Original Article

Effectiveness of computer-assisted orthodontic treatment technology to achieve predicted outcomes

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ABSTRACT

Objective: To evaluate the effectiveness of computer-assisted orthodontic treatment technology to produce the tooth position prescribed by the virtual treatment plan.

Materials and Methods: Posttreatment models of 23 patients treated with SureSmile were digitally superimposed on their corresponding virtual treatment plan models utilizing best-fit surface-based registration. Individual tooth-position discrepancies between virtual treatment plan and actual outcome were computed. Discrepancies less than 0.5 mm in mesial-distal, facial-lingual, and vertical dimensions, and less than 2° for crown torque, tip, and rotation were considered clinically ideal. One-sided test of equivalence was performed on each discrepancy measurement, with $P < .05$ considered statistically significant.

Results: Mesial-distal tooth position was clinically ideal for all teeth with the exception of maxillary lateral incisors and second molars. Facial-lingual tooth position was clinically ideal for all teeth except maxillary central incisors, premolars, and molars, and mandibular incisors and second molars. Vertical tooth position was clinically ideal for all teeth except mandibular second molars. For crown torque, tip, and rotation, discrepancy exceeded the limits considered clinically ideal for all teeth except for crown torque on mandibular second premolars and crown tip on mandibular second premolars and first molars.

Conclusions: The effectiveness of computer-assisted orthodontic treatment technology to achieve predicted tooth position varies with tooth type and dimension of movement. (*Angle Orthod.* 2013;83:557–562.)

KEY WORDS: Computer-assisted treatment; SureSmile; Treatment effectiveness; Virtual treatment plan

INTRODUCTION

Technologic advances in three-dimensional (3D) imaging of the dentition, digital model technology, computer-aided manufacturing, and robotics have catalyzed new approaches to orthodontic treatment. One of the systems utilizing these new technologies is SureSmile (OraMetrix, Richardson, Tex), an all-digital system for orthodontic diagnostics, treatment planning, and fabrication of customized archwires.[1] This system allows clinicians to manipulate a 3D digital model of a patient's teeth and jaws to develop a virtual treatment plan by simulating orthodontic treatment. Wire-bending robots then fabricate orthodontic archwires with the necessary geometry to complete treatment according to the virtual treatment plan.[2] This technology has been reported to result in better treatment outcomes and shorter treatment times when compared with conventional approaches.[3,4]

The SureSmile system utilizes standard treatment mechanics and conventional brackets and bands, and requires no special considerations during appliance placement.[5] The process begins any time after appliance placement with a scan of the patient's dentition using a handheld intraoral optical scanner (OraScanner, OraMetrix) or cone-beam computed tomography. The scan data are used to locate the bracket on each individual tooth and construct a digital model of the patient's dentition, called the *therapeutic*

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model. This segmented model can be used for detailed treatment planning and simulation as the software allows the operator to move each tooth as an independent object in three dimensions. The operator can run various treatment scenarios and simulate treatment until the optimal treatment plan is found.[2]

Based on the position of the bracket slot on each individual tooth, the software then calculates the archwire bends necessary to move the patient's teeth to the final position dictated by the virtual treatment plan.[1] The information is sent via the Internet to OraMetrix where the archwires are produced by wire-bending robots in the material and cross-section selected by the orthodontist. The robots are able to process thermally activated shape-memory alloys allowing for large working ranges. Investigations into the precision of the bends with stainless steel wire have shown less than 1° of error in bends and twists.[2]

While the ability to establish a definitive treatment goal in three dimensions is a potential advancement for more accurate treatment planning, questions remain regarding the precision and predictability of tooth movement. Therefore, the aims of this study were to evaluate the effectiveness of computer-assisted orthodontic treatment technology to produce the intra-arch tooth position prescribed by the virtual treatment plan and to quantify positional differences between the tooth position predicted by this plan and the actual treatment outcome.

MATERIALS AND METHODS

Approval to conduct this study was obtained from the University of Minnesota's Institutional Review Board. A total of 23 patients consecutively treated using SureSmile were included. Orthodontic treatment was completed by two orthodontists trained in the use of this system using nonextraction ($n = 18$) and extraction treatment plans ($n = 5$). The patients were selected for treatment using the computer-assisted technology based on the treatment protocols established in each orthodontic office; initial severity of malocclusion was not considered. The final archwires for all patients were robot-bent according to the virtual treatment plan designed by the respective treating orthodontist. The size, time of placement, and length of time spent in the final archwire was left to the clinical judgment of the treating orthodontist.

