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REVIEW

Reverse Engineering in Orthodontics

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ABSTRACT

Three-dimensional (3D) imaging has advanced greatly and is used extensively in orthodontics. It is worth outlining and reviewing the developments of reverse engineering (RE) as its applications are growing more widespread and diverse. Data from an existing object are used to create a digital model. A traditional RE process is usually performed in these stages: (1) obtaining data, (2) restructuring the surfaces, and (3) creating a useful model. They are classified as (1) laser projection based and (2) fringe projection based. This digital technology has been used in creating 3D model scanning, 3D digital model superimposition, diagnostic setup, volumetric assessment of tooth wear, soft tissue facial analysis, incorporation of digital model to 3D facial image, lip position and smile reproducibility, analysis of tooth position after orthodontic treatment, and anthropometric measurements. This system has proven itself to have a varied probability of applications and researches in the field of orthodontics. Similar to every single system, even RE has its own benefits and shortcomings. The complexity of the process and high cost are the major disadvantages reported so far. Rapid advancement of this technology possibly will rapidly inverse the negative results that emerged previously. As a future work, innovative use of RE technology is necessary to make this system triumph in the field of orthodontics.

Keywords: Digital technology, reverse engineering, three-dimensional imaging, orthodontics

INTRODUCTION

It is worth outlining and reviewing the developments of reverse engineering (RE) as its applications are growing more widespread and diverse. The term "reverse engineering" can be interpreted as copying from an original. Data from an existing object are used to create a digital model. RE shows promise in emerging applications in the field of orthodontics (1).

Reverse engineering systems were classified as (1) laser projection based and (2) fringe projection based. Intraoral scanning systems made appearance in the last decade but are scarcely used in practice (2). To be efficaciously executed in our global commercialized society, a high degree of automation will be required in these areas (1). Three-dimensional (3D) imaging grew significantly in the past few years and established abundant uses in the field of orthodontics. Diagnostic imaging is used to obtain the anatomical data that are processed by a computer and then presented on a two-dimensional screen. Depth perception causes the image to appear in 3D (3).

The quality of service, in terms of improvement of patient's satisfaction, is an increasingly important objective especially imperative in orthodontics. Digital design tools can significantly influence to enhance these procedures. However, computer-aided design/computer-aided manufacturing (CAD/CAM), RE, and rapid prototyping (RP) systems were conceived and developed for industrial applications; they should be evaluated, studied, and customized with a view to use in medicine (4). Table 1 lists several advantages and disadvantages of RE.

Orthodontics is a field that has evolved significantly within the past. 3D technology has remodeled this field, leading to a more practical and patient-friendly treatment results. Today, orthodontic clinics are loaded with

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high technical school, progressive instrumentation designed to boost the patient expertise by delivering quicker and additional economical treatment, whereas this technology has advantages to all patients, it is largely effective for complicated cases.

This technology is not inevitable, but it improves a valuable insight at the time of diagnosis and treatment planning and enhances the standard of treatment effects. Historically, fitting an orthodontic appliance on a patient was not a precise science. Similar to shoes, braces were designed based on standard average. This technology allows us to tailor the appliances that match specifically to the patient's teeth. Every patient's jaw is formed and sized otherwise. Therefore, brackets and wires are formed and sized to match every patient. This makes the patient more comfortable since the treatment is more predictable as changes are not required throughout the course that brings the results quicker and attain a smile personalized to the form of one's face and jaws.

The information obtained within the past in sort of two dimensions had few drawbacks. Teeth are physical objects and have six degrees of freedom; move in x, y, and z directions; and also have roll, pitch, and yaw. It is humanly impossible to address all six degrees at a time. Different softwares are designed to report these components each and every time. RE allows duplicating the complete patient morphology and at the same time manufacturing the appliances and templates that might increase exactness and decrease technique sensitivity and chair side time in addition to providing high accuracy to the treatment.

