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Maxime Chapuis[1,2][a], Mathieu Lafourcade[1][b], William Puech[1][c], Gérard Guillerm[2] and Noura Faraj[1][d]

[1]*LIRMM, Université de Montpellier, CNRS, Montpellier, France*

[2]*Groupe Orqual, Pau, France*

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Abstract: In this paper, we present an interactive system to adjust and animate 3D orthodontic treatment objectives, the main goal is to improve the communication tools used by orthodontists to exchange with their patients. Given a 3D pathological patient model and a treatment objective, we propose to automatically generate intermediate steps using script-like treatment scenarios. The intermediate steps can then be adjusted using intuitive manipulators, and used to produce an animation of the treatment. The resulting animation is a useful tool to help patients visualize the potential evolution of their dentition and accept the treatment. The proposed system relies on the registration of a reference model on both the treatment objective and the patient-specific 3D segmented mesh, to automatically position key feature points and create control curves. These primitives are used to both, guide teeth movements during the animation, and provide manipulators to allow for user interactions. The key contributions of this work are (a) the use of a registered reference model to position and create intuitive control primitives, and (b) the introduction of script-like treatment scenarios to facilitate and minimize user interactions during the creation of intermediate treatment steps.

1 INTRODUCTION

Computer aided orthodontic treatment planning is now the standard way of designing a treatment as it improves its outcome and allows for a 3D preview of the patient's dentition with the desired alignment and occlusion. This preview, called a *treatment objective*, is also a communication tool between the practitioner and the patient. By viewing the expected outcome, patients are able to better understand the proposed treatment, and are more likely to adhere to it. To take it a step further, an animation of the treatment can be proposed to illustrate the different states of their dentition at different stages of the treatment. However, doing a simple interpolation between the initial state and the objective is not correct, as it does not reflect the different steps of a treatment. Indeed, to be useful, a treatment animation should include intermediate steps. The question is then, how to define them? One way to do it, is to manually place each tooth in the desired position at each step. However, this solution is a tedious time consuming process. To address this issue, we propose to use a set of instructions (called *actions*) to allow the user to define a *treatment scenario*, and automatically generate the intermediate steps. A scenario contains the collection of actions for each step of the treatment. Theses actions (similar to a scripting language) reflect the intention of the orthodontist during the treatment (*extract, level, align, rotate, etc.*). In this paper, we propose a method that can take any 3D treatment objective as an input, and allows to easily create an animation of the treatment with clearly defined intermediate steps. To guide the movements during the animation, our method relies on a set a parametric curves automatically positioned on the input models, which can be modified through the use of control points. Manipulators are also provided in the case the user wants to adjust the generated intermediate steps or the treatment objective.

The rest of the paper is organized as follows. First we present related work in Section 2. Then, our proposed method is detailed in Section 3. The results of our method applied to real patient models are presented and discussed in Section 4. Finally, in Section 5 we conclude and present future work.

[a] https://orcid.org/0000-0003-0876-8711
[b] https://orcid.org/0000-0003-2832-2143
[c] https://orcid.org/0000-0001-9383-2401
[d] https://orcid.org/0000-0001-6637-0336

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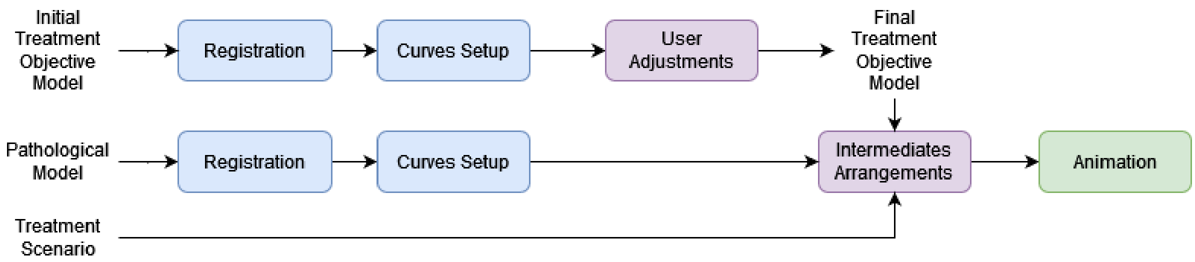

Figure 1: Overview of the system.

