis was set to 0. Any p-value showing statistical significance has a * next to is. The slope estimate means how much increase on the deviation with one unit increase of the actual movement.

Lower Arch Tooth Movement Correlated with Amount of Discrepancy

Tooth Pair	Mesial-Distal (mm)			Facial-Lingual (mm)			Vertical (mm)		
	CC	SE	p-value	CC	SE	p-value	CC	SE	p-value
central incisors	0.218	0.13 (0.08)	0.127	0.403	0.23 (0.12)	0.050	0.415	0.19 (0.07)	0.0045*
lateral incisors	0.115	0.05 (0.05)	0.369	0.000	0.05 (0.10)	0.656	0.243	0.11 (0.07)	0.144
canine	0.156	0.05 (0.04)	0.164	0.170	0.13 (0.08)	0.093	0.241	0.08 (0.04)	0.054
1st premolars	0.143	0.08 (0.08)	0.309	0.325	0.29 (0.11)	0.008*	0.357	0.24 (0.07)	0.0006*
2nd premolars	0.133	0.08 (0.06)	0.205	0.117	0.10 (0.12)	0.393	0.049	0.02 (0.10)	0.829
1st molars	-0.031	-0.04 (0.07)	0.586	0.211	0.37 (0.16)	0.0198*	0.146	0.21 (0.08)	0.0111*
2nd molars	0.213	0.08 (0.11)	0.474	0.140	0.21 (0.12)	0.077	0.062	0.03 (0.05)	0.504

Tooth Pair	Tip (deg)			Torque (deg)			Rotate (deg)		
	CC	SE	**p-value**	**CC**	**SE**	**p-value**	**CC**	**SE**	**p-value**
central incisors	0.355	0.20 (0.08)	0.0215*	0.678	0.39 (0.06)	<0.0001*	0.226	0.06 (0.03)	0.018*
lateral incisors	0.117	0.07 (0.07)	0.318	0.502	0.35 (0.06)	<0.0001*	-0.218	-0.06 (0.03)	0.094
canine	-0.048	-0.00 (0.04)	0.948	0.405	0.33 (0.08)	<0.0001*	-0.189	-0.05 (0.03)	0.110
1st premolars	0.070	0.03 (0.07)	0.595	0.554	0.34 (0.09)	<0.0001*	-0.283	-0.07 (0.05)	0.152
2nd premolars	0.109	0.11 (0.05)	0.0404*	0.213	0.17 (0.07)	0.0111*	-0.197	-0.03 (0.03)	0.393
1st molars	-0.107	-0.07 (0.10)	0.492	0.491	0.51 (0.09)	<0.0001*	0.188	0.08 (0.07)	0.213
2nd molars	0.224	0.03 (0.06)	0.622	0.346	0.33 (0.09)	0.0004*	0.113	0.11 (0.07)	0.125

Table 12b. *CC = correlation coefficient*. *SE= slope estimate with standard error in parenthesis.* Overall discrepancy between predicted and actual finished treatment was correlated to the overall amount of tooth movement throughout treatment in the lower arch. The null hypothesis was set to 0. Any p-value showing statistical significance has a * next to is. The slope estimate means how much increase on the deviation with one unit increase of the actual movement.

Summary of Results

Part 1: Discrepancy between Actual Final Result and Predicted Final Result

Mesial-distal discrepancy values exceeded clinically significant threshold levels for only maxillary 2nd molars (mean 0.58). Mesial-distal discrepancy values fell within clinically acceptable levels for remaining maxillary and mandibular tooth pairs. All maxillary teeth ended mesial to their predicted position and all mandibular teeth ended distal to their predicted position.

Facial-lingual discrepancies exceed clinically acceptable levels for the maxillary central incisors (mean 0.80), canine (mean 0.63), 1st molar (mean 0.50), and 2nd molars (mean 0.53). Mandibular 2nd premolars (mean 0.57) and 2nd molars (mean 0.61) values were also outside of the clinically acceptable range of 0.5mm. Maxillary 2nd premolars, 1st molars, and 2nd molars were positioned lingual to their predicted positions. Mandibular central incisors ended lingual to their planned position while all other mandibular teeth ended facial to their planned positions.

