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REVIEW

Precision medicine using patient-specific modelling: state of the art and perspectives in dental practice

Pierre Lahoud[1,2,3] · Reinhilde Jacobs[1,2,4] · Philippe Boisse[5] · Mostafa EzEldeen[1,2,6] · Maxime Ducret[7,8,9] · Raphael Richert[5,7,8]

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Abstract

The dental practice has largely evolved in the last 50 years following a better understanding of the biomechanical behaviour of teeth and its supporting structures, as well as developments in the fields of imaging and biomaterials. However, many patients still encounter treatment failures; this is related to the complex nature of evaluating the biomechanical aspects of each clinical situation due to the numerous patient-specific parameters, such as occlusion and root anatomy. In parallel, the advent of cone beam computed tomography enabled researchers in the field of odontology as well as clinicians to gather and model patient data with sufficient accuracy using image processing and finite element technologies. These developments gave rise to a new precision medicine concept that proposes to individually assess anatomical and biomechanical characteristics and adapt treatment options accordingly. While this approach is already applied in maxillofacial surgery, its implementation in dentistry is still restricted. However, recent advancements in artificial intelligence make it possible to automate several parts of the laborious modelling task, bringing such user-assisted decision-support tools closer to both clinicians and researchers. Therefore, the present narrative review aimed to present and discuss the current literature investigating patient-specific modelling in dentistry, its state-of-the-art applications, and research perspectives.

Keywords Precision medicine · Patient-specific modelling · Decision-making · Oral diagnosis · Finite element analysis · Dental stress analysis

✉ Raphael Richert
raphael.richert@insa-lyon.fr

1 OMFS-IMPATH Research Group, Department of Imaging and Pathology, Faculty of Medicine, KU, Leuven, Belgium

2 Department of Oral and Maxillofacial Surgery, University Hospitals Leuven, Leuven, Belgium

3 Periodontology and Oral Microbiology, Department of Oral Health Sciences, KU Leuven, Leuven, Belgium

4 Department of Dental Medicine, Karolinska Institute, Stockholm, Sweden

5 Laboratoire de Mécanique Des Contacts Et Structures, UMR 5259, CNRS/INSA, Villeurbanne, France

6 Department of Oral Health Sciences, KU Leuven and Paediatric Dentistry and Special Dental Care, University Hospitals Leuven, Leuven, Belgium

7 Hospices Civils de Lyon, PAM d'Odontologie, Lyon, France

8 Faculty of Odontology, Lyon 1 University, Lyon, France

9 Laboratoire de Biologie Tissulaire Et Ingénierie Thérapeutique, UMR5305 CNRS/UCBL, Lyon, France

Introduction

Medical knowledge and innovation in healthcare have continuously grown in the past decades, but this has added greater complexity to the decision-making process in clinical practice. As a response to the diversity of practices, evidence-based dentistry (EBD) was proposed to guide decision-making in accordance with the overall conclusions of clinical trials with a high level of evidence [1]. EBD makes it possible to provide the most recommended treatment option to an entire population. Yet, the conclusions are based on comparisons of populations and not on the characteristics of individuals. However, numerous patients still encounter treatment failures despite biomedical and digital advancements. This is particularly true in dental biomechanics, for which several recommendations were proposed to prevent cracks [2]; research methods such as finite element (FE) models have been developed to investigate reasons for failure [3, 4]. Still, many clinicians face difficulties assessing patient- and tooth-specific

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risks [5–7]. Indeed, most published results were produced using standard FE models without considering patient-specific parameters, but many of these, such as the root canal anatomy or occlusions, can modify the biomechanical behaviour of the tooth [8, 9].

Recent imaging technologies such as CBCT enable researchers and clinicians to gather patient-specific characteristics with sufficient accuracy for patient-specific modelling (PSM) [10, 11]. These digital twins are proposed to individually simulate the biomechanics of different treatments for a given patient and adapt the treatment accordingly [12]. This customised approach is well developed in several fields, such as maxillofacial surgery, in which medical devices are being developed to model surgical procedures [13] or orthopaedics where FE models based on patient femurs were reported to better predict potential bone fractures than assumptions of experimented clinicians [14]. However, its use in dentistry is still rare as PSM requires powerful computer hardware, dedicated software, time, and operator experience; these aspects have delayed the practical application of the first proofs of concept using standard FE published more than three decades ago [15]. More recently, advances in the fields of artificial intelligence (AI) have allowed the automation of several steps of the PSM, such as automated anatomical segmentations and CAD [16], reducing the time needed as well as operator experience and therefore making this digital tool more than ever available to both clinicians and researchers.

Therefore, the present narrative review aimed to present and discuss the literature investigating PSM in dentistry, its current state-of-the-art applications, and to identify future research required before its integration into routine clinical practice.

