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# Biomechanical impact of tooth root morphology to inform dental implant design

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ABSTRACT

*Objective:* Using finite element analysis (FEA), this study aims to investigate the impact of different tooth root morphologies and implant designs, including a standard implant and a custom root-analogue implant on stress and strain distribution across the mandible.
*Design:* Six models were created by varying the root morphology of one tooth (the mandibular first molar) under identical loading scenarios: an original molar root, an incisor root, a canine root, a taurodont root, a standard implant, and a custom root-analogue implant replicating the original root morphology.
*Results:* Models with the original molar and custom implant exhibited similar stress and strain distributions over the mandible and had higher principal strains (tensile and compressive) compared to the single-rooted and standard implant models. Specifically, the maximum tensile and compressive strain values in the mandible of the custom implant model reach 94.89 % and 99.15 % of those in the original tooth root model. In contrast, the other models show less than 55.68 % similarity.
*Conclusions:* Custom root-analogue implants, which mimic natural root morphology, demonstrated more favourable stress distribution patterns, similar to those of the natural molar, compared to single-root implants. Our findings suggest that multi-rooted teeth are biomechanically optimized for dissipating masticatory loads, and standard single-root implants may not adequately replicate these properties, leading to poor load distribution and increased failure risk in posterior locations. Further research is needed to refine custom root-analogue implant designs and optimize their clinical application to better match the natural biomechanical environment of the maxilla and mandible.

## 1. Introduction

Mammals, including humans, require mastication to mechanically break down food, resulting in complex adaptations in tooth structure to meet dietary demands. Many studies have focused on variations in tooth crown morphology and wear patterns to understand dietary adaptations (Demes & Creel, 1988; Plavcan & Ruff, 2008; Walker et al., 1981). However, the tooth root, which connects the crown to the mandible and transmits masticatory forces through the bone, has received less attention. Tooth root morphology is highly variable, including differences in size, shape, orientation, and the number of roots, which help manage different loading scenarios (Kupczik & Dean, 2008; Kupczik & Hublin, 2010; Pérez-Ramos et al., 2019; Spencer, 2003). These structural variations are crucial for the functional stability of teeth under different forces, yet the mechanical significance of tooth root morphology remains poorly understood.

Tooth root size and surface area play a significant role in the tooth's ability to withstand mechanical loads, as observed in different primate species where variations in root size correlate with muscle activity patterns during biting (Kupczik et al., 2009; Najafzadeh et al., 2024; Spencer, 2003). Larger root surface areas help dissipate mechanical stress more effectively and are typically found in the posterior dentition where larger forces are applied. However, this can vary between species as evidenced by the Neanderthal adolescent's anterior dentition compared to an early *Homo sapiens* adolescent (Najafzadeh et al., 2024). Root length, orientation, and number are also important factors; roots aligned parallel to the force vector minimize shear and bending forces, contributing to structural stability (Kupczik et al., 2018). The presence

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of multiple roots in molars allows for better resistance to multi-directional loads, which is necessary given the complex forces experienced during mastication at the posterior dentition (Kupczik et al., 2005, 2018).

Variation in tooth root morphology is evident within and between individuals and species (Kupczik & Dean, 2008; Kupczik et al., 2005; Pérez-Ramos et al., 2019; Spencer, 2003). In humans, maxillary molars typically have three roots, while mandibular molars have two, with notable differences even among individuals (Kondo & Manabe, 2016; Zhang et al., 2018). Conditions such as taurodontism, characterised by enlarged pulp chambers and altered root bifurcation in multi-rooted teeth, illustrate such variation (Jayashankara et al., 2013; Wright, 2007). Although this condition is rare in modern humans, its functional implications, particularly in dental treatments like extraction or endodontic therapy, are debated (Jafarzadeh et al., 2008; Manjunatha & Kovvuru, 2010). Taurodontism is also prevalent in various extinct hominins, suggesting it might be an ancestral condition rather than a derived trait in modern humans (Benazzi et al., 2015; Kupczik & Hublin, 2010).