Table 1. Advantages and disadvantages of reverse engineering process

Advantages	Disadvantages
Rapid fabrication	Difficult to acquire meaningful details, such as curve and edges
Minimal time	Complexity of process
Minimal radiation exposure	CAD modeling skills necessary
Easy handling	High cost
Better visualization	Difficult to evaluate accuracy and usability
Reuse of design	
Repeated verification	

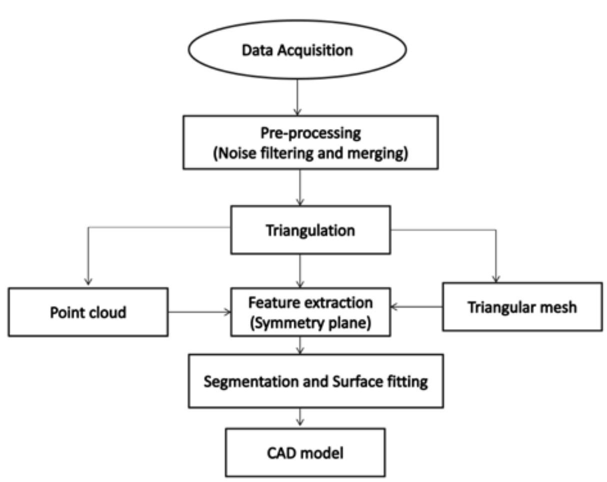

Figure 1. a, b. Flow of reverse engineering process

There are several studies that have used 3D imaging methodologies in the past; however, they have not analyzed knowledge with this technology. It might be unwise to mention that the study or its results would be different if they had used this technology as each study is exclusive in its own sense; however, for sure, innovative use of this technology can undoubtedly improve the future of orthodontia.

History

The history of RE dates back to World War II and Cold War. It was primarily employed by the military to duplicate rival's weapons, devices, and technology. In the past few years, advances within the field of computers have hugely taken an enormous leap to develop this technology. RE had gained prime importance in automotive production and aviation business to accommodate the speedy rate of reinvention of contemporary instruments and machinery.

The engineering originality of the organic structure of the human body has placed RE in an exceedingly distinctive place within the bioscience and medical device industries significantly in implementing artificial elements into the organic structure. The overview of the literature was based on the applications of RE in automobile industry, automotive industry, medical life sciences, and software industries. RE is employed in many medical fields, including manufacture of individual surgical templates; fabrication of individual surgical implants and prostheses, such as artificial knees, hip and spine implants; fabrication of hearing aids; made-to-order surgical tools; medical coaching models; and medical devices. It has vast applications within the field of dentistry as well. Manufacturing customized dental abutments and dental implants, surgical templates, computer-aided dental prostheses, customized bridges and crowns, digital dental models, and customized removable appliances (5). Various applications of RE in orthodontics include the following:

- 3D model scanning,
- 3D model superimposition,
- digital diagnostic setup,
- volumetric valuation of tooth wear,
- 3D soft tissue facial analysis,
- lip position and smile reproducibility,
- anthropometric measurements.

Process of RE

The procedural steps involve data acquisition, preprocessing (noise filtering and merging), triangulation, feature extraction, and segmentation and surface fitting (Figure 1). The whole method of RE should to be computer aided (6).

Data Acquisition

This part is meant to collect the information regarding the geometric facet of the physical half through scanning. There are several different approaches by which product surface data can be acquired. They can be classified into two broad categories: contact and non-contact methods. Contact scanners are those that contain a contact probe that moves on the silhouette of the physical half. A common example of such a scanner is the coordinate measuring machine, whereas non-contact scanners are ones that do not have a contact probe instead they use lasers, optics, and charge-coupled device sensors to capture the information.

Preprocessing

Data are obtained as a result of scanning and are then processed so as to eliminate noise and to scale back the quantity of points. This part of the process additionally offers us the advantage to merge multiple scan data sets. A number of commercial softwares are available for point processing.

Triangulation and Feature Extraction

Triangulation is a process of formation or division of point data into triangles. Feature extraction is the next step during this process that is outlined because of the method of shaping a collection of options, or image characteristics, which can most expeditiously represent the knowledge that is necessary for analysis and classification.

Table 2. Description of superimposition points

Superimposition points	Description
Point 1	Left lateral canthus
Point 2	Left medial canthus
Point 3	Soft tissue nasion
Point 4	Right medial canthus
Point 5	Right lateral canthus

Segmentation, Surface Fitting, and Solid Modeling

Segmentation is the most crucial step in RE. This section of the process involves rending a triangular mesh into submeshes to which an appropriate single surface can be fitted. This seriously affects the standard of the ensuing CAD model. New RE modules or separate software packages are commonly required for point processing.