Principles of PSM

Creating a patient-specific model can be divided into different steps, ranging from recording patient data to customised therapy. This requires first to create a digital twin representative of the given clinical situation (Fig. 1a–c). These digital twins of anatomical structures such as teeth and bone are frequently built using data from a CBCT scan that is then imported into dedicated platforms such as Amira (Mercury Computer Systems, Chelmsford, MA, USA) and Mimics 10.01 (Materialise, Leuven, Belgium) [15, 17]. Segmentation of anatomical structures on CBCT enables partitioning the initial image into multiple virtual segments of the structure of interest and its environment; for these, several strategies are reported, including grey-level threshold, region-based growing techniques, and the level-set method [16]. The segmented object is then meshed for subsequent biomechanical calculations [15, 17].

It should be noted that smaller voxel size enables for more a precise mesh, yet requires more computational power [17]. To define the biomechanical behaviour of a

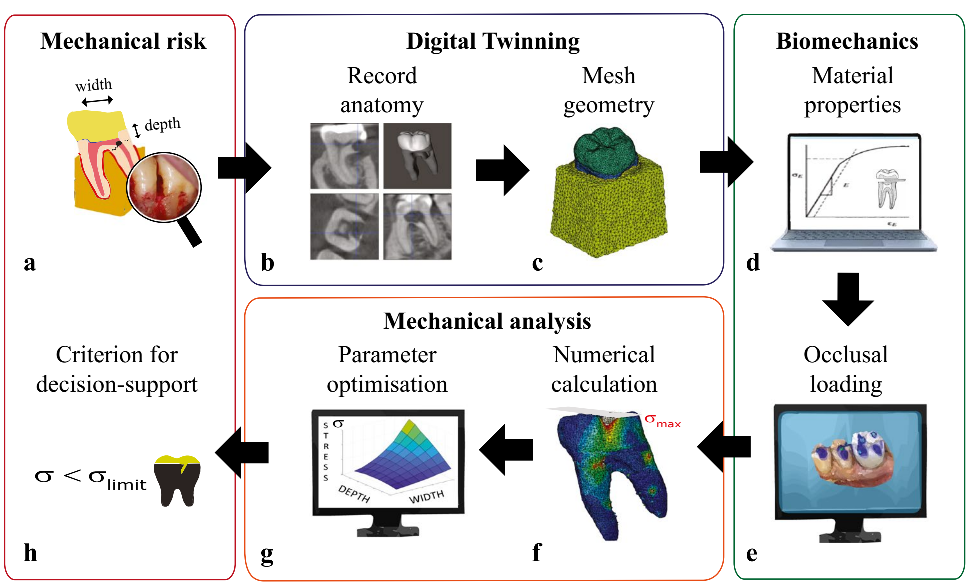

Fig. 1 Patient-specific modelling: **a** detection of a mechanical risk in a specific clinical situation: example for a damaged tooth indicated for a crown, **b** anatomical record using computed tomography illustrated by grayscale image and segmented tooth, **c** volume and surface meshing, **d** integration of material properties, illustrated by a stress/strain curve representing the capacity of the material to deform under load, **e** simulation of occlusal loading and boundaries representative of the masticatory forces of the patient, **f** numerical calculation of stress σ, **g** parameter optimisation to define the most conservative therapeutical choices (for example, width and depth for a post space preparation), and **h** decision-making supported by a mechanical criterion: herein a limit on the stress value

tooth requires the solving of complex partial differential equations, and FE analysis was reported to be the reference method due to its widespread use in multiple fields of application and implementation in many commercially available software. The principle of FE analysis is based on the division of the structure into a finite number of smaller parts called elements. In these elements, a system of algebraic equations is defined, and solutions can then be approximated and recombined into a larger system to model the entire problem [15].

Biomechanical parameters such as material laws and occlusal loading should then be considered in the model (Fig. 1d–e). Material laws have been traditionally classified according to the nature and composition of the material, ranging from soft tissues, such as the periodontal ligament (PDL), to hard tissues, such as the dentine, enamel, and bone [18]. Young's modulus value describes virtually the capacity to deform under masticatory forces [18]. This constant was reported to vary, according to the location on the tooth, from 7 to 25 GPa for dentine and from 48 to 84 GPa for enamel [17, 18]. Then, occlusal loading is commonly simulated with a unique force in PSM, ranging from 100 to 300 N, according to the type of tooth and patient profile [17, 18].

Mechanical analysis is the final step, and this enables the investigation of the stress distribution related to a specific clinical situation and the comparison between different therapeutical strategies. Numerical calculi can be conducted using software such as Abaqus (Dassault Systèmes, Vélizy-Villacoublay, France), Ansys (Workbench, Swanson Analysis Inc., Houston, TX, USA), or Nastran (MSC Software, Newport Beach, CA, USA) [17–19]. PSM promises to offer clinicians and researchers the possibility to digitally assess the influence of several biomechanical parameters such as depth of post space preparation [20–22]. This approach aims to find the optimal mathematical solution and help decide the most conservative treatment options, with minimal stress constraints and increased durability for each patient [23] (Fig. 1f–h).