2 RELATED WORK

Automatic tooth arrangement is the task of predicting a proper tooth arrangement given a pathological dental model (*i.e* a plausible result of the orthodontic treatment). Different types of methods have been developed for such a task. Kumar *et al.* proposed a simulation-based approach, minimizing the energy of a spring-mass system, where the springs represent orthodontic constraints (Kumar et al., 2013b). Cheng *et al.* based their approach on satisfying geometric constraints, by positing feature points on different planes and curves (Cheng et al., 2015). More recently, Wei *et al.* and Li *et al.* proposed two deep-learning based methods for automatic tooth arrangement (Wei et al., 2020; Li et al., 2020a). Deep-learning based methods offer good-quality tooth alignment on common cases, but require large data-sets of *pre-* and *post-*treatment orthodontic cases.

When producing a treatment animation, the goal is, given an initial and a target arrangement, to show the evolution of the dentition over time. When the two arrangements are close, using a simple interpolation to compute the intermediate states is reasonable. In the context of invisible appliances, Li *et al.* use a more elaborate strategy. They formulate the problem as a *path planning* problem (Li et al., 2020b). The objective is to find, for each tooth, a path going from the initial situation to the target, while minimizing the translation distance, the rotation angle, and avoiding collisions with surrounding teeth. To solve this optimization problem, they first initialize the solution using the interpolated values, and then refine it using an artificial bee colony algorithm. Another paper, by Li *et al.*, suggests that genetic algorithms can be used to find proper paths, but the authors only present partial results, and it is unclear how the teeth transformations are coded in their method (Li et al., 2009).

3 PROPOSED METHOD

Given a 3D visual treatment objective, we propose a method allowing for the automatic creation of intermediate treatment steps using a script-like scenario. We also provide manipulators, allowing for three levels of user interactions, to adjust the generated steps and the treatment objective. During the generation process and the interactions, teeth movements are guided by a set of control points and parametric curves automatically positioned on the input models. To achieve this our method relies on the registration of a *reference model* onto the input arrangements. The registration data allows us to transfer the *control points* of the reference model on the input models. The whole process is illustrated in Fig. 1.

In Section 3.1 and Section 3.2, we first detail the registration process and the curves setup. Then in Section 3.3 we detail the different manipulators, and finally we present the process for creating the animation with a user-defined treatment scenario in Section 3.4.

3.1 Registration Process

The goal of the registration process, is to automatically position key control points on both the pathological arrangement and the target arrangement. This process is applied on each input model independently.

The reference model R, shown on Fig. 2a, is a generic adult dentition with its teeth in a standard configuration, and control points placed at the center of the teeth vestibular faces, in the fashion of braces (Fig. 2b). The vestibular side of a tooth faces the lips and cheeks. Here, the use of a registered reference model gives the ability to transfer properties from the reference model to the input models, and to reconstruct potential missing information (such as occluded mesh parts or roots). Each control point has a reference frame computed using the up vector and the vector tangent to the arch at the point position. These reference frames are used to define the reference orientations of the teeth. Throughout the registration and the interactions, the control points are subject to the same transformations as to their corresponding tooth.

The registration process is composed of two steps, a rigid registration (Section 3.1.1), and a non-rigid registration (Section 3.1.2).

3.1.1 Rigid Registration

The main algorithm used to carry out the rigid registration is the Iterative Closest Point (ICP) (Besl and McKay, 1992; Chen and Medioni, 1992). This algorithm iteratively constructs a rigid transformation which minimizes the difference between two point-clouds by finding point correspondences in the two data-sets. As the ICP algorithm is sensitive to the initial alignment, the rigid registration (Fig. 3) starts by an initialization step. Its purpose is to place the reference model R in a good enough starting position to perform an ICP on each tooth. This initialization is done by scaling and centering R on the input model P (Fig. 3b and Fig. 3c). These operations are done "model-wise", meaning that every tooth is scaled by the same ratio and translated by the same vector. The scaling ratio is estimated by averaging the ratios between the incisors of P and R. The incisors are well suited for this purpose as they are almost always entirely visible in patient models. The two models are then roughly aligned by a model-wise ICP (Fig. 3d).

Then "tooth-wise" operations are performed: each tooth of R is scaled to match its corresponding tooth in P. To end the initialization process, the teeth bounding boxes P and R are aligned. Mandibular bounding boxes[1] are aligned on their upper center, and maxillary bounding boxes[2] on their lower center. The choice to align the top of the crowns is motivated by the fact that patient teeth are not always entirely visible. Therefore, centering them on their bounding boxes centers would result in a poor initialization for the ICP (Fig. 4).

Finally, each tooth in R is registered to the corresponding tooth in P by a tooth-wise ICP (Fig. 3e).

