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A Novel Quality Assessment Method for the Clinical Reproduction of Orthodontic Attachments Based on Differential Entropy †

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Abstract: In this study, the effectiveness of an experimental clinical technique of reproduction of attachments during an orthodontic treatment with clear aligners was evaluated using a new index (CorAl) for quality assessment that exploits the differential entropy of point clouds. The procedure involves the use of a pre-drilled template and a second pre-loaded template with high viscosity composite and is compared with the standard technique. Attachment planning was conducted on four prototypes of dental arches with extracted teeth which were divided into two groups according to the proposed operating procedures. Digital scans were utilized to capture dental impressions for both the purposes of virtual planning and to reproduce the clinical outcomes post-procedure. The point clouds obtained after the reproduction of the attachments were aligned with those from the virtual planning, and the deviation analysis was conducted using the quality index of the CorAl method. Though no significant discrepancies were found among the groups regarding morphological flaws, detachments, or maximum defect values, the differential entropy analysis revealed that the experimental technique offers good alignment in attachments placement. The outcome supports that the innovative procedure of clinical reproduction of attachments proved to be reliable and operationally simple, with additional benefits derived from using the CorAl index. Advantages of CorAl include the use of a single comparison index, no problem of comparison commutativity, noise immunity, low influence from the presence of holes and point cloud densities. This allows for the drawing of quality maps that show areas with the highest deviation.

Keywords: clear aligners; attachments; quality assessment; 3D Scan; point clouds; differential entropy

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1. Introduction

The increasing demand for aesthetic orthodontic treatments with clear aligners has led to continuous advancements in orthodontic materials and technologies [1]. The auxiliary elements or attachments in composite resin are bonded to the teeth to achieve precise tooth movements and improve treatment effectiveness [2,3]. However, factors such as attachment position, shape, size, and number can influence aligner fit and treatment outcomes [4]. Therefore, a precise bonding protocol is crucial to ensure accurate tooth movements and treatment success [5].

The clinical reproduction of attachments requires careful attention to avoid defects in shape or volume due to incomplete filling of template reservoirs or composite resin overflow around the attachments created [6]. To address this challenge, an innovative operative procedure has been developed using two types of templates, one pre-drilled and the other pre-filled with high viscosity composite, reducing operating time. By refining the bonding process and utilizing specific templates, this approach has the potential to contribute to better treatment outcomes and improved patient satisfaction in aesthetic orthodontic procedures.

To achieve optimal outcomes, it's crucial that the clinical reproduction of the attachments closely mirrors their virtual placement. The scans, in their most basic form, exist as point clouds, a geometric representation consisting of a collection of points within 3D space. These points collectively define the surface of the object. To verify if the attachments have been placed appropriately, one can resort to the conventional deviation analysis methods. These are techniques that, once two point clouds are aligned, enable the assessment of the extent to which one point cloud differs from the other. The prevailing quality measures are deviation analysis and statistical methodologies such as ANOVA [7,8]. Traditional approaches centred around the Euclidean distance suffer from a lack of universal applicability. As highlighted by Cignoni et al. [9], the Euclidean distance's lack of symmetry leads to different results when comparing point cloud 1 with point cloud 2, as opposed to the vice versa scenario. Since these methods rely on evaluating the distance between points, the parameters being assessed are the mean and standard deviation of these distances. In acquisitions, it's probable that gaps (unscanned parts of the surface), differences in point density, noise, and variations in the extent of point clouds may occur. Although measures can be taken to mitigate errors, the average and standard deviation, values that typically differ when assessing distances between point cloud 1 and point cloud 2 or vice versa, pose challenges for a quantitative assessment of differences between the point clouds.

The authors have referenced the study by Qi et al. [10] in the scientific literature, where the CorAl method is introduced for assessing the alignment between two point clouds using a distinctive quantitative index (Q). This index, based on Differential Entropy (DE), approaches 0 as two point clouds become perfectly aligned. The aim of this research is to introduce the CorAl method as a quality control tool, with a specific focus on quantitatively and uniquely evaluating the degree of alignment between the actual placement of attachments on teeth and the desired positioning.

2. Methods

2.1. Preparation of Prototypes

Four prototypes of dental arch models with extracted teeth for orthodontic or periodontal reasons were created. Teeth with carious lesions, prosthetic crowns, or restorations were excluded. The prototypes were divided based on their anatomical morphology to represent upper and/or lower dental arches. The intraoral scanner (iTero Element Flex, Align Technology, San Jose, CA, USA) was used to obtain dental impressions and scans were sent to the aligner manufacturer (Lineo, Micerium Lab, Avegno, Genova, Italy) to produce templates for the placement of the attachments. Within the experimental group, two prototypes named "exp 1" and "exp 2" were produced, and for the control group, two prototypes named "control 1" and "control 2" were developed.