More recently, democratisation of AI and machine learning have enabled the development of new models based directly on meshes or results of FE models. The principle of AI is based on classification of data primarily by learning their key features and then making predictions using the resulting models. Different AI approaches have been applied in medicine, such as principal component analysis, to generate automatically FE models representing the anatomy of a femur [24] or model order reduction to minimise computing time [25]. Another important aspect of AI is its capacity to deal with missing data due to artefacts in the acquisition for example [16].

Current applications of PSM in dentistry

Restorative dentistry

For the last 50 years, the development of adhesive materials and techniques has dramatically changed the mechanical concepts of modern restorative dentistry by progressively aiming for minimally invasive restorations and therefore the preservation of more dental tissue [26]. This paradigm shift has led to colossal research on the biomechanical properties of teeth, and numerous materials have been developed to minimise the stress concentration induced by restorations. This was achieved by adapting the modulus of elasticity of new restorations to that of the natural dental tissue, but no ideal direct restoration has emerged from published clinical studies [27, 28]. Similarly monolithic zirconia crowns have recently conquered the market and were presented as a promising alternative to conventional metal-ceramic crowns considering 3 years [29]; however, a weaker clinical performance was also found at 5 years [30]. These contradictory results highlight the difficulty of adequately understanding the biomechanical factors involved in the restorative procedure owing to numerous hurdles such as adequate follow-up or sufficient recall rate. In comparison, fine mechanisms have been discovered through FE studies, and new studies based on PSM appear to be of utmost importance to link material development to clinical use. For instance, Ausiello et al. (2004) developed a FE model to investigate the biomechanical behaviour of the inlay restoration and found that composite inlay transmits less stress to the other tooth structures [31]; however, the morphology of the dentine and enamel was defined from the literature which limits the clinical significance of these findings. Later, Barak et al. validated by interferometry a new FE model of a premolar based on CBCT and found that enamel mostly dictates the mechanical behaviour of the whole tooth [32]. Similar models were used by Magne and Oganesvan to evaluate the influence of material for inlays and smaller cuspal deformations were reported for ceramic compared to composite resins [33]. These biomechanical studies could be used to understand fine mechanisms explaining the most frequently reported clinical failures such as chipping or loss of retention; this does not seem to be the case for the many randomised clinical trials (and the systematic reviews of these) that have been conducted to explain these failures owing to differences in the baseline characteristics of the included patients such as amount of tissue [27, 34, 35]. These obstacles could be overcome by systematically simulating the biomechanics using patient-specific models and predicting the true impact of each factor such as the amount of tissue or occlusion. There is a real opportunity to connect FE studies to clinical data and reach a higher level of understanding of adequate material properties for each patient.

Stress analysis was also widely used to investigate potential factors influencing biomechanics, and more than 20 possible parameters have been reported to explain the fracture of restorations [36]. In this regard, FE models are proving to have great potential due to their ability to numerically assess each parameter separately and in combination [36]. This digital tool could help clinicians and researchers identify factors having the greatest influence on biomechanics. For example, general guidelines were proposed to avoid failure of adhesive restorations mostly by evaluating residual tooth structure and wall thickness. However, more recent studies suggest that occlusion contributes to 49% of stresses, whereas the cavity's interaxial thickness 1%, and isthmus width 5% [36]. Measuring the occlusion for individual patients in clinical practice is technically complex; this is unlikely to be done in routine. Therefore, PSM constitutes an interesting tool to simulate this patient-specific parameter. A protocol based on force sensors was thus recently developed and proposed to adapt restorations according to the results of a FE analysis [22]. Such accurate assessments based on PSM could open new ways to conceive biomimetic and personalised rehabilitations, potentially widening the indication of direct restorations instead of systematically crowning teeth.

Endodontics

In the past decades, guided endodontics and conservative access cavity designs have gained interest in the dental community [37, 38]. As for restorative dentistry, this reflects a will to conduct minimally invasive endodontics as the success of endodontically treated teeth greatly depends on mechanical conditions such as vertical root fracture [39]. Many studies have tried to investigate this fracture resistance using extracted teeth or standard FE models, but the biomechanical behaviour of the root in clinical practice is mostly influenced by patient-specific parameters such as bone level, root canal curvature, or root length [40]. These parameters are now considered in PSM using patient CBCT and this appears; therefore particularly adapted to predict the ideal fibre post rehabilitation in clinical practice [20, 22]. More recently, extended FE models were developed to define the ideal access cavity by identifying the model with the lowest risk of crack propagation [41]. A perspective would then be to combine these approaches with guided endodontics to reproduce the mechanically optimal strategy in the patient, which could reduce the risk of iatrogenic damage to the root but also treatment time.

FE analysis has also been widely used to investigate the mechanisms behind the separation of endodontic instruments. In 2008, Neeschi et al. developed models to compare the stress distributions in different rotary instruments and found that the radius and position of the canal curvature as the most critical parameters in determining the stress [42]. This work led to the restriction of stainless files and favoured Ni–Ti ones in in the apical portions of highly curved root canals. Similar models were used by Lee et al. to understand cyclic fatigue fracture [43]; it was found that stiffer instruments presented the greatest stress and stiffness which was related to a smaller number of rotations in the cyclic fatigue test compared to less rigid instruments. More recently, FE models based on patient CBCT were used to compare instrument removal strategies and help practitioners decide the most conservative strategy [44]. This approach could also be used to understand the biomechanical stresses of endodontic instruments to choose an instrument that is the most adapted to each root anatomy, but also to design new instruments for a more personalised treatment to avoid breakage.