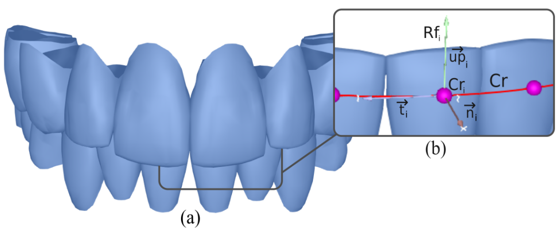

Figure 2: a. Front view of our reference model, b. Control points are placed at the center of the teeth vestibular faces.

[1] *Mandibular* refers to the lower arch.
[2] *Maxillary* refers to the upper arch.

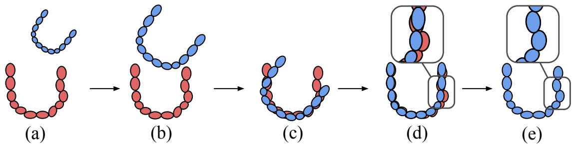

Figure 3: Reference model rigid registration (blue) on the patient model (red): a. Initial alignment, b. Uniform scaling, c. Centering, d. Model-wise ICP, e. Tooth-wise scaling, centering and ICP.

Only the vertices contained in the bounding boxes of the patient's teeth are considered during the ICP. The result of the rigid registration is a modified version of R called P', with the same tooth arrangement as the patient.

3.1.2 Non-rigid Registration

The teeth of the reference model are generic teeth and thus, do not match the patients teeth geometry. These differences are mitigated by projecting the reference crowns vertices onto the patient's crowns using the projection method APSS (Guennebaud and Gross, 2007). To avoid unwanted deformations, care should be taken to only project overlapping vertices. The result of this final registration step is shown on Fig. 5a and Fig. 5b.

3.2 Curves Setup

On each arch, two curves are created, the *reference curve* Cr, and the *arch curve* Ca. The former is used to translate and orient teeth along the arch, and the latter to adjust the shape of the arch with the appropriate manipulator (Section 3.3.3).

3.2.1 Reference Curve and Patient Curve

The control points of the teeth of the reference model R are used as the control points of a parametric curve $Cr(t)$, called the *reference curve*. This *reference curve* is a Catmull–Rom spline (Catmull and Rom, 1974). The choice to use a Catmull–Rom spline is motivated by its interpolating properties (the curve goes exactly through the control points), and its relatively low computational cost. This curve gives the ability

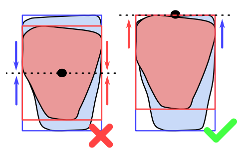

Figure 4: a. The bounding boxes of a mandibular reference tooth (blue) is centered on the bounding box of its corresponding patient tooth (red), b. The same teeth are aligned on the upper center of their bounding boxes.

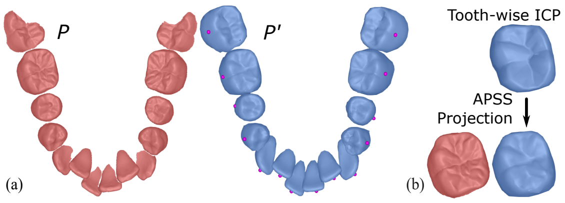

Figure 5: a. Views of the lower arches of the patient model P (red) and the fully registered reference model P' (blue), b. Comparison of the right lower first molar before APSS (top) and after (bottom).

to define a reference position and orientation at any parameter t. It also has the benefit of being an intuitive primitive for orthodontists, as it resembles an orthodontic wire with braces. The orientation used for each control point corresponds to its initial reference frame multiplied by the rotation part of the transformation computed during the registration.

The *patient curve* Cp is constructed in a similar way using the control points of the registered reference P'. The positions and orientations along Cp reflect the dental disorders of the patient.

3.2.2 Arch Curve

Following the method proposed by Kumar *et al.* (Kumar et al., 2013a), cusps and incisal edges are computed on the treatment objective (R). Theses features are then transferred to the pathological model (P') using the previously computed registration transformations. Since we transfer the feature points, we ensure that they are the same on both models. Their respective arch forms can then be derived as the curves passing through the distobuccal cusps of the first molars, the canines cusps and the midpoint of the incisors of each arch as illustrated on Fig. 6. The arch forms are represented by Catmull–Rom splines made of five control points each (blue spheres on Fig. 6).