Understanding tooth root variation is crucial for dental restoration and rejuvenation, as tooth loss can significantly affect an individual's quality of life by altering nutrition and risking further dental and bone health (Gerritsen et al., 2010; Taguchi et al., 1995). Dental implants aim to replicate natural tooth function but face challenges such as the absence of the periodontal ligament (PDL), which affects load distribution and reduces the capacity for alveolar socket displacement (McCormack et al., 2017). Optimizing load transfer is critical to reducing implant failure risks, where osseointegration fails, the implant itself breaks, or there is an onset of peri-implantitis characterised by inflammation and bone loss (Falcinelli et al., 2023; Liu et al., 2020). During normal activity, such as chewing, bone will deposit, maintain (commonly referred to as the "lazy zone", where the activity of osteoblasts and osteoclasts are in equilibrium), or resorb in response to the loading environment. It is suggested that this remodelling is optimised for an individual's unique anatomy and functional activities following the "mechanostat" model of bone regulation (Buck et al., 2010; Frost, 2003). Mechanical strains can induce a signalling cascade for bone growth or resorption, where strain that is too high can lead to fracture, whereas lower strain can induce atrophy. Therefore, the mandible requires an optimum distribution to facilitate osseointegration of dental implants and minimise bone degradation or fracturing (Frost, 2003). A deeper understanding of the biomechanical function of natural tooth roots can inform the design of more effective dental implants.

Current dental implantation techniques are standardized, typically involving a fixture that screws into the bone, a cusp that superficially replicates the crown, and an abutment that connects the two (Kelekis-Cholakis et al., 2018). The fixture serves as a root replacement by drilling a hole in the mandible and inserting a threaded body to enable bone osseointegration. However, poor longevity outcomes are not uncommon in dental implants, often due to the breakdown of the tissue-implant interface (Oh et al., 2002). There are a number of proposed aetiologies for these outcomes. After implantation, loads can be much higher (up to nine times) on dental implants (Graf et al., 2022). Poorly distributed loads in current designs can lead to implant failure or bone atrophy around the implant site, particularly in the posterior dentition (Roccuzzo et al., 2009). These higher and/or incorrectly distributed loads can be due to surgical trauma and/or implant placement error (Oh et al., 2002). Furthermore, occlusal overload can cause mechanical load to be directly transferred to the mandible, due to the lack of a mechanoreceptive, shock-absorbing structure (the periodontal ligament) (Sadowsky, 2019). Given that the posterior mandible has lower bone density, with increased cortical and decreased trabecular bone, multi-rooted structures may offer improved stability in such conditions (Di Stefano et al., 2019; Ibrahim et al., 2021). Custom-made root-analogue implants, which mimic natural tooth roots, present a promising solution for improving implant success by better distributing stress across a larger surface area, enhancing aesthetics, and reducing the risk of peri-implantitis (Dantas et al., 2021, 2022; Figliuzzi et al., 2022; Liu et al., 2023; Pessanha-Andrade et al., 2018; Tribst et al., 2024). Recent advances in finite element analysis (FEA), computer-aided design (CAD), and 3D printing, have improved the design and stability of these implants, demonstrating more favourable stress distribution compared to traditional designs (Aldesoki et al., 2023; Falcinelli et al., 2023; Lee et al., 2021; Thompson & An, 2023; Tribst et al., 2024; Trivedi, 2014; Van Staden et al., 2006). Nevertheless, challenges remain in optimizing these custom implants for clinical use, particularly in ensuring proper positioning and primary stability (Aldesoki et al., 2023; Lee et al., 2020; Saeidi Pour et al., 2019). Furthermore, the vast majority of studies that evaluate root analogue implants look at single roots only (Anssari Moin et al., 2016; Dantas et al., 2020; Lee et al., 2020; Liu et al., 2020; Nimmawitt et al., 2022). Numerous studies have found that edentulism is more common in molars and premolars (multirooted teeth) than incisors or canines (single rooted teeth) (Baelum et al., 1997; Bahrami et al., 2008) Therefore, it is crucial that custom implants are evaluated for multi-rooted teeth. We also have limited knowledge about the stress or strain environment in the full mandible after implantation of a root-analogue implant, compared to the natural dentition and a standard single-root implant.