Prosthodontics

Recently, digital smile design and augmented reality concepts have profoundly changed how prosthetic rehabilitations are conceived by delivering real-time smile projections [45, 46]. Consequently, patient's expectations for a customised 'ideal' smile are getting increasingly greater [45]. However, these new aesthetic expectations of prosthetic treatments require rigorous biomechanical analyses to avoid early failures and prosthetic breakage. Such treatment failures can be caused by various reasons, most frequently crown loosening, prosthetic fracture, or root fracture. Historically, the mechanisms leading to crown loosening were studied using FE analysis based on CBCT scans of extracted teeth [4]. These studies suggested notably a higher fracture rate of teeth reconstructed using a metal post due to the high Young's modulus of metal and helped understand the essential role of the ferrule effect [47, 48]. Recently, advances in CAD and CAM have allowed us to conceive and produce prostheses with a high degree of precision and reproducibility, unachievable before. These possibilities open a new field of investigation to identify the dimensions of prostheses that have the optimal mechanical properties, and FE models prove to be the ideal tool capable of studying and optimising clasp and crown design with regard to supported stresses (Fig. 2) [49, 50]. Considering overdentures, a perspective could be a more individualised design and lighter prosthesis for better comfort without increasing the risk of failure, similarly to that done in other medical fields using topology optimisation to calculate the ideal design of, for instance, craniofacial implants [23]. This could be of potential value as the time and cost related to digital denture protocols are reported to be smaller than conventional complete denture protocols [51], but the literature remains scarce on the