At the time of appliance removal, alginate impressions were taken and poured in plaster to fabricate posttreatment models. The posttreatment models were digitized as stereolithography (.stl) files using an R700 orthodontic model scanner (3Shape A/S, Copenhagen, Denmark). The virtual treatment plans, from which the final archwires were fabricated, were exported from the SureSmile software as .stl files. For further analysis, the .stl files of the posttreatment models and corresponding virtual treatment plan for each individual arch were converted to digital models using emodel 9.0 digital model software (GeoDigm Corporation, Falcon Heights, Minn).

The posttreatment digital models of each individual arch were globally superimposed on the virtual treatment plan models utilizing best-fit surface-based registration (Figure 1). Initial registration was completed by three-point match based on the mesial-buccal cusps of first molars and the incisal contact point between central incisors. The initial registration was then refined using an iterative closest-point algorithm to align the posttreatment digital model and virtual treatment plan model according to the best fit for each individual arch. Alignment was based on a predefined fit region, which consisted of the occlusal surfaces of the first molars and premolars, tips of canines, and incisal edges of lateral and central incisors. This region was chosen to represent the average occlusal plane for each arch. Alignment of the posttreatment digital model to the virtual treatment plan model was completed by 30 transformations of the iterative closest-point algorithm.

Figure 1. Arch registration for model superimposition. (A) Selection of points for initial three-point match registration on mesial-buccal cusps of first molars and incisal contact point between central incisors. (B) Selection of fit regions containing occlusal surfaces of first molars and premolars, tips of canines, and incisal edges of lateral and central incisors. (C) Best-fit registration of posttreatment digital model (green) on virtual treatment plan model (white).

Differences in individual tooth position between posttreatment digital model and virtual treatment plan model were analyzed using emodel Compare 8.1 software (GeoDigm). To ensure that the analysis was based solely on tooth-surface features, interproximal papillae and the model base apical to the gingival margin were removed from both the posttreatment digital model and virtual treatment plan model (Figure 2). The software allowed surface feature-based superimposition of individual teeth contained in the virtual treatment plan on the corresponding tooth in the posttreatment model by iterative closest-point matching. The direction and magnitude of transformation to achieve best fit was calculated to quantify the discrepancy between the tooth position dictated by the virtual treatment plan and the actual treatment outcome. Transformation with respect to six dimensions of tooth movement, including mesial-distal, facial-lingual, and occlusal-gingival bodily movement as well as crown rotation, mesial-distal crown tip, and facial-lingual crown torque, was calculated in reference to a coordinate system approximating the center of resistance for each individual tooth. Transformations were completed by the software's auto superimposition function.

To exclude the possibility of alignment bias during the whole-arch registration process, mean discrepancy values for each dimension were compared independently for maxillary and mandibular arches, between all teeth right of the midline, and all teeth left of the midline. Right/left comparison demonstrated equal distribution of values for each dimension.

For further analysis, right and left analogous teeth within each arch were combined. The sample size varied among tooth types (Table 1) as two patients were treated with extraction of maxillary first premolars, two patients with extraction of maxillary and mandibular first premolars, and one patient with extraction of a mandibular central incisor. A total of 12 maxillary and two mandibular second molars were missing, unerupted, or not included in the virtual treatment plan.

Discrepancy calculations contained both positive and negative values for each dimension. In order to eliminate the possibility that summation of positive and negative discrepancy values would give the illusion of clinical accuracy, absolute values of each individual discrepancy were calculated.

One-sided test of equivalence was performed on the absolute value of each discrepancy measurement for each tooth type with respect to six dimensions of tooth movement. The threshold values for equivalence testing were set at ± 0.5 mm for mesial-distal, facial-lingual, and vertical discrepancies and at $\pm 2^\circ$ for crown torque, tip, and rotation. These threshold values were selected as they represent accepted professional standards: during case evaluation using the American Board of Orthodontics (ABO) objective grading system (OGS), points are subtracted for teeth that deviate 0.5 mm or more from proper alignment in the categories "alignment" and "marginal ridges."[6] A crown-tip inadequacy of 2° causes a marginal ridge discrepancy of 0.5 mm in an average-sized molar.

To determine if the final tooth position met the selected threshold, 95% confidence intervals for each tooth type with respect to each dimension of tooth movement were calculated. While absolute discrepancy values indicate the magnitude of discrepancy between the final tooth position and the virtual treatment plan, they do not indicate the direction in which the final tooth position deviates from the plan. Therefore, mean discrepancy values for each dimension were calculated for each tooth type to determine the direction of discrepancy.

