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A new protocol to accurately track long-term orthodontic tooth movement and support patient-specific numerical modeling

Revision 2

Original Article

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ABSTRACT (183 words)

Numerical simulation of long-term orthodontic tooth movement based on Finite Element Analysis (FEA) could help clinicians to plan more efficient and mechanically sound treatments. However, most of FEA studies assume idealized loading conditions and lack experimental calibration or validation. The goal of this paper is to propose a novel clinical protocol to accurately track orthodontic tooth displacement in three-dimensions (3D) and provide 3D models that may support FEA. Our protocol uses an initial cone beam computed tomography (CBCT) scan and several intra-oral scans (IOS) to generate 3D models of the maxillary bone and teeth ready for use in FEA. The protocol was applied to monitor the canine retraction of a patient during seven months. A second CBCT scan was performed at the end of the study for validation purposes. In order to ease FEA, a frictionless and statically determinate lingual device for maxillary canine retraction was designed. Numerical simulations were set up using the 3D models provided by our protocol to show the relevance of our proposal. Comparison of numerical and clinical results highlights the suitability of this protocol to support patient-specific FEA.

21 **1. INTRODUCTION**

22 Orthodontic treatments usually rely on an orthodontic archwire passing through braces
23 bonded on the teeth, which can be associated to accessory elements like elastic chains or
24 springs. Orthodontic forces transmitted to the teeth are related to the elastic deformation of
25 these materials and to the friction and sliding of the archwire in the braces. These forces
26 trigger alveolar bone remodeling and lead to orthodontic tooth movement (OTM) (Henneman
27 et al., 2008; Krishnan and Davidovitch, 2009; Wise and King, 2008). Nowadays, orthodontic
28 treatment strategies are primarily based on orthodontists' clinical experience. In some cases,
29 unwanted effects may appear like orthodontic external root resorption (OERR) (Viecilli et al.,
30 2013; Zhong et al., 2019) or difficulties in planning and predicting tooth movement might
31 arise (Burstone, 2015).

32
33 Modeling and simulation have a great potential to support clinical activity (Likitmongkolsakul
34 et al., 2018). In solid mechanics, Finite Element Analysis (FEA) is one of the most attractive
35 numerical approaches. Recent advances in imaging techniques allow the set-up of image-
36 based, patient-specific FEA whose relevance is largely acknowledged in several clinical
37 domains. However, numerical simulation of long-term (several weeks or months) OTM
38 remains a challenge despite the wealth of works existing on this subject (Table 1) (Bourauel
39 et al., 2000; Chen et al., 2014; Hamanaka et al., 2017; Hasegawa et al., 2016;
40 Likitmongkolsakul et al., 2018; Marangalou et al., 2009; Schneider et al., 2002; Wang et al.,
41 2014).

42
43 A critical issue in the development of FEA of long-term OTM concerns the availability of
44 suitable clinical data. Most of the existing works based on FEA showed no experimental
45 calibration or validation. To the best of our knowledge, only two studies compared their
46 numerical results with clinical data of one and two patients, respectively (Table 1) (Chen et
47 al., 2014; Likitmongkolsakul et al., 2018). Numerical models cannot trustfully support clinical

48 practice as long as they are not properly validated against experimental data (Albogha and
49 Takahashi, 2015; Hannam, 2011). In order to generate accurate three-dimensional (3D)
50 patient-specific models of craniofacial structures, the main imaging techniques that may be
51 used are Computed-Tomography (CT) and Cone Beam CT (CBCT) (Table 1). Due to its
52 broad accessibility and low-dosimetry protocols, CBCT is more commonly used in
53 orthodontics procedures (Kapila and Nervina, 2015). Although CBCT cannot be regarded as
54 a standard method of diagnosis, its use can be justified for carefully designed research
55 purposes (Kapila and Nervina, 2015). As with any radiographic examination, the three basic
56 principles of radiation protection (justification, optimization and limitation) must be strictly
57 observed, and CBCT scans cannot be repetitiously used to track OTM all along an
58 orthodontic treatment. As shown in Table 1, only one published study tracked clinical OTM in
59 order to update its model geometry, using scanned dental models (Likitmongkolsakul et al.,
60 2018).

61
62 Furthermore, modeling assumptions, including loading conditions and material behavior, are
63 key in order to set up reliable FEA. Accurate modeling of clinically realistic force systems is a
64 major challenge of orthodontic simulations (George et al., 2019; Roberts et al., 2015). For
65 example, friction and sliding of the archwire is very rarely considered, even in situations
66 where it can have a major clinical impact (Table 1) (Hamanaka et al., 2017). The friction
67 between the archwire and the braces can be hardly measured *in vivo* and therefore prevents
68 an accurate calibration of patient-specific biomechanical models (George et al., 2019). More
69 generally, a proper definition of the boundary conditions is a critical issue as long as the
70 orthodontic forces are statically indeterminate as it is usually the case with traditional
71 orthodontic treatments. Additionally, an inaccurate description of the orthodontic forces
72 entails issues in the calibration of the constitutive models of the materials making up the
73 maxillary structures. Indeed, an accurate knowledge of the prevailing mechanical forces and
74 of the stress-strain distribution in the maxillary structures is required to understand the
75 mechanical response and to calibrate suitable constitutive models for these materials. Thus,

76 coarse approximations on the description of the orthodontic forces can seriously threaten the
77 reliability of the numerical simulations.

78

79 The main goal of this paper is to propose a new tracking protocol to generate 3D models of
80 the maxillary system (bone and teeth) that can be used to set up and validate numerical
81 models. It relies on one initial CBCT scan and monthly intra-oral scans (IOS). The frequency
82 of IOS corresponds to the typical frequency of appointments in orthodontic practice. We
83 tested the relevance of our proposal in a clinical situation, and used the 3D models to
84 develop preliminary FE models (FEM) of the relevant maxillary structures. In order to reduce
85 the bias in modeling the orthodontic forces, a frictionless and statically determinate lingual
86 device for maxillary canine retraction was designed. Material parameters of the FEM were
87 matched against clinical data.