2.2. Clinical Procedures for Orthodontic Attachments Placement

The first template developed for the experimental technique was designed with holes corresponding to the attachments to be created. The second template contained attachment reservoirs filled with high viscosity composite (ENAMEL plus Hri Enamel, GDF GmbH, Fredersdorf-Vogelsdorf, Germany), which was not polymerized at this stage.

The clinical attachments reproduction involved similar procedural steps in experimental and control groups. The enamel pre-treatment process differed between the groups. In the experimental group, the pre-drilled template was used to expose dental enamel and a 37% orthophosphoric acid gel (ENA Etch, Micerium S.p.A., Avegno, Genova, Italy) was applied for 30 s. In contrast, the control group had the gel applied directly to the buccal surface of the teeth for the same duration. Subsequently, a bonding agent (ENA Bond, Micerium S.p.A., Avegno, Genova, Italy) was applied and light-cured for 20 s on all etched surfaces in both groups. The next step involved the realization of the attachments. In the experimental group, a second template with pre-loaded composite was placed directly on the teeth, and each attachment shape was light-cured following the composite instructions. No finishing or polishing procedures were performed after removing the template. On the other hand, in the control group, the template was first loaded with low viscosity composite before being adapted to the teeth for light-curing of the attachments according to the composite instructions. Like the experimental group, no finishing or polishing procedures were conducted after template removal.

2.3. Devation Analysis

To determine the accuracy of the attachments reproduction, a deviation analysis was conducted between the point cloud coming from the virtual planning models (PC1), and the point cloud coming from the models obtained after clinical procedures through the scan (PC2), both corresponding to the same prototype. The deviation analysis was carried out using the open-source software CloudCompare [11]. The alignment process unfolded in two key stages. Initially, a manual approach was taken, identifying four sets of matching points. Subsequently, the Iterative Closest Point (ICP) algorithm was employed to achieve the final three-dimensional overlay. After completing this phase, the distances between the two point clouds [12] was calculated.

2.4. CorAl Method

The CorAl method is grounded in the assessment of DE as applied to point clouds, offering a quantitative gauge of how points are distributed in space. The method capitalizes on the DE properties inherent to point clouds to ascertain the alignment between two of these clouds. CorAl draws upon the use of dual DE measurements, the first computed individually within each point cloud, and the second computed within the composite point cloud that joins them. The DE of two properly aligned point clouds should not exceed the DE computed individually for each separate point cloud. Conversely, within the combination of a pair of misaligned point clouds, the joint DE increases. All the steps outlined by the CorAl method, which have also been implemented in the experimental segment of this paper, are discussed below. Considering a point cloud P, composed of a set of points in three-dimensional space, each represented as p_i = [x y z], CorAl computes the DE, denoted as hi, for every point in P, as illustrated in the following equation:

$$h_i(p_k) = \frac{1}{2} ln[(2\pi e)^N |\Sigma(p_k)|] \quad (1)$$

In this context, where N represents the dimensionality of the data (which equals 3 in this instance), k denotes the count of points within a neighborhood defined by a radius r and centered around each point p_i. Additionally, $|\Sigma(p_k)|$ signifies the determinant of the sample covariance, calculated by considering the points p_k situated within the neighborhood of pi. Summing up the results of all the computed h_i values for every point collectively contributes to the overall DE of the point cloud P.

$$H(P) = \sum_{i=1}^{|P|} h_i(p_k) \quad (2)$$

In this equation, $|P|$ signifies the count of points within the point cloud P. When presented with two distinct point clouds (P_a and P_b), it becomes feasible to compute their individual average DE (denoted as H_{sep}) as well as their collective average DE (designated as H_j):

$$H_{sep} = \frac{H(P_a) + H(P_b)}{|P_a| + |P_b|} \quad (3)$$

$$H_J = \frac{H(P_{joint})}{|P_{joint}|} = \frac{H(P_a \cup P_b)}{|P_a| + |P_b|} \quad (4)$$

where P_{joint} represents the composite point cloud formed by combining the individual point clouds P_a and P_b, while $|P_{joint}|$ signifies the size of this joint point cloud, measured in terms of the number of points it encompasses. The measure of alignment quality, denoted as $Q(P_a, P_b)$, is subsequently computed using the following formula:

$$Q(P_a, P_b) = H_J - H_{sep} \quad (5)$$

A desirable alignment between P_a and P_b should yield a $Q(P_a, P_b)$ value close to 0, ideally reaching 0 when the two point clouds overlap seamlessly after alignment. Moreover, it's feasible to assess the quality index on an individual point basis:

$$q_i(p_k) = [h_i(p_k)]_{joint} - [h_i(p_k)]_{sep} \quad (6)$$

This approach will be employed in this study to generate a point cloud that is color-coded based on the per-point quality index. This visualization will provide a graphical representation highlighting regions where there is greater deviation of the actual attachments from the reference model. The CorAl method application was carried out in MATLAB [13].