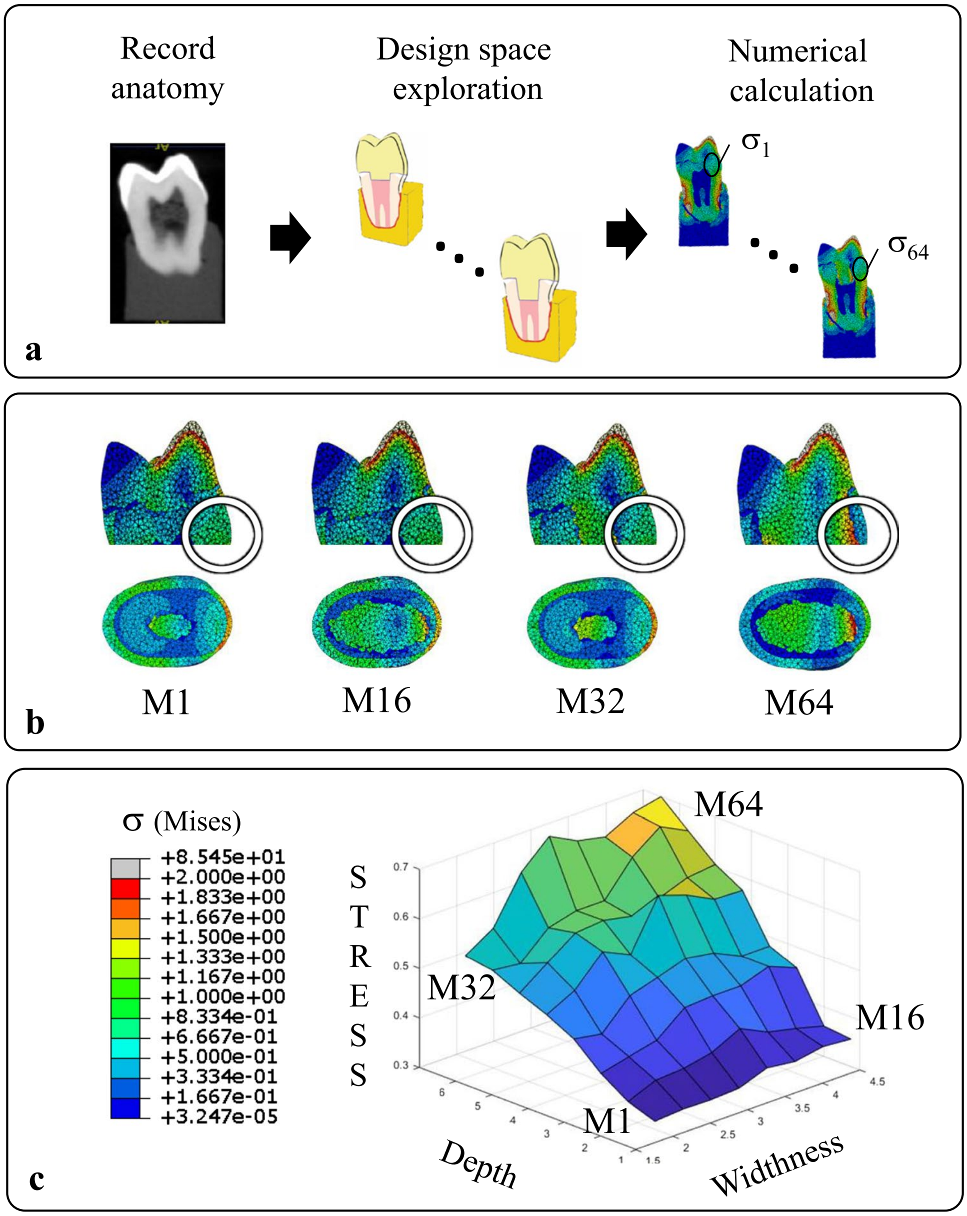

Fig. 2 Parameter optimisation for an endocrown rehabilitation with **a** process of constitution of models to evaluate the impact of width and depth of pulp chamber cavity on a specific damaged premolar: 64 models were generated by design space exploration to calculate stress values σ; **b** sagittal and occlusal views of 4 representative models: M1: small width and depth of pulp chamber, M16: large width and small depth of pulp chamber, M32: small width and high depth of pulp chamber, M64: large width and depth of pulp chamber; the model M64 presented an unfavourable stress distribution with high stresses on the resin luting (white circle); and **c** surface of response generated by each mean stress value σ of the resin luting for the 64 finite element models; width alone has a small impact on stresses but depth of pulp chamber had a great impact increasing stresses by 115%

mechanical indicators required to guarantee the clinical performance promised by digital dentistry.

Orthodontics

The practice has greatly evolved in orthodontics following the high demand of adult patients for aesthetic treatments such as lingual brackets and clear aligners [52]. This has been made possible following the development of CBCT-based models and has led to a shift towards virtual treatment planning (VTP), relying on integrated soft tissues, hard tissues, and dentition [53]. One major advantage of such modelling lies in the possibility of assessing and comparing different treatment options, such as extraction versus non-extraction strategies. The promise of VTP is to reproduce the perfect alignment predicted before treatment on the virtual setup [53]. Despite great hopes brought by initial proof-of-concept studies, our understanding as to the effectiveness and stability of ideal orthodontic treatments remains relatively low. However, interactions between teeth, bone, PDL, and the orthodontic appliances are currently being widely assessed using standard FE analysis to better understand these interactions and their repercussions on the treatment and its long-term stability [54, 55]. PSM could simulate with greater precision the mechanical response of each patient, leading to customised treatments and possible personalised designs of orthodontic appliances [56]. This approach could also be combined with AI algorithms to train meta-models based on clinical data to better predict outcomes, reduce treatment time, and increase long-term treatment stability.

Implant dentistry

Prosthetic failures in dental implant therapy are strongly related to mechanical complications such as prosthetic failure or bone loss [57, 58]. Numerous FE models have been developed to investigate the reasons of failure, leading to reinforce implant-retained overdentures [59], or the effects of implant length, leading to prefer longer implants in a jaw with bone of low density [60]. Other patient-specific parameters, including bone anatomy, greatly influence mechanical failure in dental implants or bone analogues [61]. These parameters are now simulated in the PSM based on CBCT scans, which led to the development and evaluation of personalised prosthetic rehabilitations using FE analysis [62–64]. Personalised prosthetic rehabilitations present more favourable stress distributions than traditional prosthetics, and customised bone analogues have lower bone stresses and higher success rate after 1 year compared to conventional methods [64]. These positive results led to the development of software to mathematically optimise the design of plates and bone analogues to minimise bone stresses and thus favour osteointegration [62, 63]. In addition, since its development, guided implantology has been increasingly used and PSM offers new possibilities to adjust the position planned for guided implant surgery or dynamic navigation following mechanical expectations delivered by FE analysis.

Traumatology and tooth auto-transplantation

Oral and maxillofacial trauma represents a major public dental health problem, particularly due to its high prevalence in children [65]. More recently, strategies preserving or regenerating the pulp are now recognised approaches to maintain the biological functions of traumatised teeth [66]. Similarly, tooth auto-transplantation (TAT) also became a reference strategy in cases of complete tooth loss or agenesis due to the limited treatment options available for children and its potential for preserving the alveolar ridge and consequently future growth [67]. Despite great hopes, these strategies are difficult to plan and execute adequately due to the complexity of the workflow involved in precisely planning TAT surgery [68]. However, recent advances in PSM have led to increased surgical predictability of CBCT-guided TAT compared to conventional approaches, thanks to the use of digital twins to shape the recipient site and match the virtually planned position of the transplant without damaging the PDL and dental components of the donor element (Fig. 3) [68].