3.3 Manipulators

The manipulators available allow the users to express their domain expertise by adjusting the treatment objective and the generated intermediate steps. To make sure they were relevant to the domain, the different manipulators were developed in collaboration with an orthodontist. We propose several manipulators, of increasing sophistication, permitting the adjustment at different levels: individual teeth, groups of teeth, or arch-forms. The usage of the different manipulators is demonstrated in the companion video.

3.3.1 Teeth Manipulators

The simplest manipulator allows to freely translate and rotate the individual teeth around their local axes. The local axes of a given tooth are deduced using the local frame of its corresponding control point. If needed, this frame can be adjusted with the dedicated manipulator. The selection of multiple teeth is possible, and allows the user to apply a translation to every teeth of the selection. Note that there is a dedicated manipulator to level a group of selected teeth. This has the action of setting every control point of the selection to the same level on the vertical axis (based on the vertical position of the first tooth of the selection). Finally, the extraction manipulator removes a tooth from the arrangement. Tooth extraction is a typical way to make room when the teeth are too cluttered to be aligned properly.

3.3.2 Space Corrections

The spaces manipulator can be used to close interdental spaces on a given range of teeth. This action is done by moving each ill-positioned tooth along the reference curve Cr, going from the incisors to the molars. The induced collisions are resolved along the way, as if the moving tooth was pushing its neighbors, as illustrated on Fig. 7.

When included in the range, the pair of central incisors have to be treated first then, the left and right side can be processed independently.

3.3.3 Arch Form Deformation

Each arch form is represented by a Catmull–Rom spline made of five control points Ca. The arch deformation manipulator allows, by moving one of point of Ca, to move every teeth accordingly (every control point of Cr). The procedure is the following. When an arch point is moved, the arch curve Ca is modified (slightly) and produces Ca'. To propagate this modification to the teeth, we compute the translation to apply to each control point Cr_i as the difference in position between $Ca'(t)$ and $Ca(t)$ (where t is the curve parameter corresponding to the projection of Cr_i on Ca). The teeth collisions induced by the translations are resolved as described is Section 3.3.2. Once the teeth are in their correct positions, their orientation are adjusted to match the reference orientations of the newly formed Cr (the reference orientations are computed as described in Section 3.2 .)

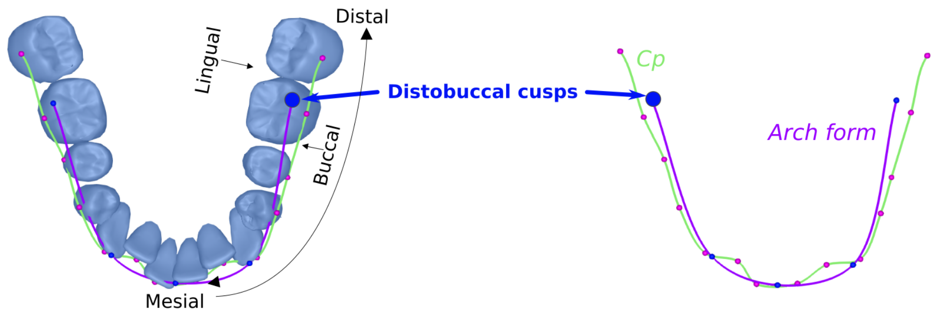

Figure 6: The main features extracted on the lower arch of P'. In green, Cp made of the registered control points. In purple, the arch form going through the distobuccal cusps of the first molars, the canines cusps and the midpoint of the incisors.

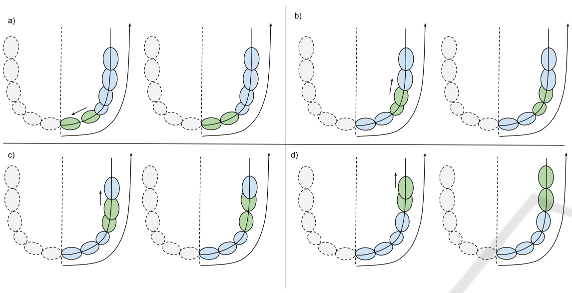

Figure 7: The space between each ill-positioned pair (green) is adjusted. The spaces can either be closed (a) or opened to de-intersect teeth (b),(c),(d).

3.4 Animation

To create the intermediate treatment steps necessary for the animation, our method relies on user-defined *treatment scripts*.

3.4.1 Treatment Script

```
step:
extract lower first premolars
extract upper second premolars

step:
level teeth

step:
align teeth
```

Listing 1: Example of treatment script defining intermediate steps.