88

89 **2. MATERIALS AND METHODS**

90 **2.1. *Clinical procedure***

91 After verbal and written information about the research, one patient accepted to be included
92 in the study. This 28-year-old patient showed a class I malocclusion, with significant anterior
93 crowding and protrusion of incisors. The orthodontic treatment plan aimed at correcting the
94 malocclusion with avulsion of upper and lower first premolars, recoil of the canines and
95 repositioning of the incisors with controlled posterior anchorage loss. In the maxilla, after the
96 avulsion of the upper first premolars, three Temporary Anchorage Devices (TADs) and a
97 personalized lingual device were placed (Figure 1). This device was designed so as to apply
98 a statically determinate system of orthodontic forces at the theoretical initial center of
99 resistance of the canines—the point that a force should pass through in order to obtain a
100 pure translation of the tooth. Details about the clinical procedure are given in the
101 Supplementary Materials, Section A. This study was approved by the ethical committee of
102 protection of persons (CPP Paris Ile-de-France 1, reference 2016-dec.14420 ND).

103

104 **2.2. Data acquisition**

105 A CBCT scan of the maxilla was acquired before the placement of the TADs using NewTom
106 VGi EVO (NewTom, Verona, Italy) set at 110 kV, 6.9 mA, exposure time of 4.3 seconds, 12 x
107 8 cm field of view and 0.150 mm voxel size. The DICOM (digital imaging and
108 communications in medicine) files were exported. On the same day (T*), an IOS of the
109 maxilla arch was performed with TRIOS scanner (3SHAPE, Copenhagen, Denmark) and the
110 Standard Tessellation Language (STL) file was exported. These two acquisitions were used
111 to digitally design and manufacture the personalized lingual device.

112

113 The orthodontic treatment started 14 days later (T₀). A new IOS of the maxilla arch was done
114 on this day and at every appointment of the patient (every four to five weeks). This resulted
115 in the export of *n* STL files of the maxillary teeth crowns in high resolution, which were used
116 to create the initial and intermediate models.

117

118 Once the retraction of the canines was clinically acceptable, the lingual mechanism was
119 removed. A CBCT scan of the maxilla was acquired using the same unit and the same
120 settings as the first one. The study then stopped, and the orthodontic treatment of the patient
121 was carried on with vestibular braces.

122

123 **2.3. 3D reconstruction of initial (T₀) model**

124 The segmentation of the initial CBCT scan was performed by a trained operator using Mimics
125 Innovation Suite software (version 17 Research edition, Materialise, Leuven, Belgium). A
126 semi-automated process was followed in accordance with best practice usage, by
127 thresholding the main elements (maxilla and teeth) and manually refining the missing parts
128 and artifacts. The maxillary bone and the teeth were individually isolated into different
129 elements (see Figure 2, top-left panel) and, for each of them, 3D surface parts were exported
130 in STL files. At this step, the periodontal ligament was not modeled.

131

132 For the following steps of the study, detailed anatomy of the posterior teeth crowns
133 (premolars and molars) was needed. This anatomy could not be retrieved from the CBCT
134 scan, due to the resolution of the acquisition and to artifacts caused by metallic restorations
135 (Baan et al., 2021; de Waard et al., 2016). To get a surface model with precise anatomy of
136 posterior teeth crowns, Geomagic Studio software (version 2012, Geomagic, Rock Hill, USA)
137 was used to fuse the result of the segmentation of the initial CBCT and T0 IOS (no clinical
138 changes were found between superimposed T* and T0 IOS which were taken 14 days apart,
139 see Figure S1). In order to align the IOS with the segmentation, we used an Iterative Closest
140 Point algorithm (ICP) (Besl and McKay, 1992) localized on the posterior teeth crowns (“Best
141 Fit Alignment” in Geomagic software). ICP registration is a reliable and frequently used
142 method for alignment of similar surfaces (Baan et al., 2021; de Waard et al., 2016; O’Toole et
143 al., 2019). This process is illustrated in Figure 2 and detailed in the Supplementary Materials,
144 Section B.

145

146 **2.4. 3D reconstruction of intermediate (T1 to Tn) models**

147 To reconstruct the intermediate 3D models (named T1 to Tn), Geomagic Studio software
148 was used to reposition the segmented canines of the T0 model on the canines’ crowns of the
149 intermediate IOS.

150

151 To align the IOS on the model, we used the same process of ICP alignment (“Best Fit
152 Alignment” in Geomagic software) localized on the crowns of the premolars and molars,
153 considered as stable references. These “Best Fit Alignments” of several IOS using a
154 reference structure have been shown to be highly reliable (O’Toole et al., 2019). Then, we
155 used a second ICP alignment localized on the canine crowns to align the segmented canines
156 (T0 model) with the intermediate position of the canines. Since the segmented teeth
157 contained their roots, we were able to precisely track the position of the canines in the

158 maxilla at any time of the study. This process is illustrated in Figure 3 and detailed in the
159 Supplementary Materials, Section B.

160

161 **2.5. Validation of the tracking protocol**

162 To validate our intermediate model reconstruction, a CBCT was used to retrieve the final
163 position of the canines. This final position was compared to the position of canines from the
164 last intermediate model (T_n).

165

166 First, the final CBCT was aligned with the initial CBCT using a local 3D voxel-based
167 superimposition taking the maxillary bones as stable structures (Dot et al., 2020). To this
168 aim, we used the open-source software ITK-SNAP (version 3.6.0; www.itksnap.org)
169 (Yushkevich et al., 2006) and 3D Slicer (version 4.7.0; www.slicer.org) (Fedorov et al., 2012),
170 following Dental and Craniofacial Bionetwork for Image Analysis (DCBIA) method (Ruellas et
171 al., 2016).

172

173 Once the final CBCT was aligned with the initial one, it was imported in Mimics software to
174 retrieve the segmented models of the canines at the end of the study. Rigid body
175 displacements between the position of canines in the T_n model with these latter segmented
176 canines were calculated.

177

178 **2.6. Evaluation of clinical results**

179 The displacement of the canines was evaluated both qualitatively and quantitatively using 3D
180 Slicer software. We performed visualization via the “Model To Model Distance” and “Shape
181 Population Viewer” modules of the SlicerSALT project (salt.slicer.org) (Vicory et al., 2018).