Vertical discrepancy values all fell within clinically acceptable parameters. All vertical discrepancies ended negligibly close to 0 with no significant pattern of error to either the occlusal or gingival aspect.

Discrepancies in tip exceeded levels of clinical significance (>2 degrees) for maxillary 2nd molars (mean 2.3), and mandibular 2nd molars (mean 2.4). All maxillary teeth finished with excess distal tip compared with their predicted positions. All mandibular teeth ended with excess mesial tip compared to their predicted positions.

Torque discrepancy values exceeded levels of clinical significant for all tooth pairs in both arches: maxillary central incisors (mean 3.65), lateral incisors (mean 2.03), canines (mean 3.03), 2nd molars (mean 3.09), canines (mean 2.56), 2nd premolars (mean 2.89), and 1st molars (mean 2.0). Maxillary central incisors, lateral incisors, canines, and 1st premolars ended with more lingual crown torque than their predicted position. Maxillary 2nd premolars, 1st molars, and 2nd molars ended with more buccal crown torque than their predicted position. Mandibular central incisors ended with more buccal crown torque than their predicted position while all other mandibular teeth ended with more lingual crown torque than their predicted position.

Rotation discrepancy values exceeded levels of clinical significance for maxillary 1st molars (mean 2.49). All mandibular teeth finished within acceptable standards. Maxillary central incisors, canines, and 1st premolars ended with their facial surface distal to the prediction while maxillary lateral incisors, 2nd premolars, 1st molars, and 2nd molars ended with their facial surface mesial to the predicted position. Mandibular canines ended with their facial surface distal to the predicted position while all other mandibular teeth ended with their facial surfaces mesial to the predicted position.

Part 2: Correlation between overall tooth movement and discrepancy in predicted SureSmile movement

Overall tooth movement throughout treatment showed the greatest values in tip, torque, and rotation.

Mesial-distal correlation between discrepancy found in SureSmile prediction and overall tooth movement was statistically significant for the maxillary central incisors, canines, and 1st premolars (Correlation coefficients .319, .334, and .217 respectively). Overall Mesial-distal treatment correlation and treatment discrepancy showed concurrent statistical significance for only maxillary canines.

Facial-lingual correlation between discrepancy and overall tooth movement was statistically significant for the maxillary central incisor, lateral incisor, 2nd premolar (0.423, 0.343, and 0.346 respectively) and mandibular 1st premolars, and 1st molars (0.325, 0.111 respectively). Facial-lingual overall treatment correlation and treatment discrepancy showed concurrent statistical significance for maxillary central incisors.

Vertical correlation between discrepancy and overall tooth movement was statistically significant for the maxillary canines, 2nd premolars, 2nd molars (0.227, 0.251, 0.374 respectively) and mandibular central incisors, 1st premolars, and 1st molars (0.415, 0.357, and 0.146 respectively).

Tip correlation between discrepancy and overall tooth movement was statistically significant for the maxillary central incisors, lateral incisors, canines, and 1st premolars (0.364, 0.238, 0.362, and 0.212 respectively) and for mandibular central incisors, and 2nd premolars (0.355, and 0.109 respectively).

Torque correlation between discrepancy and overall tooth movement was statistically significant for the maxillary central incisors, lateral incisors, 1st molars (0.3676, 0.358, and 0.346 respectively) and all mandibular teeth (0.678, 0.502, 0.405, 0.554, 0.213, 0.491, and 0.346). Torque overall treatment correlation and planned treatment discrepancy showed concurrent statistical significance for maxillary central incisors, lateral incisors, 1st molars, and all mandibular teeth.

Rotation correlation between discrepancy and overall tooth movement was statistically significant the maxillary 1st molars (0.508) and for mandibular central incisors (0.226). Rotational overall treatment correlation and planned treatment discrepancy show concurrent statistical significance for maxillary 1st molars.