Application of RE in Orthodontics

3D model analysis

The accuracy and authenticity of digital study models are evaluated by linear, surface, and volumetric parameters, surface scanning devices that are used to record the surface detail of such models, and its genuineness is renowned from the literature. 3D orthodontic study model superimposition system for evaluating tooth movements was concluded to be consistent and dependable (7) after comparison of cephalometric superimposition with 3D digital model superposition. INUS dental scanning solution was used for 3D scanning of dental casts, and surface-to-surface matching was used to perform the superimposition. Keating et al. (8) assessed the precision of surface details of plaster study

Table 3. Different RE applications in orthodontics are compared on their mode of modeling software and RE software

Author	Application	Scanning technique	Reverse engineering software
Cha (7)	Superimposition of tooth movement	INUS dental scanning solution	Rapidform 2002; INUS Technology Inc., Seoul, South Korea
Choi et al. (13)	Maxillary expansion and protraction	3D optical scanner; Orapix; Orapix Co., Seoul, South Korea	Rapidform 2002; INUS Technology Inc., Seoul, South Korea
Duran (14)	Molar distalization	Dental scanner; Activity 850; Smart Optics, Bochum, Germany	Rapidform; INUS Technology Inc., Seoul, South Korea
Kihara (16)	Digital models	3D surface scanner; RexcanDS; Solutionix, Seoul, South Korea	Rapidform 2006; INUS Technology Inc., Seoul, South Korea
Park (20)	Tooth wear	Laser surface scanning system; KOD300, accuracy 50 mm, Orapix Co., Ltd., Seoul, South Korea	Rapidform XOR3; INUS Technology Inc., Seoul, South Korea
Yook (28)	Volume changes of lip at bonding and debonding	Rexcan III 3D scanner; Solutionix Corp., Seoul, South Korea	Rapidform XOR/REDESIGN 3; INUS Technology Inc., Seoul, South Korea
Dindaroglu (29)	Lip position	3dMD Flex; 3dMD, Atlanta, GA, USA	Geomagic Control 3D Systems, Rock Hill, SC, USA
Dindaroglu (30)	Smile reproducibility	3dMD; Flex System; 3dMD, Atlanta, GA, USA	Geomagic Control, 3D Systems Inc., Cary, NC, USA
Deli (31)	Soft tissue	Five high-definition digital single-lens reflex cameras with flash; Canon 40D, 10 Mpx	PhotoModeler™ Scanner version 6; Eos Systems Inc., Vancouver, BC, Canada
Kau et al. (32)	Growth changes	Minolta Vivid VI900 3D; Osaka, Japan	Rapidform™ 2004; INUS Technology Inc., Seoul, South Korea—RF4
Djordjevic et al. (33)	Facial asymmetry	Two Minolta Vivid 900 laser scanners; Konica Minolta, Tokyo, Japan	Rapidform 2006; INUS Technology Inc., Seoul, South Korea
Elnagar et al. (34)	Maxillary protraction	Facial Insight 3D Scanner; Motion View Software, Chattanooga, TN, USA	Geomagic Control 14; Geomagic, Research Triangle Park, NC, USA
Ivanov et al. (35)	Soft tissue changes after RME	Roland LPX-250 laser scanner; Roland DG, Hamamatsu, Japan	Roland DG, Hamamatsu, Japan
Yu et al. (36)	Nasoalveolar molding	Vivid 910; Konica Minolta Holdings, Inc., Tokyo, Japan	Rapidform 2006; INUS Technology Inc., Seoul, South Korea

models recorded using a 3D optical laser scanning device. It was concluded that capturing the surface details using Minolta Vivid 900 is consistent and is aimed at capturing the details of plaster models with high accuracy. Data obtained from such reliable scans are subjected to RE software for further analysis.

i) 3D digital model superimposition

Assessments of treatment results are possible only by the superimposition of before and after lateral cephalograms. They are currently the most extensively used means for evaluating various tooth movements despite its inherent errors. Its major drawbacks are difficulties in the identification of inherent landmarks, high costs, tracing errors, frequent radiation exposure, technique sensitivity, and head position variation between serial radiographs (9, 10).