182

183 The global rigid body displacements of the canines’ centroids were calculated. Rigid body
184 translation components were calculated along the x, y and z axis. Euler extrinsic angles were
185 calculated based on a right-handed orthogonal basis centered on the centroid of the canines,

186 with the z axis pointing towards the apex of the teeth, the y axis towards their distal side and
187 the x axis orthogonal to the yz plane. The order of the rotations was x, y', z''.

188

189 **2.7. Finite element analysis**

190 A preliminary FEM was developed to underpin the relevance of our tracking protocol in
191 supporting FEA. Only the key points of the FEM are outlined here. More details are given in
192 the Supplementary Materials, Section C.

193

194 In order to reduce the computational time, part of the T0 model was used to set up the
195 geometry of the FEM which included the trans-canine arch, the two canines, their periodontal
196 ligament (PDL) and part of the maxillary bone (Figure 4). The two bone parts were extracted
197 from the whole maxilla by making virtual cuts far enough from the studied teeth, and their
198 displacement was restricted (Figure S4). The personalized orthodontic device designed for
199 this study allowed an accurate description of the point of application and orientation of the
200 orthodontic forces in the FEM (Figure S4). Their magnitude was set to 100 cN according to
201 clinical data.

202 Maxillary structures are heterogeneous and exhibit an anisotropic, nonlinear behavior. As our
203 goal was to show the relevance of our 3D tracking protocol to support FEA, we were not
204 concerned with detailed constitutive modeling. Thus, as a first step and for illustration
205 purposes, we used simplified constitutive models for all the structures of the FEM. Teeth
206 were considered as rigid bodies. The lingual device and the PDL were modeled as linearly
207 elastic materials. In order to allow for irreversible OTM, bone was modeled through a Zener
208 model (Figure S5), whose constitutive law reads:

$$209 \quad \sigma = \sigma_e + \sigma_v, \quad \sigma_e = \mathbb{C} \varepsilon_e, \quad \sigma_v = 2 \eta \dot{\gamma}_v,$$

210 where σ is the stress tensor, additively split into an elastic stress σ_e —related to the elastic
211 strain ε_e through the elastic tensor \mathbb{C} — and a (deviatoric) viscous stress σ_v —related to the
212 (deviatoric) viscous strain rate $\dot{\gamma}_v$ through the viscosity coefficient η , the latter being related
213 to the characteristic time τ of the OTM. This parameter is strongly patient-specific: patient's

214 age and health state, biological activity, bone microstructure—just to mention a few—may
215 affect the value of τ . Moreover, as the mechanobiological response of bone is likely
216 nonlinear, it should not be expected to be a constant.

217
218 All the elastic coefficients were fixed according to relevant literature. Thus, overall, only one
219 free material parameter was left, *i.e.* the characteristic time τ , that was calibrated against
220 clinical data (models T0 to Tn). Comparison between clinical and numerical results was
221 performed with respect to the rigid body translations and Euler extrinsic angles of the
222 canines.

223

224 **3. RESULTS**

225 **3.1. Clinical results and surface models**

226 The retraction treatment lasted 7 months. Figure 5 shows the clinical calendar and the
227 associate data acquisition. Starting from T0, a total of 8 IOS were acquired, leading to
228 models T0 (initial model) to T7 (final model).

229

230 **3.2. Validation of the tracking protocol**

231 A qualitative evaluation of the 3D voxel-based superimposition of initial and final CBCT
232 visually showed no displacement of maxillary premolars and molars (Figure 6 and
233 Supplementary movie SM1). This confirmed the possibility of using these teeth as stable
234 structures for the construction of the intermediate models. Incisors teeth and especially left
235 lateral incisor showed a small displacement with a spontaneous resolution of a few
236 millimeters of their crowding, probably due to the space created by the recoil of the canines.
237 These observations justified the assumption to have considered only the maxillary bone
238 around the canines in this study.

239

240 The differences in positions of the canines in the T7 model and in the final CBCT were
241 quantified by the rigid body displacements between the two models, computed through
242 Geomagic Studio software (Table ST1 of Supplementary Materials). These displacements
243 were less than 0.2 mm in translation and less than 1° in rotation. They were clinically
244 acceptable and within the actual spatial resolution of CBCT. These results validated the
245 proposed tracking protocol and our process of reconstruction of intermediate models.

246

247 **3.3. Evaluation of clinical results**

248 Figure 7 shows the displacement fields of the right and left canines in models T3, T5, and T7,
249 taking T0 as reference. Colors refer to the magnitude of the displacement. At T7, the range
250 of values [minimal – maximal] taken by the magnitude of the displacement field was [2.4 - 5.6
251 mm] for the right canine, and [2.2 - 6.2 mm] for the left one. The higher displacement was
252 found at the tip of the cusps, and a slight intrusion (around 2 mm) was observed at the apex.
253 The measured rigid body displacements of the canines (translations and Euler angles in the
254 x, y', z'' order, referred to the canine centroids) from step T0 to T1 through T7 are reported in
255 Figure 8 and in Table ST2 of Supplementary Materials.

256

257 **3.4. Finite Elements Analysis**

258 Clinical data obtained from models T0 to T7 were used to calibrate the free parameter of our
259 FEM, i.e. the OTM characteristic time τ . To this aim, we performed a parametric analysis
260 searching for the values of τ best matching the clinical data. A preliminary observation of
261 clinical data revealed two main features. First, the OTM in the direction of the applied loads is
262 much larger than in the other directions. Secondly, OTM is characterized by two time scales,
263 being slower during the first half of the treatment. Therefore, for the sake of simplicity, the
264 identification of the characteristic time τ was performed only with respect to the translation of
265 the canines in the y direction and separately in the two phases of the treatment. A good
266 match was found by taking $\tau = 0.12$ hours between T0 and T4, then $\tau = 0.06$ hours between

267 T4 and T7. Simulated displacements (translations and rotations) of both right and left canines
268 showed a good agreement with the corresponding clinical data, with exception of the
269 translations along z axis. Rotations around the x axis were also slightly overestimated by the
270 numerical model. The simulated rigid body displacements of the canines (referred to the
271 canine centroids) from step T0 to T1 through T7 are reported in Figure 8 and in Table ST2 of
272 Supplementary Materials.