Statistically significant data from Part 1 and Part 2 that overlapped for the same tooth pair were compiled below to highlight teeth that had the greatest discrepancy to movement correlations (see table 13 below).

Maxillary Linked Data

	Correlation			Absolute Value Discrepancy	
	CC	SE	p-value	mean	p-value
	Mesial-Distal (mm)			Mesial-Distal (mm)	
canines	0.334	0.25 (0.10)	0.014	0.43	0.108
	Facial-Lingual (mm)			Facial-Lingual (mm)	
central incisors	0.423	0.29 (0.10)	0.006	0.8	1
lateral incisors	0.343	0.24 (0.11)	0.03	0.39	0.068
	Torque (deg)			Torque (deg)	
central incisors	0.367	0.28 (0.09)	0.002	3.65	>0.9999
lateral incisors	0.358	0.38 (0.09)	<0.0001	2.04	0.559
1st molars	0.346	0.40 (0.12)	0.001	1.71	0.161
	Rotate (deg)			Rotate (deg)	
1st molars	0.508	0.39 (0.10)	<0.0001	2.49	0.926

Mandibular Linked Data

	Correlation			Absolute Value Discrepancy	
	CC	SE	p-value	mean	p-value
	Facial-Lingual (mm)			Facial-Lingual (mm)	
central incisors	0.403	0.23 (0.12)	0.05	0.4	0.05
	Torque (deg)			Torque(deg)	
central incisors	0.678	0.39 (0.06)	<0.0001	1.81	0.262
lateral incisors	0.502	0.35 (0.06)	<0.0001	1.97	0.451
canines	0.405	0.33 (0.08)	<0.0001	2.56	0.967
1st premolars	0.554	0.34 (0.09)	<0.0001	1.7	0.109
2nd premolars	0.213	0.17 (0.07)	0.011	2.9	0.999
1st molars	0.491	0.51 (0.09)	<0.0001	2	0.512
2nd molars	0.346	0.33 (0.09)	0	3.89	>0.9999

Table 13. CC = Correlation Coefficient, SE = Slope Estimate. Various teeth and selective movements that showed both a statistically significant discrepancy between predicted Suresmile outcome and correlation with overall tooth movement throughout treatment in either the upper or lower arch.

Discussion

All study patients were treated at a single orthodontic practice that has been using SureSmile for several years and treats all of their comprehensive cases using the technology. This eliminates the possibility of case selection bias and ensures provider competency. Thus, for the present study, the decision to use SureSmile was independent of the severity of the malocclusion. Regardless of the results of this investigation, all cases were of high quality and a successful outcome.

The results of this study are generally in agreement with the findings of Vaubel *et al* (2013): Regardless of the arch, second molars consistently demonstrated the largest discrepancy between the simulated and actual treatment outcome. This finding is in agreement with field tests from the American Board of Orthodontics clinical examination, establishing the trend that 2^{nd} molars tend to be the most commonly misaligned tooth from an ideal finish (Campbell et al., 2007, Yang-Powers et al, 2002**).**

To gain an understanding of the magnitude of discrepancy between planned and actual treatment outcome the absolute value was implemented to avoid opposing signs (+ and -) that denote directionality in each of the six dimensions of movement from cancelling each other out thus giving an inappropriate average. For example, a linear measurement using the + sign to denote right and the – sign to denote left. If half the subjects had a discrepancy in tooth movement that was 5mm right giving a mean of +5 and the other half of the subjects had a mean discrepancy of 5mm to the left giving a -5, the overall mean would inaccurately show that the population has 0 discrepancy.