Progress technically during this technology permits superimposition of the maxillary dental arch with the help of a 3D digital model scanning software. This technique was established for the superposition of digital orthodontic models, and it allowed detailed amounts of movements in all the dimensions (11). 3D digital orthodontic model superposition techniques were declared to be clinically as dependable as cephalometric superimposition for evaluating orthodontic tooth movement (7), and it was verified that the superposition of the dental arch digitally was repeatable (12).

ii) 3D model analysis after rapid palatal expander (RME) and protraction headgear

Choi et al. (13) assessed the validity of the digital models three dimensionally in patients who received treatment with rapid maxillary expansion and protraction headgear. Maxillary dental casts were scanned using a non-contact 3D optical scanner. Rapidform 2002, a reverse modeling software, was used to perform reconstruction and superimposition. 3D models were superimposed using the palate to measure various tooth movements. They concluded that this 3D model superimposition method was reliable as cephalometric superimposition for assessing anteroposterior movements. Cases managed with orthopedic appliances, such as maxillary protraction headgear and rapid maxillary expansion, can also be assessed in a similar manner.

iii) 3D model analysis after miniscrew-supported molar distalization

Duran et al. (14) evaluated the dentoalveolar effects of miniscrew-supported molar distalization by 3D RE method. The dental casts were scanned by an optical dental scanner (Activity 850; Smart Optics, Bochum, Germany). The scans were converted into digital data, and data were imported into the RE software (Rapidform). The authors of these studies concluded that the method is clinically reliable, and with this method, the movement of each tooth over the arch can be analyzed in all three planes of space, and measurements can be performed frequently since digital models do not involve radiation.

iv) Digital diagnostic setup

Virtual surgical splint was fabricated in virtual articulator (15); it consumed less time than to perform the mock surgery of dental casts for the fabrication of the surgical splint.

Visualization of tooth roots was also possible in digital models by registering exact crown prototypes to cone beam computed tomography (CBCT) scans (16). The process for visualizing tooth roots in a digital model was created by a non-contact 3D surface scanner of each patient's dentition.

v) Integration of 3D digital cast and 3D facial photo

3D setup greatly helps an orthodontist in various stages of diagnosis along with determining several treatment possibilities; it assists in monitoring the changes after treatment and records the predicted and final treatment outcomes (17).

Rangel et al. (18) presented practicality of the integration of a digital dental cast into a 3D facial picture. A digital dental model was matched to place on a 3D photograph of the patient in the precise anatomical location. These images can improve the preciseness of diagnosis and treatment planning along with providing a scope for future investigation about non-cephalometric analysis or superimpositions.

vi) 3D assessment of volumetric tooth wear

Loss of occlusal surface by attritional wear disturbs the vertical dimensions of dentition and may cause tooth interferences; it was also reported that the increased activity of the masticatory system executed increased stress on the underlying structures (19).

Park et al. (20) suggested appraisal of tooth wear that emerges in the course of orthodontic management by using the digital superimposition method. They concluded that recording the teeth in 3D models remains valuable and can be intended for the assessment of tooth wear in orthodontic patients.

3D Soft Tissue Facial Analysis

Appraisal of facial morphology is vital in the field of orthodontics right from the diagnosis to the effective treatment planning (21). Medical CT or CBCT has replaced the traditionally used lateral radiographs earlier used for facial analysis (9).

i) Soft tissue superimposition

Advances in technology led to the development of many procedures, including laser scanners (22), stereophotogrammetry (23), and structured light systems (24), which are used to obtain the digital images of the dentition and craniofacial structures. Simplicity and rapidity in usage has made the laser scanner system, which is also known as optical surface scanner, the most extensively used system, and therefore it has various possibilities of scientific uses and researches (22,25,26). Its principle application is to monitor growth and treatment-related changes in all the different planes of space (26). Superimposition is possible by the registration of analogous regions on two different overlapped images (27,28). Moss et al. (27) combined five anatomical landmarks as shown in Table 2 together with five fabricated points on the forehead. The forehead was suggested to be a stable area for superimposing 3D images of the face (12).

ii) Volumetric changes in the lip after placement and removal of fixed appliance

Yook et al. (28) evaluated volumetric change in the lips after placement or removal of labial fixed orthodontic appliances using a 3D surface scanning system. 3D facial scanning was performed before placement, immediately after placement of the labial orthodontic appliances, before removal, immediately after removal, and 3 to 6 months after removal of the appliances. They established that the upper and lower lips are immediately protruded after bonding and retruded after debonding them.

iii) Lip position and smile reproducibility

Dindaroglu et al. (29) evaluated the reproducibility of the lip position at rest in three dimensions using the RE software and stereophotogrammetric images. The outcome of the study suggests that the rest position can be replicated both on the same day and between the sessions in a small range.