273

274 A qualitative assessment of the simulation results can be made using transparent overlays of
275 the clinical canine models over the simulation models. As showed in Figure 9, the simulated
276 teeth showed a movement of rotation around their apex, in accordance to the clinical data.
277 The clinical displacement that was not simulated correctly was the intrusion of the teeth.

278

279 **4. DISCUSSION**

280 **4.1. *Tracking 3D orthodontic tooth movement***

281 The main goal of this paper was to propose a protocol to effectively track the 3D orthodontic
282 movement of the canines. Our method of tooth movement tracking, using only one
283 acquisition with ionizing radiation, proved to be effective and showed a clinically acceptable
284 error. The ability to track teeth and roots displacements is clinically appealing, and the
285 possibility to do so with a low ionizing radiation dose is a main asset (Lee et al., 2015, 2014).

286

287 We tested our protocol by tracking the 3D OTM of a patient undergoing canine retraction
288 over a seven-month period. Intermediate models of the canines were generated monthly at
289 each clinical appointment. The efficiency of our process of reconstruction of intermediate
290 models was checked by a second CBCT scan at the end of the study. Being used only for
291 validation purposes, the second CBCT scan shall not be included in the clinical protocol. This
292 final validation shows the clinical transfer potential of this technique, and had not been
293 performed previously (Likitmongkolsakul et al., 2018). Our new protocol represents an

294 improvement of a technique previously described by our team (Bouton et al., 2017). Our new
295 technique is more accurate and automatized as it uses an ICP algorithm and can be applied
296 to a much longer treatment.

297

298 **4.2. Supporting FEA**

299 FEA has a great potential to improve quality and efficiency of orthodontic treatments, but for
300 now there is no prospective model of human OTM. The main issue is the availability of
301 reliable clinical data to calibrate and validate the models. Our new protocol can usefully
302 support FEA of OTM. We illustrated this point by developing a preliminary, patient-specific
303 FEM to simulate the seven-month canine retraction of a patient. Clinical data were used to
304 calibrate the OTM characteristic time τ in the FEA. Calibration was eased by the
305 personalized orthodontic device designed for this study, delivering a statically determinate
306 system of forces. Other orthodontic devices could be used but this may introduce uncertainty
307 in the calibration process. Calibration was performed with respect to the main orthodontic
308 displacement, i.e. the canine retraction in the occlusal plane (y direction). The numerical
309 model was able to reproduce the latter with excellent accuracy. However, translation along z
310 axis did not match the clinical intrusion movement, which suggests that this movement might
311 be due to functional forces (i.e. occlusal or muscular forces) not simulated in our study.
312 Moreover, the value of τ was observed to change somewhere between T4 and T5. This
313 might be due to a change of the occlusal forces or of the biological activity but the source of
314 this effect remains unclear (de Gouyon Matignon de Pontouraude et al., 2021). These
315 difficulties underline the relevance of clinical data to support the development of reliable
316 FEM.

317

318 **4.3. Perspectives and limitations**

319 Our preliminary model could be used to explore the consequences of variations of the force
320 system and therefore provide clinical cues. For example, it is possible to assess the position

321 of the 3D center of resistance of the canines or to identify the line of action of the forces
322 producing a target OTM.

323

324 This study has some limitations that may impact our goals and conclusions. These issues
325 are briefly discussed below and will be addressed in future investigations.

326 1. The proposed 3D tracking procedure can be used for research purposes but a higher
327 degree of automation shall be attained before it to be transferred to clinical practice.

328 Indeed, our protocol requires operators trained in computer modelling and remains
329 tedious because of the need of thorough segmentation of the CBCT image and
330 manipulation of the 3D models to fuse the crowns of the IOS with the tooth models
331 obtained from the segmentation. It would also be useful to test this procedure using
332 CBCT images acquired using low dose protocols, which might hinder the segmentation
333 process.

334 2. Our procedure needs stable landmarks to align the intermediate IOS on the initial model.
335 In our study, we were able to use the posterior crowns as stable structures, as they were
336 not included in the force system. To apply this method with more traditional orthodontic
337 appliances, TADs or palatal rugae could be used as stable structures (Chen et al., 2011;
338 de Gouyon Matignon de Pontouraude et al., 2021; Likitmongkolsakul et al., 2018). We
339 could not use them in our study because these structures were not properly recorded in
340 our IOS.

341 3. Canine root morphology was clear at the time the device was made and the initial center
342 of resistance was estimated as per Fig. 1-C. However, the position of the center of
343 resistance depends on the type of OTM (Meyer et al., 2010) and mechanical
344 considerations should be made for each case (Kum et al., 2004). Therefore, our
345 estimate of the center of resistance might not be accurate. This could have a relation
346 with the tipping of the canines clinically observed, as the real position of the center of
347 resistance of the canines was probably apical to the line of action of our forces.

- 348 4. Boundary conditions of the FEM may not be accurate. In particular, we did not include
349 functional forces in our model. This could have a relation with the difference between
350 clinical and numerical results in terms of intrusion/extrusion. This shows the major
351 difficulty to obtain the full force system experienced by the teeth, undesired functional
352 forces being sometimes non-negligible. The use of light-cured cement placed on top of
353 molars to create a gap between upper and lower teeth might have helped to reduce
354 undesired occlusal loading of the moving canines due to contacts with the lower teeth
355 (Zhong et al., 2019).
- 356 5. The constitutive models of our FEM shall be improved, namely to account for the
357 anisotropic, nonlinear response of the PDL and for the alveolar bone remodeling, as well
358 as for the heterogeneity of maxillary structures. This question is out of the scope of this
359 paper and will be addressed in future work. It should be mentioned that several models
360 of bone remodeling have been proposed (Chen et al., 2014; George et al., 2019;
361 Hamanaka et al., 2017). However, clinical data to support these models are hardly
362 accessible and it is still challenging to obtain reliable information about
363 mechanobiologically relevant parameters (Van Schepdael et al., 2013), bone density
364 and micro-anatomy (Cattaneo et al., 2005), and precise periodontal ligament
365 compartment (Uhlir et al., 2016).