3. Results and Discussion

The results presented provide valuable insights into the effectiveness of the CorAl method and its comparison with standard deviation analysis. These findings are essential for orthodontists and researchers seeking reliable techniques for assessing the quality of attachments reproduction in orthodontic treatments.

Figure 1, which visualizes the point cloud colored according to the per-point index, offers a clear representation of areas with the most significant deviation from the reference point cloud. This visualization serves as a practical tool for clinicians, allowing them to identify precise regions where attachments placement may require further attention or adjustments. This visual feedback can guide clinicians in optimizing attachments reproduction for enhanced treatment outcomes.

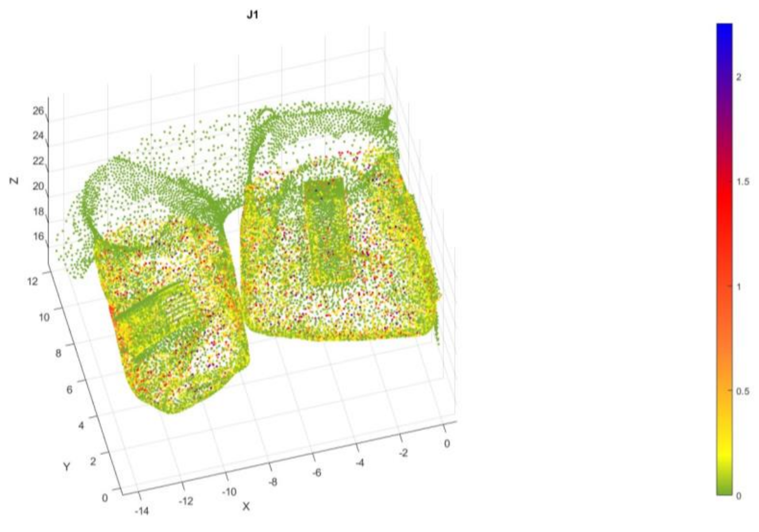

Figure 1. Example of per-point quality index.

The results of the CloudCompare deviation analysis and the CorAl method are shown in Table 1. The comparison of Q values between experimental and control groups, provides critical insights. The minimal differences observed in Q values between exp 1 and exp 2 when compared to control 1 and control 2 suggest that the experimental technique consistently achieves similar levels of attachments placement quality as the standard method. This consistency is a positive outcome, indicating that the new technique is a reliable alternative for attachments reproduction.

Table 1. Results of quality index, mean, and standard deviation (SD) for all models considered.

		EXP 1	EXP 2	CONTROL 1	CONTROL 2
-	Q	0.103	0.111	0.097	0.162
PC2 vs. PC1	Mean (SD)	0.125 (0.1)	0.108 (0.067)	0.107 (0.076)	0.141 (0.095)
PC1 vs. PC2	Mean (SD)	0.152 (0.14)	0.158 (0.16)	0.172 (0.176)	0.173 (0.172)

A noteworthy aspect is the commutativity issue in the deviation analysis performed with CloudCompare. The fact that the alignment results differ depending on the direction of comparison underscores a limitation of this traditional analysis method. In contrast, the CorAl method, with its unique Q values, does not suffer from this commutativity problem. This observation is crucial because it implies that CorAl provides a more consistent and objective assessment of attachments placement quality, irrespective of the order in which point clouds are compared. In particular, the quality index Q shows a trend comparable to the PC2 vs. PC1 comparison. Conversely, in the PC1 vs. PC2 comparison, the trend changes, indicating that the mean and standard deviation results heavily depend on the choice of the point cloud considered as a reference and the one used for comparison. Overall, these results emphasize the superiority of the CorAl method in providing a standardized and consistent approach to evaluating attachments placement quality. The ability to obtain unique Q values simplifies the assessment process. Orthodontists can rely on CorAl as a robust tool for objectively assessing quality of the attachments placement, ultimately leading to more precise and predictable orthodontic treatments.

4. Conclusions

The method introduced offers a viable alternative to traditional deviation analysis and is suitable for models created using both conventional methods and additive manufacturing techniques. From the analyses conducted, the clear benefits that CorAl can bring to quality assessment become apparent. This technique provides a unique Q index that accurately determines the quality of the sample examined. With CorAl, there's no ambiguity related to the order in which point clouds are compared, thus overcoming the limitations of methods based on Euclidean distance, which lack commutative properties. The method described effectively handles point clouds of different densities and is adept at managing scans with holes or imperfections. Lastly, it can be observed that the experimental procedure is valid, as it produces results consistent with the control method.

In clinical terms, the CorAl method offers dentists a powerful and reliable tool to evaluate placement quality of orthodontic attachments. Its unique Q index, freedom from commutative limitations and ability to manage imperfect scans make CorAl an invaluable resource in finding precise and predictable orthodontic treatments. Additionally, the successful validation of the experimental procedure reinforces its potential as a dependable tool in orthodontic practice. This method holds the potential to enhance treatment outcomes and improve patient care in the field of orthodontics.

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