These approaches also raise questions as to the mechanical resistance of the damaged or transplanted tooth. These questions were widely investigated using laboratory studies, but these approaches could appear limited to understanding certain mechanical mechanisms as tested mature teeth

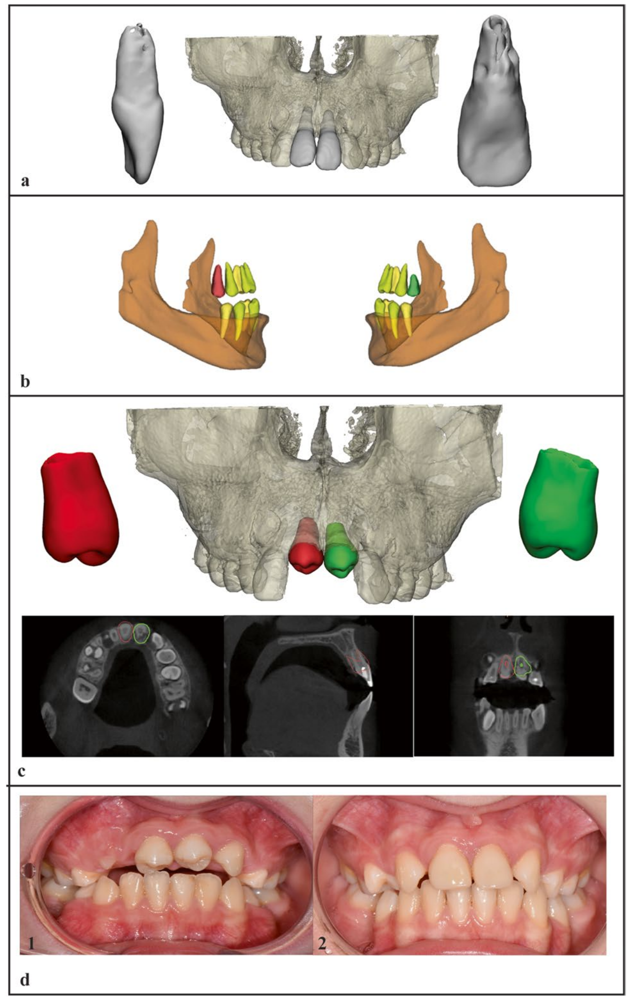

Fig. 3 Case simulation to illustrate the virtual treatment planning for tooth autotransplantation. Following detection of post-traumatic external root resorption at the level of the maxillary central incisors (**a**), potential donor teeth, consisting of maxillary and mandibular premolars, are assessed regarding their dimensions and developmental conditions to find the optimal donor element and its ideal position with regard to the recipient site (**b**). The chosen donor elements (in this case right upper premolar in red and left upper premolar in green) are then modelled and a simulation of the final position of the transplantation is performed regarding the 3D virtual model and of the CBCT slices (**c**). Subfigure **d(1)** shows a vestibular view of the outcome of the autotransplantation 3 months after surgery and subfigure **d(2)** a vestibular view 1 year after autotransplantation and aesthetic rehabilitation of the two maxillary central incisors

were cut to mimic immature ones [69, 70]. FE models offer the possibility to simulate the true anatomy of immature teeth based on CBCT and appear effective in improving our understanding of these complex phenomena [71–73]; these approaches were used on extracted teeth to understand the mechanical behaviour of apical plug or even compare strategies of revascularisation and apexification [72, 73] and, more recently, simulated patient-specific bone to evaluate the mechanical value of root maturation and type of restorative material [71]. More generally, young patients present high variability of tooth anatomy, position and/or occlusion, which is extremely difficult to reproduce *in vitro* and PSM appears therefore to be the most effective method to consider the many patient-specific parameters [74].

Periodontics

Digital dentistry has also considerably altered the way to diagnose and treat periodontitis. In first, recent developments in intraoral scanners have allowed the visualisation of gingival margin changes in patients who had undergone root coverage procedures and treatment of periodontal disease in a non-invasive and precise manner [75]. Secondly, patient-specific surgical guides were proposed in guided bone augmentation procedures to help improve the accuracy of the resulting graft shape and reduce the amount of graft material placed outside the planned volume [76]. Considering biomechanics, influence of periodontal ligament or bone level was widely evaluated using FE analysis in several fields, including apicoectomy, orthodontics, and implantology [54, 60, 77]. Different biomechanical laws were also developed and experimentally validated to simulate these tissues and considerations of periodontium appear decisive in constructing a PSM [78, 79]. While clinical studies show that several biomechanical factors such as excessive occlusal forces or bone loss play a decisive role in the patient-specific response to periodontal infection [80], there is, to the best of our knowledge, no published FE study that has explored this.

Current limitations and futures challenges of PSM

In dental research, FE analysis has already proven its great potential for the study of biomechanisms owing to its capacity to obtain the stress distribution of the tooth without destroying it [4]. PSM could now bring dental practitioners into a new more predictive era of medicine, but such evolutions raise technical, ethical, and economic questions among the different stakeholders.