366

367

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371

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374 commercial, or not-for-profit sectors.

375

376 **Conflict of interest statement**

377 None to declare.

378

379 **Research Data**

380 3D surface model files of IOS, T0 model used for the simulation and canines models (T0 to
381 T7) are available from the authors upon request.

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Figure legends

Figure 1: Individualized lingual mechanism used in this study. A: intra-oral occlusal view (see supplementary materials for details). B and C: posterior and right lateral view, respectively, of the flat portion of the trans-canine arch (CBCT segmented model), designed to be at height of the theoretical initial center of resistance of canines (in purple).

Figure 2: 3D reconstruction of initial (T0) Model. Red/blue colors: selected/unselected parts for Iterative Closest Point algorithm (ICP).

Figure 3: 3D reconstruction of the intermediate model T_i ($i=1..n$). Only the teeth of T0 model are shown in the upper images. Red/blue colors: selected/unselected parts for Iterative Closest Point algorithm (ICP).

Figure 4: T0 surface model after preparation for FEA with coordinate system. A. Front view with transparent bone overlay. B. Occlusal view with transparent bone overlay. C. Lateral right view.

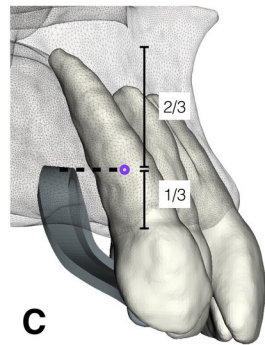
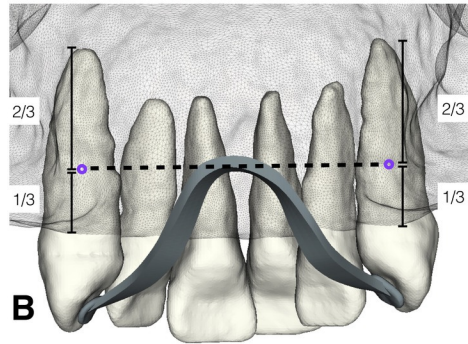
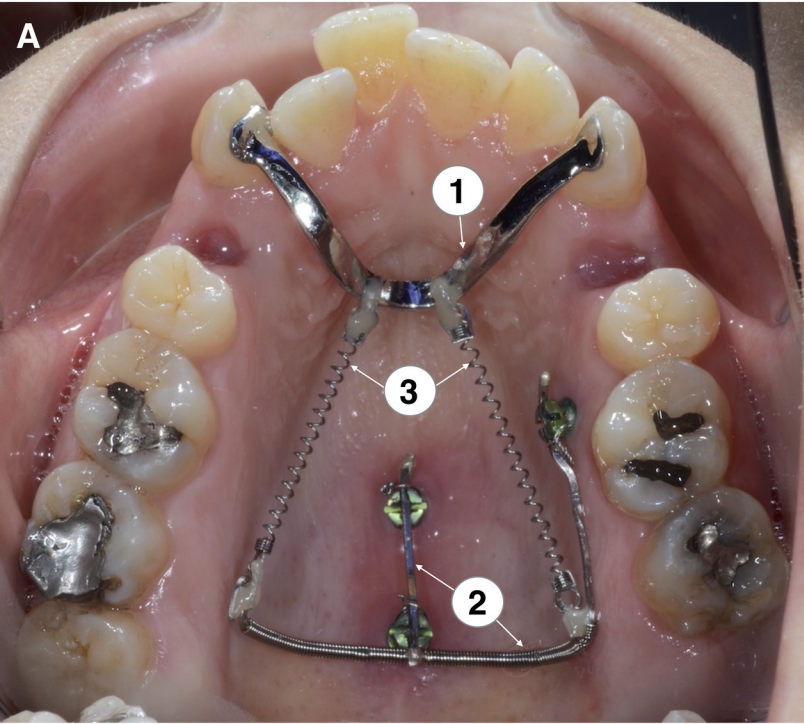
Figure 5: Clinical calendar and data acquisition.

Figure 6: Cross-section in the axial plane of initial (grey level) and final (red) superimposed CBCT scans. White arrows point to the left (LC) and right (RC) canines considered in this study. Their orientation indicates the point of view in Figures 7 and 9.

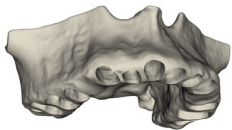
Figure 7: Vector fields of right (upper panel) and left (lower panel) canine displacement from situation T0 to T3, T5, and T7 (vectors at scale 1). The point of view is depicted by the white arrows in Figure 6.

Figure 8: Rigid body translations (T_x , T_y , T_z) and rotations (R_x , R_y , R_z) of right and left canine from step T0 to steps T1 through T7: comparison of clinical ("clin" labels, blue lines) and simulation ("sim" labels, orange lines) results.

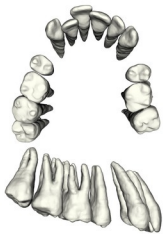
Figure 9: Qualitative evaluation of canine displacement from situation T0 (plain white) to T7 clinical (blue overlay) and simulation (orange overlay). A: Right canine; B: Left canine. The points of view are depicted by the white arrows in Figure 6.



CBCT Segmentation



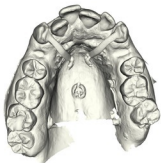
Maxilla



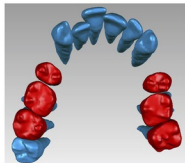
Teeth
roots + low definition posterior crowns

Intra-oral scan (time T0)

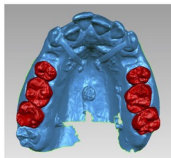
Teeth
high definition posterior crowns



Segmentation *selection of teeth crowns*



Local ICP alignment of intra-oral scan

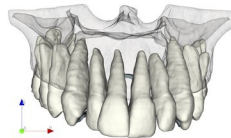
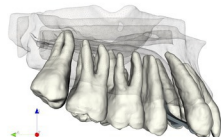
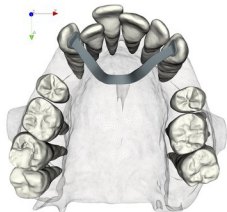