Given a target arrangement, and an initial pathological one, the user defines for each step, the set of *actions* to execute in order to get to the objective. These actions take the form of verbs, reflecting the intention of the orthodontist, and can be applied to a particular tooth, a group of teeth, or every tooth of an arch. An example of treatment script is shown in Listing 1. In this example, three intermediate steps are defined. The first one contains two *extract* actions, applied on two groups of teeth (the lower first premolars and the upper second premolars). Actions applied to a group of teeth are applied to each tooth of the group. The second step applies the action *level* on every tooth, which has the effect of putting the teeth on the same horizontal plane (based on what is defined in the objective). The third one, positions the teeth in their target position using the action *align*. There is a fourth implicit step which is, getting to the objective.

3.4.2 Actions

The set of currently available actions is described in Table 1. Every action is implemented using the control points or the curves computed in Section 3.2.

The process used to generate the steps is the following. Starting from the initial arrangement, every time a new step is declared in the script with the *step* action: copy the current arrangement and apply the actions of the step. The application of an action depends on its implementation. Most of the time, it is done by computing the transformation difference between the current arrangement and the target arrangement, and only applying a particular component of the resulting transformation (the component relevant to the action).

3.4.3 Arrangements Interpolation

The animation between two given dental arrangements is done by linearly interpolating the positions and orientations of the teeth. Let Pi_j and Oi_j be the position and orientation of the tooth j in an initial arrangement, and Pt_j and Ot_j be the position and orientation of the tooth j in a target arrangement, then for a given interpolation value t (with $0 \leqslant t \leqslant 1$):

$$\begin{aligned} P_j(t) &= lerp(Pi_j, Pt_j, t) \\ O_j(t) &= slerp(Oi_j, Ot_j, t), \end{aligned} \tag{1}$$

where the *lerp* function is the regular linear interpolation and the *slerp* function is the *quaternion spherical* *interpolation* (Shoemake, 1985). Here, the *slerp* function is used to produce constant-speed rotations. Note that we have a t value for the position t_p and a second one for the orientation t_o. This gives the ability to define different interpolation speeds for the position and the orientation. Similarly to Li *et al.*, we limit the amount of rotation and translation possible for a tooth during one animation step (2° of rotation, and 0.2mm of translation) (Li et al., 2020b). These empirical values are here to represent the limits of the alveolar bone reconstruction process.

Given every intermediate steps of a treatment, the resulting animation is the interpolation between the successive arrangements.

4 EXPERIMENTAL RESULTS

To illustrate our method, we show our pipeline applied to two representative patient cases, and compare the resulting animation with the simple linear interpolation between the initial and target arrangement.

Case A (the red model on Fig. 9) presents moderate disorders. The main issues are its upper right second premolar position (tooth 15), and its anterior teeth inclination. The treatment scenario for this case is: first level the teeth, then re-position tooth 15 and finally align and rotate the remaining teeth. The animation is illustrated on the maxilla in Fig. 9. The objective is shown in blue, the produced intermediate steps are in green. The top part of the figure shows the linear interpolation for the same animation times t_1 and t_2 (in grey), and the bottom part is our complete animation.

Case B (the red model on Fig. 10) illustrates a case where the provided treatment objective needs to be adjusted. This can happen when using an automatic teeth arrangement method to generate the objective (Section 2). These methods don't usually predict teeth extractions or arch expansion. The real treatment plan for this case suggests the extraction of the premolar. Therefore, as a preliminary step, the first premolars are extracted and the anterior teeth are re-positioned using the manipulators described in Section 3.3. The edited objective is shown on Fig. 8. The treatment script used to produce the animation is same as Listing 1. The resulting animation on the mandibula is shown on Fig. 10.

The linear interpolation animation is shown in grey for both cases at the top of Fig. 9 and Fig. 10. Due to the fact that the interpolation corrects the rotation and position of every teeth simultaneously, we observe multiple differences. On case A, at t_1, our animation only straightens up the teeth to position them on a same horizontal plane, whereas in the interpolation animation, the teeth moved uniformly closer to the objective. The difference is clear on tooth 15 (zoomed in). Similar differences are be observed on case B. The companion video includes the animations of both cases.

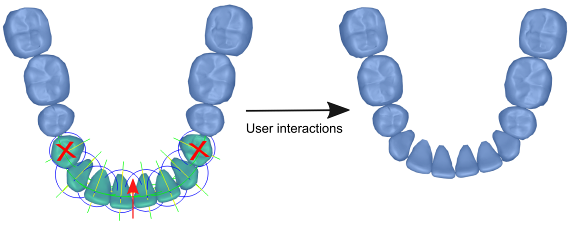

Figure 8: Adjustment of the initial treatment objective by extracting the premolars, and re-positioning the anteriors.