CBCT artefacts and perspective with an intraoral scan

Since the advent of CBCT, distortions and segmentation errors have been noted and labelled as artefacts. Such artefacts are mainly related to the beam hardening phenomenon and can be correlated to the presence of high-density materials such as amalgam and alloys [81, 82]. These artefacts greatly reduce image quality and consequently the clinical potential of PSM. However, several strategies have been recently developed to treat these; for example, intraoral scanners (IOS) register the dental surfaces without radiographic artefact and could be combined with CBCT for a more precise PSM [83, 84], and AI methods have recently been developed to automate CBCT segmentation and could be trained to reduce the effects of artefacts during the volume reconstruction (Fig. 4) [16, 85].

Technical and scientific challenges

Numerous technical and scientific challenges currently limit the clinical scope of FE analyses. For instance, the mechanical behaviour of the tooth has been reported to be greatly modified by patient-specific characteristics surrounding the tooth, including the PDL, bone, and occlusion [86, 87]. However, most of our knowledge is currently based on experimental studies and FE models from extracted teeth, which, by definition, does not consider the tooth environment [17, 18]. An open-source PSM was recently proposed to consider the complete mandible, but this approach involved large meshes and multiple dental contacts, therefore resulting in long calculation times that are unrealistic to implement in the everyday clinical practice [88]. A solution to this may lie in new strategies such as model order reductions (MOR) that have been proposed for real-time simulations of complex biomechanical behaviour such as for tongue or guidewires for endovascular surgery [89, 90]. These approaches are based on different mathematical techniques, mainly proper orthogonal decomposition methods, but further developments remain crucial before its full implementation in the dental field [24, 25, 89, 90]. Simulation of the dental and periodontal environments appears therefore of great importance, yet still extremely challenging. Furthermore, these complex simulations will require user-friendly software to encourage dental practitioners to use PSM approaches. Such software are yet to be developed in dentistry but do exist for maxillofacial surgery where they have recently been reported to lead to more streamlined and predictive orthognathic surgery [13].

Several limitations are also raised by imaging of soft tissues surrounding the tooth using CBCT, in particular the PDL, which has been reported to possess Hounsfield unit values similar to those of the surrounding bone and dental cement, further complicating the segmentation of these structures [79]. Consequently, the PDL is often not segmented and artificially simulated with a continuous thickness of 0.2 mm around the tooth [17, 79]. Moreover, the PDL was reported to present *in vitro* a complex mechanical behaviour associating non-linearity, viscosity, and time dependency [77–79]. While these complex material laws still require to be experimentally validated, experimental tests are reported to be extremely difficult due to rapid tissue damage caused by dehydration [91].