Intra-oral scan *selection of teeth crowns*

Data fusion

Fusion

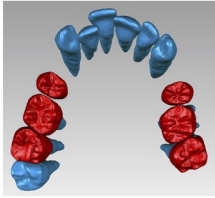
*teeth from segmentation
with posterior crowns
from intra-oral scan*



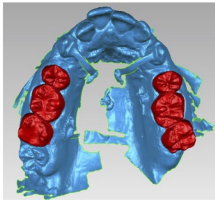
Intermediate model 3D reconstruction

T0 Model

selection of posterior teeth crowns



**Local ICP alignment
of intra-oral scan**

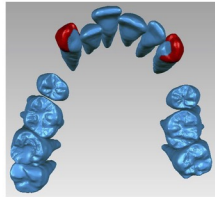


Ti intra-oral scan

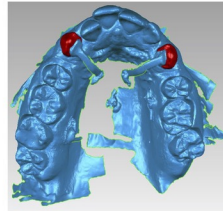
selection of posterior teeth crowns

T0 Model

selection of canines crowns

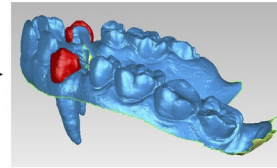


**Local ICP alignment
of canines**



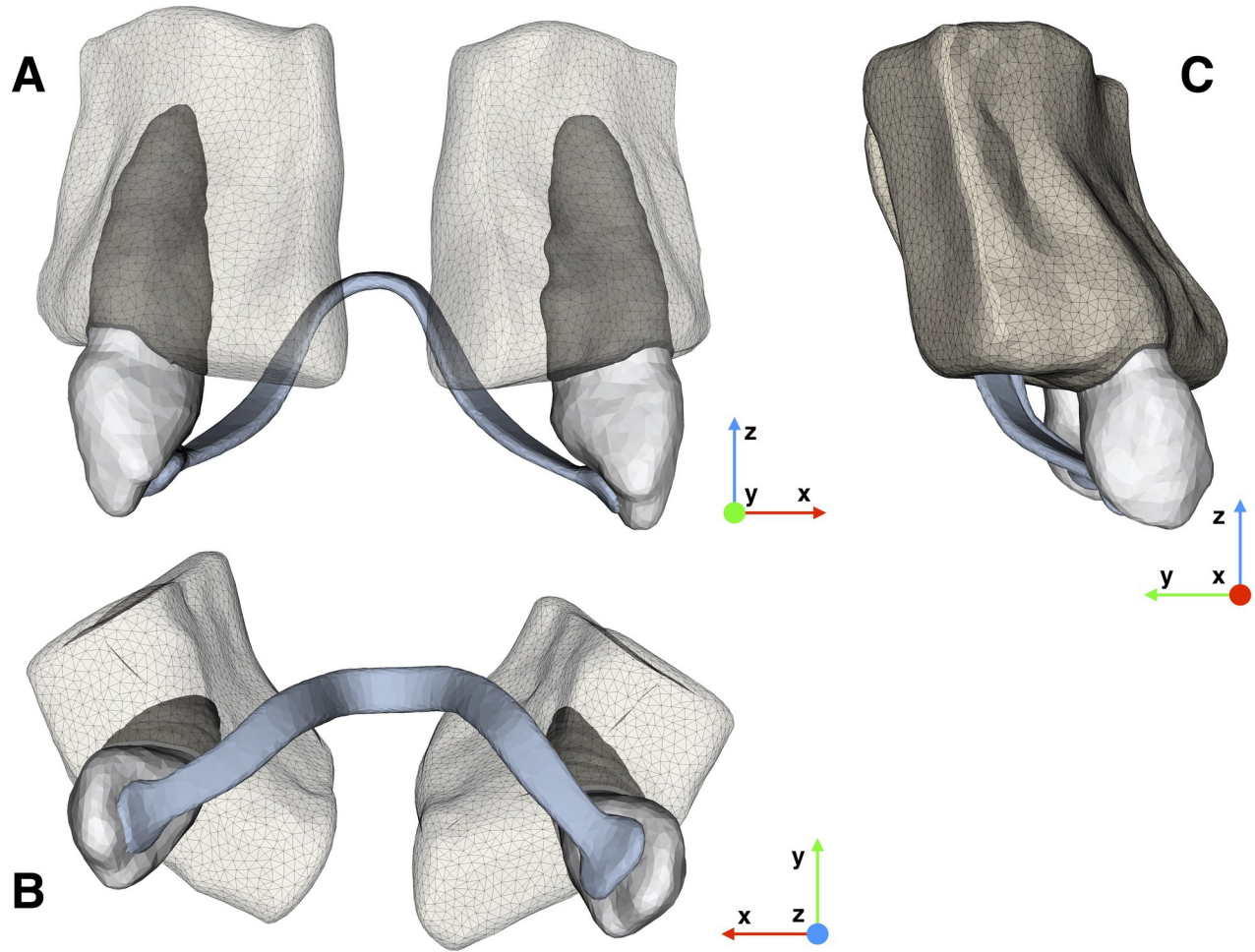