Statistical analysis was performed using R Statistical Software 2.9.2 (R Foundation for Statistical Computing, Vienna, Austria). *P* values of less than .05 indicated discrepancy within the selected limits and a final tooth position considered "clinically ideal."

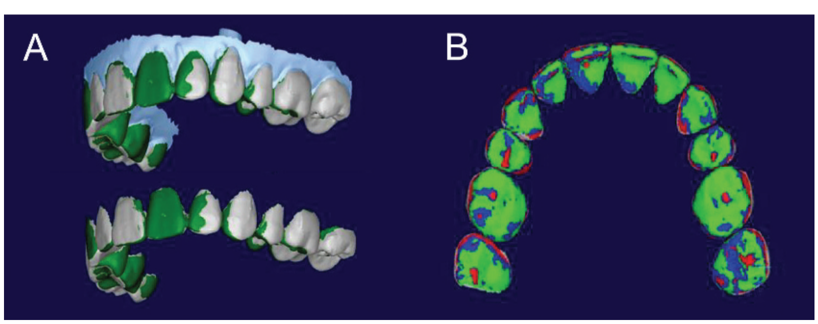

Figure 2. Tooth-position analysis. (A) Removal of interproximal papillae and model base apical to the gingival margin to ensure that the analysis was based solely on tooth-surface features. (B) Individual tooth feature-based superimposition of models (green: difference $<$ 0.1 mm; blue: difference 0.1–0.2 mm; red: difference $>$ 0.2 mm).

Table 1. Discrepancy Between Final Tooth Position and SureSmile Virtual Treatment Plan[a]

	n	Dimension					
		Mesial-Distal, mm	Facial-Lingual, mm	Vertical, mm	Torque, Degrees	Tip, Degrees	Rotation, Degrees
Maxilla							
Central incisor	46	0.16 ± 0.35*	0.14 ± 0.59	0.14 ± 0.26*	−1.21 ± 4.58	−0.10 ± 2.28	−0.92 ± 2.38
Lateral incisor	46	0.41 ± 0.43	−0.12 ± 0.44*	−0.13 ± 0.32*	0.22 ± 3.33	−0.77 ± 2.85	−1.69 ± 3.19
Canine	46	0.30 ± 0.46*	−0.23 ± 0.36*	−0.30 ± 0.36*	−0.16 ± 2.64	−0.46 ± 2.70	−0.17 ± 3.58
First premolar	38	0.19 ± 0.39*	−0.49 ± 0.46	−0.21 ± 0.29*	0.06 ± 3.04	0.22 ± 2.54	−0.26 ± 2.27
Second premolar	46	0.19 ± 0.44*	−0.52 ± 0.50	−0.03 ± 0.27*	1.07 ± 2.94	−0.11 ± 2.38	0.29 ± 3.14
First molar	46	0.23 ± 0.38*	−0.41 ± 0.53	−0.07 ± 0.16*	1.08 ± 1.86	−1.42 ± 2.25	4.68 ± 3.11
Second molar	34	0.49 ± 0.46	−0.43 ± 0.84	0.02 ± 0.53*	4.57 ± 3.86	−2.51 ± 3.43	2.91 ± 4.27
Mandible							
Central incisor	45	0.01 ± 0.39*	−0.38 ± 0.56	0.01 ± 0.38*	1.73 ± 4.11	0.10 ± 2.74	−0.05 ± 2.48
Lateral incisor	46	−0.04 ± 0.40*	−0.39 ± 0.56	−0.04 ± 0.39*	2.02 ± 3.86	1.06 ± 3.08	0.71 ± 2.63
Canine	46	0.19 ± 0.38*	−0.20 ± 0.41*	−0.12 ± 0.31*	0.28 ± 2.97	−0.50 ± 3.29	−0.60 ± 2.36
First premolar	42	0.03 ± 0.40*	−0.12 ± 0.40*	−0.15 ± 0.30*	−0.53 ± 3.13	0.05 ± 2.52	1.32 ± 3.68
Second premolar	46	0.05 ± 0.36*	−0.12 ± 0.55*	−0.09 ± 0.21*	−0.33 ± 2.11*	0.22 ± 1.90*	1.17 ± 3.36
First molar	46	0.13 ± 0.40*	−0.17 ± 0.49*	0.04 ± 0.14*	1.25 ± 2.37	0.22 ± 1.77*	2.79 ± 2.69
Second molar	44	0.04 ± 0.45*	0.25 ± 0.57	0.09 ± 0.70	0.59 ± 4.99	1.41 ± 3.05	1.95 ± 4.49

[a] Results are mean values ± standard deviations. n indicates number of each tooth type used for analysis. Negative values indicate a final tooth position more distal, lingual, or apical, or with less buccal crown torque, less mesial tip, or a facial surface rotated more distally than the virtual treatment plan.