When reviewing the six types of tooth movement in this study, significant absolute discrepancy between planned SureSmile treatment and actual outcome of treatment occurred primarily in the facial-lingual and torque dimensions of movement. The ability of the Compare Software (GeoDigm Corporation, Falcon Heights, MN) to differentiate between buccal crown torque and facial movement and their respective opposing movements is unclear and operator dependent. The digitized models from this study only include the clinical crowns of the teeth in question. The operator must determine the long axis of each tooth based solely on crown form. A second source of error is the placement of the center of resistance. Variation is also seen in facial-lingual movement versus torque when the center of resistance is moved more occlusal or gingival. Between the error in operator axis placement and the estimation of the center of resistance it is very difficult to completely distinguish between these two dimensions of movement. However, intra-examiner statistics were completed using the Altman-Bland test that showed intraexaminer reliability.

Systematic differences in the buccal-lingual dimension were found for the maxillary 1st and 2nd premolars, 1st and 2nd molars, which consistently finished lingual to their predicted final position. This finding is consistent with Vaubel (2011). Meanwhile, mandibular 1^{st} and 2^{nd} premolars, 1^{st} and 2^{nd} molars all ended buccal to their predicted goal. Explanations for this can vary but can include the anatomical limitations of the maxilla to achieve predicted expansion, elastic wear and other auxiliary mechanics. SureSmile's prediction software may model alveolar bone as homogenous and may not take into consideration the differing biomechanical properties of cortical and trabecular bone.

Discrepancy in the vertical dimension between predicted plan and post-treatment outcome was not significant. This finding matches University tests and prior data. (Campbell et al. 2007; and Vaubel 2011) In the present study arch registration was based off of 3-points on the occlusal surface. Despite this potentially being seen as a bias, there is evenly distributed variation between teeth finishing occlusal and gingival to predicted position with no apparent pattern.

Similar to findings by Vaubel (2011), maxillary teeth tended to finish with more distal tip than their predicted position while mandibular teeth finished with more mesial tip than their predicted position. The subject data does not specify if and what auxiliary mechanics may have been used but class II elastics would cause such an effect that was not considered when formulating the SureSmile plan. The same mechanics can explain why maxillary anterior teeth lack buccal crown torque when compared with the SureSmile predicted outcome.

Rotation was only discrepant in the maxillary 1st molar and lower central incisor. The maxillary molar also showed significant correlation with distance traveled and amount of discrepancy (correlation coefficient = 0.51). Confirming results by Müller-Hartwich *et al*., (2007) that maxillary incisors show good precision in achieving their predicted rotational movements. It is unclear why the lower central incisor shows statistically significant discrepancy in the current work.

The dimension of torque (i.e. buccolingual inclination) showed the greatest consistency in clinical discrepancy between predicted and actual outcomes. A trend is evident in that mandibular posterior teeth finished with excess lingual crown torque and maxillary posterior teeth finished with excess buccal crown torque. These systematic differences can be explained by the clinician failing to treat within the limitations of trabecular bone and impinging upon the cortical plate. It is impossible to quantify the amount of constraint the cortical plate places on root movement since it is assumed that some degree of remodeling occurs. Such a limit on root movement could have transformed some of the prescribed buccal translation of a tooth into additional buccal crown torque. Another possible explanation for the systematic torque differences between simulated and actual final positions is Compare Software's inability to accurately differentiate between facial-lingual movement and torque. Data shows the opposite discrepancy of maxillary and mandibular posterior teeth with respect to facial-lingual position. Recall from earlier that the facial-lingual position appears to error in the opposite direction: maxillary teeth finish lingual to the projected position and mandibular teeth finish buccal. Following a systematic review of torque, varying degrees of torque range prior to active engagement would be expected (Archambault et al. 2010). The amount of range between engagement would vary depending on bracket slot size, prescription, wire cross section, type of wire, and individual manufacturer tolerances. (Sebanc, Gioka, C and Eliades T. 2004) Reviewing the archwires used throughout treatment, the great majority of cases were finished in 19x25 Cu-NiTi, SureSmile milled, archwires using a .022 bracket system. A superelastic arch wire should exert the same amount of force independent of the degree of activation within a wide range, a phenomenon due to a stress-induced martensitic transformation from an austenitic phase (Waters 1992). However, torsional properties of NiTi wires show a higher activation level due to their rounded edges (Meling 1998). The mechanical properties of the wire should be considered for this as well as other discrepancies noted in the posterior segments. We can expect a higher discrepancy between predicted and achieved position as the wire extends further posterior due to the diminishing mechanical properties at the free ends of an archform.