5 CONCLUSION

In this paper, we present a method allowing to intuitively adjust a 3D treatment objective, and to generate intermediate treatment steps given a user-defined treatment scenario. The resulting animation is a more faithful representation of the intended treatment hence is a better illustration than the simple interpolation between the initial situation and objective, and may improve the patient's understanding of his treatment.

In future work, we plan on providing *arch-wire* actions to mimic the use of arch-wires of different shapes (round, rectangular, squared) and stiffness (low, medium, high). This requires the use of additional patient data such as roots and surrounding cranio-facial structures. One considered solution is the registration of a dental cone beam computed tomography on our 3D model.

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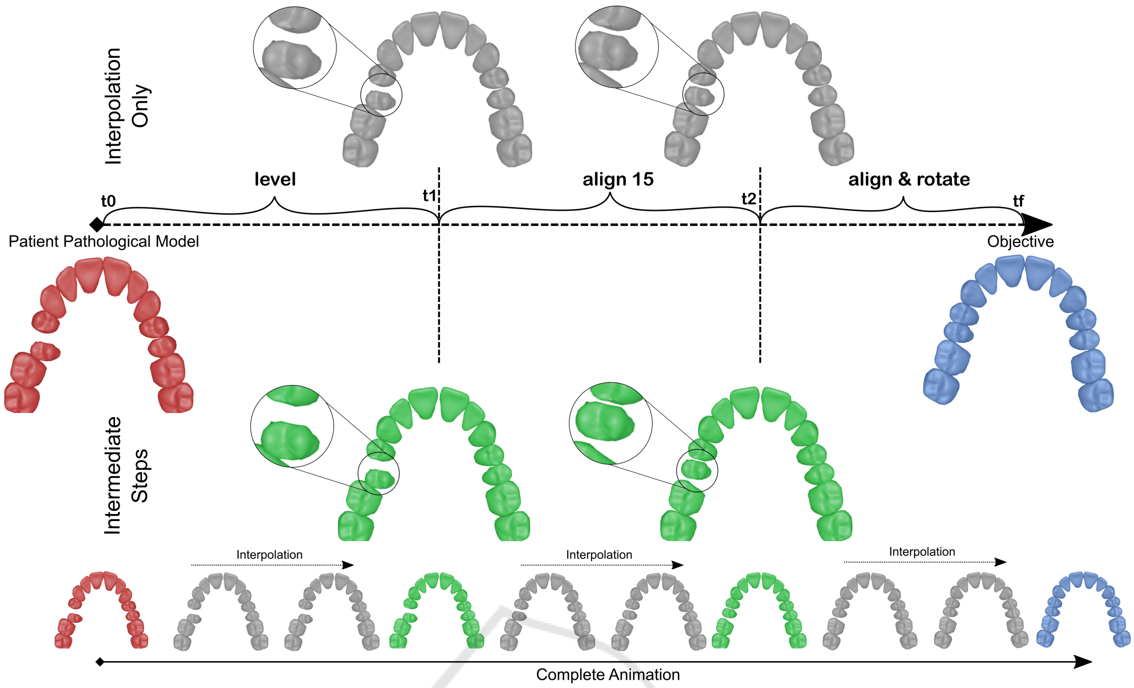

Figure 9: Animation for Case A: Given the initial pathological model (in red) and the objective (in blue), each step produces an intermediate arrangement (in green). At the top, the linear interpolation in shown for the same animation times t_1 and t_2. Our complete animation is shown at the bottom.

Figure 10: Animation for Case B: Given the initial pathological model (in red) and the *edited objective* (in blue), each step produces an intermediate arrangement (in green). The red crosses indicate the extraction of two premolars. At the top, the linear interpolation between the initial situation and the *unedited objective* is shown. Our complete animation is shown at the bottom.

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APPENDIX

Table 1: Currently available actions.

Action	Effect
step	Declare a new step, and initialize it with the current configuration.
extract	Extract a tooth from the current configuration.
level	Position the teeth on the same horizontal plane.
rotate	Correct the orientation of a tooth on its up axis (local y axis).
incline	Correct the orientation of a tooth on its mesio-distal axis (local z axis).
lock /unlock	Prevent the tooth from moving move.
align	Position the teeth at their target position on the arch.
close spaces	Close inter-dental spaces.