Ti intra-oral scan aligned

selection of canines crowns



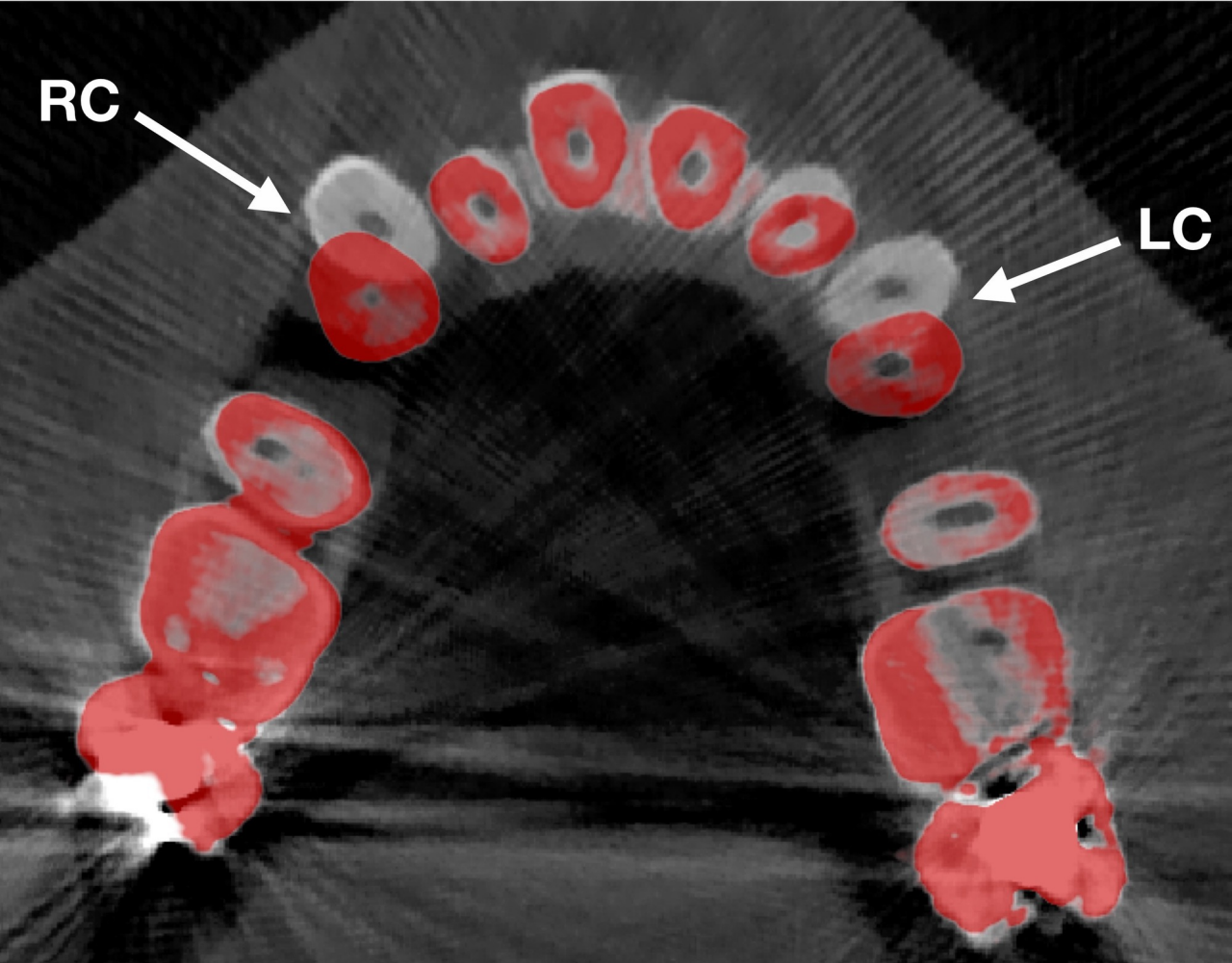
Canines aligned

*canines with roots aligned
on Ti intra-oral scan*

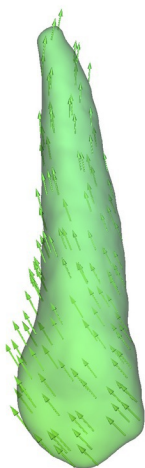


RC

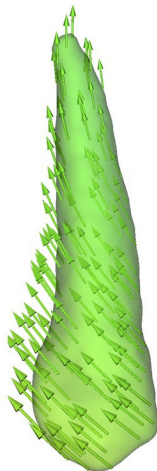
LC



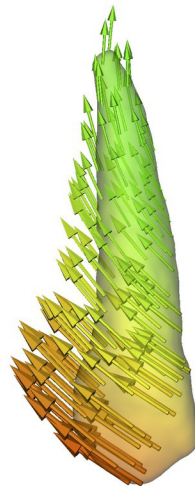
Right
Canine



T0 to T3

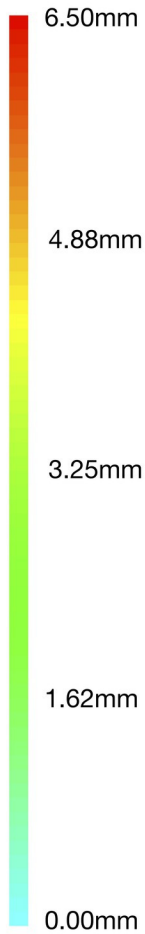
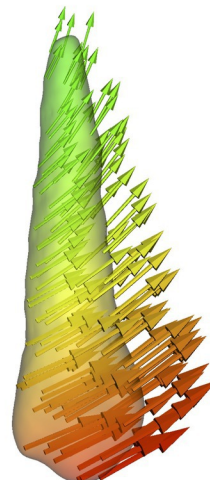
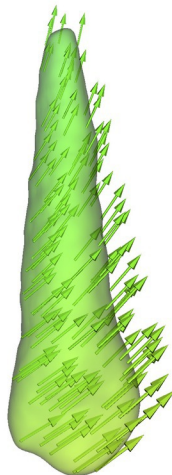


T0 to T5

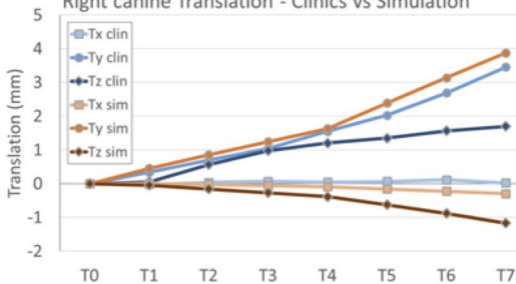


T0 to T7

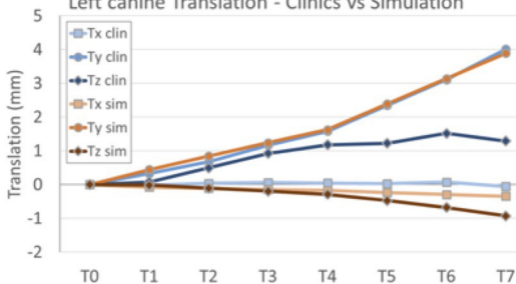
Left
Canine



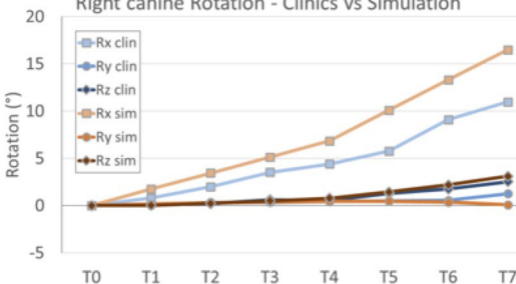
Right canine Translation - Clinics vs Simulation