In Part 2 of the study human error was introduced as casts were manually adjusted in an attempt to superimpose relative positions of pre-treatment and post-treatment skeleto-dental relationships. No stable skeletal landmarks were used to assist in this process. Acceptable assumptions were made regarding treatment mechanics by reviewing wire sequences, and auxiliary mechanics allowing the operator to implement a consistent protocol to reasonably align the arches. Up until this portion of the data, the operator took all steps to remove human error from data collection. Software was implemented to use the iterative closest point algorithm to maintain accurate and reliable results. Compare Software has been used in several other studies focused on quality control and outcome assessment. (Vaubel, 2011; Grünheid *et al*., 2014; Gyllenhaal, 2015; Grünheid *et al*., 2016 Tai, 2017;) In the current work and previous studies implementing Compare Software, Altman-Bland plots do show acceptable intraexaminer reliability.

The greatest correlation between discrepancy in planned movement and amount of overall tooth movement existed in the torque dimension of dental movement in the mandibular arch. A similar argument from earlier in the discussion can be repeated regarding torque discrepancy based on manufacturer error in both archwires and brackets.

Conclusion

Similar to findings by Vaubel (2011), the effectiveness of SureSmile to achieve predicted tooth position is highly variable for tooth type and dimension of movement. Facial-lingual and torqueing movements show the greatest discrepancy. Upper and lower 2nd molars show the most consistent discrepancies across several dimensions of movement.

Significant correlation between distance traveled throughout treatment and discrepancy found between actual and predicted outcomes was variable and limited to only several teeth in specific dimensions. Despite these limited findings, clinicians can better understand potential treatment fallacies by observing the overall trends presented here. For example, when basing final treatment goals off of the ideal maxillary incisor position, it may be wise to compensate for facial-lingual and torque discrepancies shown in the findings from the current work. Regardless of these select clinically significant treatment discrepancies, overall tooth position is consistently acceptable and satisfactory.

Future Studies

The present study attempted to investigate if any correlation exists between the amount of tooth movement throughout treatment and the amount of discrepancies found between post-treatment tooth positions versus predicted final tooth position prescribed into the SureSmile treatment plan. As mentioned in the discussion above, there were several points throughout the current study where error was introduced or could have been potentially introduced by the operator.

The goal of future study would be to further minimize any error introduced by the operator. By using 3D registration of both skeletal and dental components the superimposition of dental bases can be done digitally by computer logarithm avoiding any human error. By using stable skeletal landmarks, dental casts taken at different time points can still accurately be superimposed (Park et al, 2012). For example, the palatal rugae have been found to be a stable skeletal landmark in the maxilla (Lebret L., 1962) Other reports found superimposition of the maxilla using palatal rugae accurate with reproducibility equivalent to 2D cephalometric analyses (Hoggan BR, 2001; Miller et al., 2003). This would define a stable anteroposterior point. The current work had difficulty assessing true anteroposterior position of the dentition between time points as the arch length changes throughout treatment. Park et al. (2012) found that mandibular dental arch superimposition can be reproducible and reliable when using a surface-based registration. This method relies on a 3D surface-to-surface matching (best-fit-method) using a least-root-mean-squared algorithm (Park et al, 2012). The drawback of this method for mandibular superimposition is that it only applies to non-growing patients.

Another way to further reduce operator error would be to maintain accurate 3D renderings of the dental crown and root when placing reference coordinates. If this were possible, the operator could more reliably assess the accuracy of reference points that determine the long axis of each tooth.

With the implementation of the previous recommendations a future study could reproduce this entire study with greater accuracy and reliability.

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