* $P < .05$, indicating a final tooth position within the limits considered clinically ideal.

RESULTS

Mean discrepancy values between actual final tooth position and virtual treatment plan for each tooth in six dimensions of tooth movement are shown in Table 1.

Mesial-distal final tooth position was within ±0.5 mm of the position predicted by the virtual treatment plan for maxillary central incisors, canines, premolars, and first molars as well as all mandibular tooth types. In contrast, discrepancy exceeded ±0.5 mm for maxillary lateral incisors and second molars. For all tooth types, with the exception of the mandibular lateral incisors, the final tooth position was mesial to the virtual treatment plan.

Facial-lingual final tooth position was within the limits considered clinically ideal for maxillary lateral incisors and canines as well as mandibular canines, first and second premolars, and first molars but not for maxillary central incisors, first and second premolars, and first and second molars as well as mandibular central and lateral incisors, and second molars. For all tooth types, with the exception of maxillary central incisors and mandibular second molars, the final position was located lingual to the virtual treatment plan.

Vertical final tooth position was clinically ideal for all tooth types except maxillary second molars. There was a tendency for maxillary lateral incisors, canines, and premolars as well as mandibular canines and premolars to be positioned apically to the virtual treatment plan, while both maxillary and mandibular central incisors and second molars tended to be positioned occlusally to the virtual treatment plan.

Absolute torque discrepancy exceeded the predefined threshold of ±2° for all tooth types with the exception of mandibular second premolars.

Absolute crown tip discrepancy was below the predefined threshold of ±2° only for mandibular second premolars and first molars. The direction of the crown tip discrepancy varied among tooth types: maxillary anterior teeth, second premolars, and molars as well as mandibular canines had increased distal tip relative to the virtual treatment plan, while maxillary first premolars as well as mandibular incisors, first premolars, and second molars had increased mesial tip when compared to the virtual treatment plan.

Absolute rotational discrepancy exceeded the predefined threshold of ±2° for all tooth types. Mean discrepancy values revealed mesial rotation of maxillary second premolars and first and second molars as well as mandibular lateral incisors, premolars, and molars relative to the virtual treatment plan. All other teeth were rotated distally compared to the virtual treatment plan.

DISCUSSION

Using mathematical superimposition of digital dental models, it has become possible to quantify treatment changes[7] and, as in the present study, discrepancies between virtual treatment plans and actual treatment outcomes. Our study evaluated the outcomes of patients consecutively treated using SureSmile from two orthodontic offices. Since no cases were excluded and patients were treated based on the clinical judgment of each orthodontist, potential case selection bias was minimized and the study represents realistic conditions in which this technology is utilized.

The multistep process used to create the posttreatment digital models constituted a potential source of error; however, it allowed data collection at minimum risk for the patient. A final high-resolution cone-beam computed tomography scan may have reduced the potential error, but could not be ethically justified because it would have exposed the patients to ionizing radiation without any diagnostic or therapeutic benefit.

The effectiveness of orthodontic treatment using the computer-assisted treatment technology to achieve predicted tooth position varied with tooth type and dimension of movement. SureSmile-directed tooth movement was most effective in the vertical dimension. This finding is in agreement with an outcome assessment of cases treated with conventional fixed appliances, which have little deficiency in the vertical dimension.[8] In the present study, maxillary canines and premolars tended to be positioned apically to the virtual treatment plan. Similarly, mandibular incisors and molars tended to be positioned more occlusally than the virtual treatment plan, while canines and premolars tended to be positioned apically. As orthodontic treatment frequently involves the correction of a deep bite by leveling the Curve of Spee, ie, relative intrusion of incisors and relative extrusion of premolars, these patterns of vertical discrepancy can be best explained by incomplete leveling of the dental arches.

In the facial-lingual dimension, all teeth, with the exception of maxillary central incisors and mandibular second molars, tended to be positioned lingual to the virtual treatment plan, which indicates a narrower final arch form than prescribed. It is conceivable that transverse expansion built into the virtual treatment plan was not fully expressed, which resulted in a narrower, but slightly longer dental arch, as suggested by the more facial position of the maxillary central incisors.