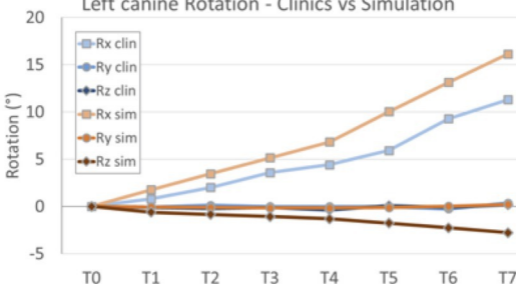
Left canine Translation - Clinics vs Simulation

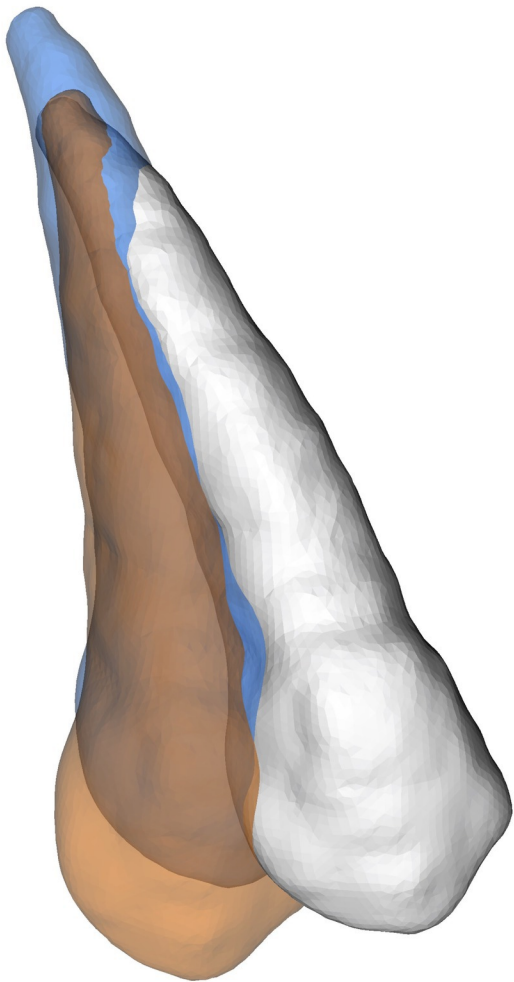
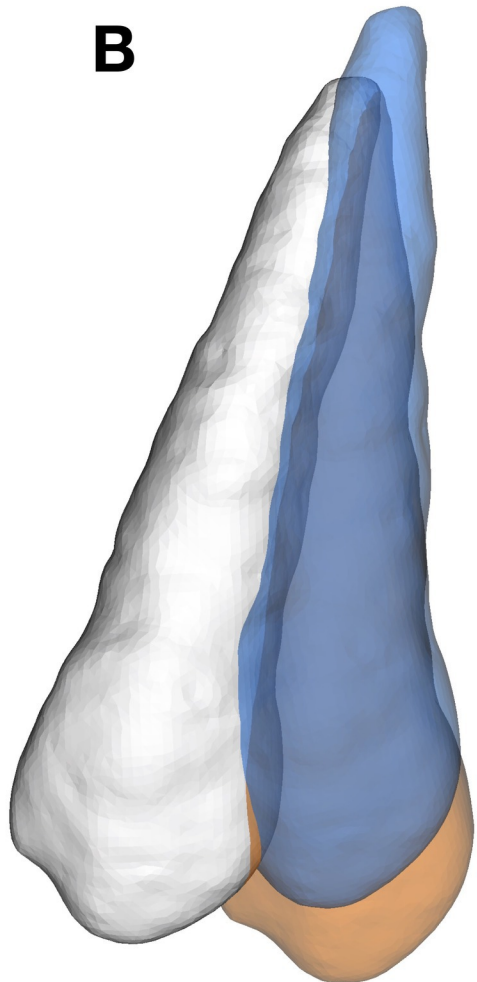


Right canine Rotation - Clinics vs Simulation



Left canine Rotation - Clinics vs Simulation



A**B**

<i>Authors, Year</i>	<i>Initial model geometry</i>	<i>Updated model geometry (clinical OTM tracking)</i>	<i>Mechanical loading</i>	<i>Clinical validation of numerical results</i>
<i>Bourauel et al. 2000</i>	CAD	n/a	Theoretical loadings applied at crown level (no friction/sliding)	n/a
<i>Schneider et al. 2002</i>	CAD	n/a	Theoretical loadings applied at crown level (no friction/sliding)	n/a
<i>Marangalou et al. 2009</i>	CT-Scan (1 patient)	n/a	Theoretical loadings applied at crown level (no friction/sliding)	n/a
<i>Wang et al. 2012</i>	CT-Scan (1 patient)	n/a	Theoretical loadings applied at crown level (no friction/sliding)	n/a
<i>Chen et al. 2014</i>	CBCT scan (1 patient)	n/a	Theoretical loadings applied at crown level (no friction/sliding)	1 patient followed for 3 months
<i>Hasegawa et al. 2016</i>	CT-Scan (1 patient)	n/a	Theoretical loadings applied at crown level (no friction/sliding)	n/a
<i>Hamanaka et al. 2017</i>	μCT scan (1 dry skull)	n/a	Sliding mechanics with contact boundary conditions	n/a
<i>Likitmongkolsakul et al. 2018</i>	CBCT scan (2 patients)	Scanned dental models	Sliding mechanics with contact boundary conditions	2 patients followed for 4 months

OTM: Orthodontic Tooth Movement; CAD : Computer-aided design; CT : computed tomography; CBCT : cone beam computed tomography; n/a : not applicable.

Table 1. Published numerical models for long-term orthodontic tooth movement (OTM)