Dindaroglu et al. (30) used the 3D stereophotogrammetry and RE technology to assess social smile reproducibility. Social smile images of White adolescents were obtained. Sixteen social smiles were recorded on each individual at 3-minute breaks. They stated that there exists individual variability in duplication of social smile, and that this discrepancy was not noticeable under routine clinical observation.

iv) Anthropometric measurements

Deli et al. (31) conducted a study with the objective to describe a procedure that is perfect, accurate, repeatable, quick, and beneficial for soft tissue analysis of anthropometric characteristics. A new clinical procedure was used to perform this investigation. It involved four separate stages: setting up of a portable equipment on which field analysis could be achieved, scanning of dissimilar expressions, preparation of the subject and spatial positioning, and treatment and processing of data. They established that this innovative protocol for the attainment of anthropometric measurements is quick, repeatable, reliable, and precise.

v) Soft tissue growth changes

As children behave differently from adults in front of laser scanning devices, a study (32) was performed prospectively to define the changes that occur when attaining a set of laser scans from children and adults and to determine if children could be appropriate subjects for the study of facial morphology employing a laser scanning technique. Laser scans were performed, and the obtained information was transferred to reverse modeling software for analysis. It was concluded from this study that children are reliable candidates for laser-based studies of facial morphology, and the laser scanning system employed in this study has great potential in the capture and study of facial morphology.

vii) Facial asymmetry

Quantification of facial symmetry in healthy adolescents and exploration if there is any gender variations were administrated with the assistance of the RE process. The surface matching between the first face and its likeness was measured for the full face, upper, middle, and lower facial thirds. Additionally, three angular and 14 linear parameters were measured. The faces of 15-year-old male adolescents were less symmetric than those of female adolescents, however the distinction within the quantity of symmetry. The upper, middle, and lower thirds of the face did not differ in the amount of 3D symmetry. Angular and linear parameters of facial symmetry did not show any gender distinction (33).

vii) Maxillary protraction

3D facial soft tissue changes in growing patients with maxillary jaw deficiency associated with maxillary jaw protraction were performed using an innovative approach consisting of 3D stereophotogrammetry and sophisticated RE software (34). Facial images were scanned and imported to RE process package for additional analysis. The 3D analysis of the soft tissue changes showed vital favorable changes including advancement of the soft tissues of the upper lip; significant changes were observed in the middle face. Additionally, redirection of soft tissue growth was evident within the lower lip and mandible areas.

viii) Soft tissue changes after RME

Visualization and evaluation of transverse palatal soft tissue changes were performed following maxillary expansion treatment in 33 Caucasian children with posterior crossbite. They were treated with tooth-borne Haas-type expander. Colored palatal maps were generated that clearly showed the change in width of palatal soft tissues following RME. This method allowed to measure and present correlation between intermolar widths measured on the plaster models, to width changes on soft tissue palatal surface. The expansion appliance in children resolved the crossbite and led to palatal widening that was clearly visualized by creating mathematical morphometric models (35). 143

ix) Nasoalveolar molding (NAM) for cleft lip and palate

A novel technique of presurgical NAM was developed based on a computer-aided RE and RP technique in infants with unilateral cleft lip and palate. The upper denture casts were recorded using a 3D laser scanner, and a digital model was constructed that was analyzed to simulate the NAM procedure with RE software. The appliances were fabricated based on the RP technique. With this innovative approach, the treatment design and appliance fabrication was simplified (36).

Different RE applications in orthodontics are compared on their mode of modeling software and RE software used as illustrated in Table 3.

CONCLUSION

Quick advancement of CAD/CAM technology and persistent progress in 3D imaging systems facilitate a clinician not only to diagnose but also to view the effects of treatment from several perspectives. RE projects require amalgamation of the finest approaches and technologies from different alternatives available, making it a daunting task. An increasing number of scanner service bureaus offers RE services, making it effortlessly reachable. Experts point their opinion that RE is destined to persist as a market niche. This advanced methodology is readily accessible, and efforts should be made by each and every practitioner to avail the most out of it.

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