In addition, maxillary posterior teeth had increased buccal crown torque compared to the virtual treatment plan. It is conceivable that expansion prescribed by the virtual treatment plan was expressed by buccal tipping of teeth rather than bodily movement. Mandibular incisors, too, were found to have increased buccal crown torque when compared to the virtual treatment plan, while buccal crown torque was decreased on maxillary central incisors. SureSmile is a tool to fabricate precision archwires, but it does not eliminate the need for auxiliary mechanics. Class II mechanics, such as interarch elastics, are routinely used during orthodontic treatment using this technology. The observed torque discrepancies in the maxillary and mandibular incisors are, therefore, most likely the result of side effects of Class II mechanics and torque loss during retraction of the upper anterior segment.

The present findings on buccal-lingual inclination are in agreement with studies on treatment outcomes for cases finished using conventional fixed appliance treatment, which have cited buccal-lingual inclination as the most common deficiency when scored using the ABO OGS criteria.[8,9]

Crown tip discrepancies were most pronounced in the posterior segments with increased distal tip of maxillary molars and increased mesial tip of mandibular molars. Again, these findings are best explained by the side effects of Class II mechanics.

Rotational discrepancies were also largest in molars; both maxillary and mandibular molars showed increased mesial-lingual rotation when compared to the virtual treatment plan. This finding may be a consequence of intra-arch space-closure mechanics as mesial-lingual rotation of the terminal tooth connected to the force-generating element is often found when elastic chains or coil springs are used.

In all dimensions, second molars showed the most frequent and largest positional discrepancy. This finding is in agreement with field tests of the ABO clinical examination, which suggest that alignment of second molars can be problematic and is, therefore, the most common deviation from an ideally finished occlusion.[8,9]

The discrepancies between the virtual treatment plan and the actual treatment outcome cannot be attributed completely to a lack of effectiveness of the computer-assisted treatment technology to produce the tooth position prescribed by the virtual treatment plan. Numerous variables influence treatment efficiency and effectiveness in orthodontics. While errors in bracket placement and variations in adhesive thickness are mostly overcome by the SureSmile technology,[2] appropriate diagnosis, treatment planning, and selection of mechanics rely on the skill and clinical judgment of the treating orthodontist. Furthermore, several studies have shown that the dimensional accuracy of the bracket's archwire slot often is less than the manufacturing tolerances claimed by the respective manufacturer.[10–13] Moreover, bone density, root anatomy, or occlusal forces may prevent a tooth from moving exactly as planned, and patient compliance with auxiliary mechanics may not always be ideal. Regardless of patient age, 24% of the variability in treatment effectiveness has been explained by the number of missed appointments and broken appliances.[14]

Although we were unable to demonstrate that the intra-arch tooth position predicted by the virtual treatment plan is consistently achieved within 0.5 mm in the mesial-distal, facial-lingual, and vertical dimensions, and that crown torque, tip, and rotation are within 2°, these findings in no way suggest unsatisfactory treatment results. In fact, the limits within which tooth position for the purpose of this study was considered clinically ideal are very narrow. For instance, a torque discrepancy of 2° is significantly lower than the calculated torque play with the archwires typically used for space closure.[15]

At present, very few studies have evaluated the efficiency and effectiveness of treatment using the SureSmile system. In 2010, Saxe et al.[3] compared clinical outcomes of cases treated using this system with cases treated using conventional fixed appliances. Treatment outcomes were evaluated using the ABO OGS, a tool developed to objectively evaluate the quality of orthodontic treatment. When compared to conventional fixed appliances, significantly lower OGS scores, which indicate a higher quality treatment outcome, were found for cases treated using SureSmile in categories including maxillary rotations, maxillary marginal ridges, and maxillary buccal-lingual inclination. Most recently, a similar study by Alford et al.[4] found a strong trend of lower OGS scores for cases that had been treated using SureSmile. However, in contrast to the report by Saxe et al.,[3] this finding did not reach statistical significance. Together with the findings of the present study, these results suggest that utilization of computer-assisted treatment technology during comprehensive orthodontic treatment can achieve results equivalent or superior to conventional fixed appliance treatment.

CONCLUSIONS

- The effectiveness of orthodontic treatment delivered using SureSmile technology to achieve predicted tooth position varies with tooth type and dimension of movement.
- Clinicians are encouraged to utilize the knowledge of dimensions in which the final tooth position is less consistent with the predicted position to build compensations into the virtual treatment plan.

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