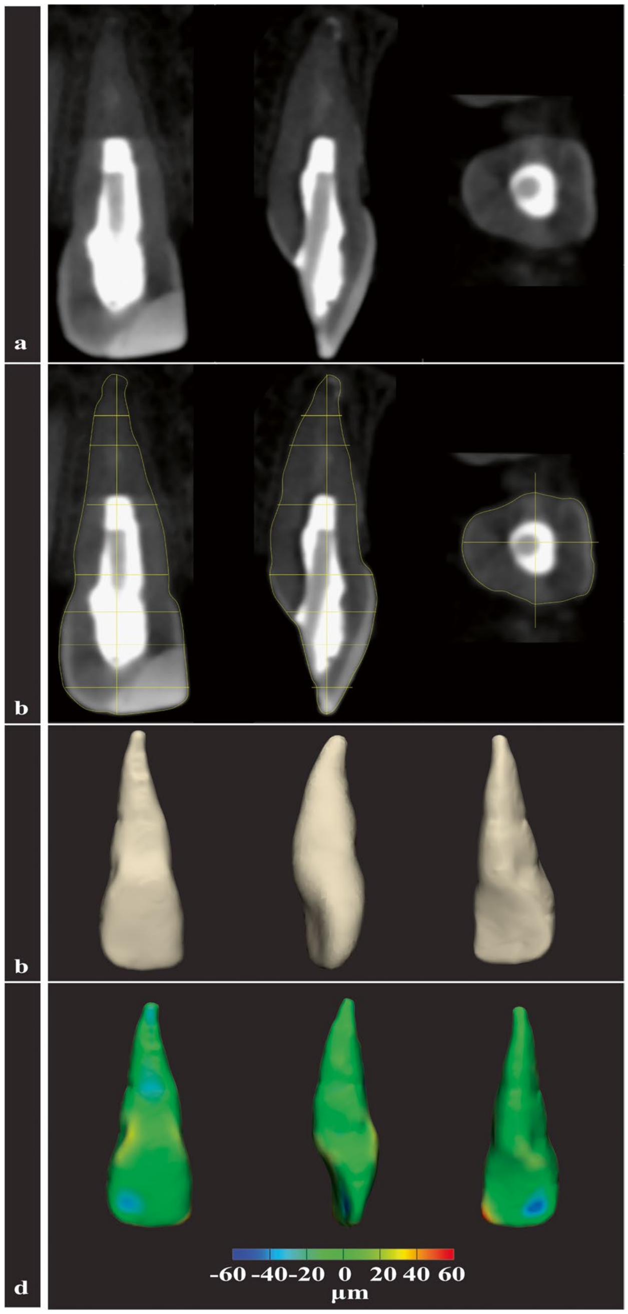

Fig. 4 Interest of AI-driven tooth segmentation with: **a** sagittal, frontal, and horizontal views of the cone-beam computed tomography (CBCT) of a maxillary central incisor presenting artefacts due to the root canal treatment and coronal rehabilitation; **b** automatic detection of the borders of the tooth (yellow lines) using the AI-algorithm; **c** automatic 3D segmentation based on the interpolation of the segmented slices (yellow lines); and **d** vestibular, lateral, and palatal views of a part comparison analysis deriving from the superimposition of expert manual segmentation (taking on average 12 min for completion) and fully automated AI segmentation (< 30 s for completion). The colour map depicts a mean deviation of 7.85 µm between the 2 segmentation methods (manual versus AI)

Model validation and economic considerations before clinical implementation

The premise of PSM is to propose to practitioners optimal treatment options based on anatomical, aesthetic, and biomechanical considerations. However, inappropriate models could result in unfavourable therapeutic decisions and potentially dramatic clinical consequences [92]. Model verification and validation were largely described *in vitro*, but no error estimator is currently available for a clinical use [19]. Moreover, recent reviews have highlighted the increasing number of published papers reporting FE models, although most of these have not yet been experimentally validated [92, 93]. This observation raises the question of the appropriate choice of model parameters and emphasises the need to develop protocols to reduce uncertainty of future PSM software.

PSM is already partly used in numerous medical fields such as orthopaedics [94], and FE studies are currently recognised as necessary for the design of personalised osteosynthesis to reconstruct the human mandible [23]. Furthermore, several software now exist to help practitioners decide the most appropriate treatment, such as PrediSurge (PrediSurge, Saint-Etienne, France) to optimise stent deployment in cardiac surgery [95]. However, such dedicated software is still not commercially available in the dental field although this seems technically possible as teeth are more easily obtainable than cardiac tissue for experimental studies and their behaviour as hard tissue has been analysed and validated many years ago [18]. This is likely to be related to the proven economic value of PSM in many medical fields but which has yet to be explored in dentistry. For instance, the use of computer-aided surgical simulation divides by two the time needed for complex cranio-maxillofacial surgery, and it was reported that the cost of the software is amortised for 6 patients per year [96]. These reductions in time and cost were also found for shoulder arthroplasty and orthognathic surgery in different countries and what is now to be determined is when virtual model surgery will completely eliminate the need for traditional surgery [13, 97, 98]. Furthermore, all these evolutions will require a training effort from the health professionals, dentists, assistants, and prosthetists. It was reported that 2 weeks of training would be necessary to use the software for orthognathic surgery [96]. However, it is unclear if dental practitioners are ready to such evolutions in their daily practice, as it could reduce clinical time for simulation and virtual planning. Consequently, a growing number of companies is emerging to plan and send surgical guides to dental practitioners, but it raises questions as to the responsibility in cases of failure.

Ethical issues in precision medicine

Following the rise of computing power, an increasing amount of data are being generated, which led to a new trend for data-driven models, not only based on physical properties but also factors related to the medical or dental history of the patient [99]. Nonetheless, this trend raises several legal and ethical questions as to the use and potential applications of such models, but these considerations are unfortunately rarely discussed in the development of PSM, mainly because the medical and dental communities remain "ill-informed" about the ethical complexities that budding AI or PSM technologies can introduce [100]. PSM software are likely to require an additional cost for the patient, whereas the development of PSM may use a patient data and medical information to be calibrate and then commercialise the software without having directly paid these patients. This additional cost for treatment could aggravate the inequalities in access to healthcare [101], but the economic discrimination could be even worse if these models begin to be used by insurance companies to justify higher premiums in cases where there is a greater risk of treatment failure. Numerous laws such as the Artificial Intelligence Act in Europe are currently under development to protect patients and regulate research, but the exact definition of AI is difficult to establish and is a rapidly evolving technology that makes it hard for governments to remain well informed. States, digital dentistry companies, and the field of dental research must therefore collaborate to provide full transparency for both patients and practitioners through detailed and exhaustive informed consent and ethical approval [100]. This collective effort might help reduce ethical concerns and misconception, which could thus strengthen confidence between industry, clinicians, and patients.

Conclusion

The growing use of CBCT in clinical practice has opened doors to gathering the data required to develop patient-specific models based on anatomical, biomechanical, aesthetic, and other derived patient-specific parameters. PSM may allow optimised surgical treatment planning, increase predictability, and potentially lower risks of pre- and post-operative complications. Recent advancements in the fields of AI may allow for the automation of several parts of these laborious modelling technologies, bringing user-assisted decision-support tools closer than ever to both clinicians and researchers. More research is still needed to develop *in vivo* protocols to enable implementation and clinical validation of PSM in dental practice. At the same time, ethical and legal constraints should be carefully considered when applying data-driven models in current clinical practice.

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Declarations

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Consent to participate Not applicable.

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