FEA provides the ability to test this virtually. FEA is a rapidly expanding tool in dentistry and in understanding the feeding mechanics in humans and their relatives (Falcinelli et al., 2023; Ledogar et al., 2016; Panagiotopoulou, 2009; Toro-Ibacache et al., 2016; Trivedi, 2014). Here, we compare the mandibular stress and strain between the natural dentition, altered tooth root morphologies (e.g., taurodontism, single roots vs. multiple roots), standardised implants, and a customised root-analogue dental implant. Our primary hypothesis is that a custom root-analogue implant will provide more optimal stress and strain distribution within the mandible, more closely resembling the natural dentition. This is with the assumption that the original dentition will provide optimal parameters during occlusion, thereby offering the safest mechanical performance. A comprehensive understanding of the biomechanical consequences of tooth root variation may also lead to better understand of the variation in teeth during human evolution and elucidate how these changes may be related to diet as well as dental anthropology and dental pathology.

## 2. Materials and methods

### *2.1. Data acquisition*

A presumed male adult *Homo sapiens* mandible specimen was obtained from the Hull-York Medical School teaching collection and scanned using a medical computed tomography (CT) scanner at the York Teaching Hospital. There are no records indicating provenance for this specimen and it is held in accordance with the Human Tissue Act (2004). This specimen was chosen as it had retained the complete mandibular dentition.

### *2.2. Model construction*

From CT, a volumetric surface was generated in Avizo Lite 9.2.0 (ThermoFisher Scientific) through automatic and manual segmentation. Semi-automatic segmentation using the Magic Wand tool was used to isolate the teeth and roots from the bone, to be able to assign different material properties to each volume. The right-side first mandibular molar (RM1) and its crown were segmented from the mandible, and the enamel crown was separated from the root following the shape of the enamel in the CT images. All loads and root modifications, detailed below, were then applied to the RM1. The RM1 was chosen because most mastication is performed on the first mandibular molar and the premolars (up to 90 %) (Broadbent, 2000), so this tooth provides a good model for masticatory function.

Modifications were made to the original model to replicate different tooth root morphologies and implant designs. Variations of the original tooth root were made to replicate a smaller tooth root like that of an incisor, a single straight tooth root like a canine, and a larger taurodont root like that of a Neanderthal. In addition, the RM1 was digitally removed and replaced with a standardised monotype implant mesh obtained from Sketchfab (Hq3dmod, 2022). The implant was composed of two separate materials: the screw fixture, and the crown. The abutment was integrated into the fixture structure to simplify the model. The mandible was then re-meshed to imitate complete osseointegration and ensure the fairest functional comparison. Finally, the morphology of a custom implant was developed from the original model as the aim was to maintain the original morphology of the tooth root and alveolar socket. The RM1 was split at the base of the crown, with a connection between the two replicating the fixture-cusp complex of the standard implant to separate into different material properties.

To maintain uniform conditions between models that represent "natural" teeth compared to implants, we have not modelled a periodontal ligament (PDL). Although the absence of a PDL in FE modelling has shown artificial stiffening (Gröning et al., 2012), we have removed the PDL as a variable for comparative purposes. Dental implants do not retain a PDL and including one in our comparative natural tooth-root model would have confounded interpretation of the results, making it difficult to determine whether differences in stress or strain was due to the geometry of the root or due to the presence of the PDL.

Following this, each surface model was simplified and smoothed to improve the triangle aspect ratio and tetrahedral quality. Triangle aspect ratios were reduced to below 10, and all other quality tests, such as ensuring there were no holes or intersecting triangles in the mesh, were all passed before generating the solid tetrahedral finite element meshes.

### 2.3. Finite element analysis

Each solid tetrahedral model was imported into Abaqus CAE (Dassault Systèmes, 2022) for finite element analysis. To reduce computational time to run the models and to ensure that results were related to changes in root morphology rather than variations in material properties, the material properties were simplified as homogenous linear elastic isotropic materials (Table 1). Bone was modelled with approximate material properties of cortical bone (Gröning et al., 2012). Dentine and enamel were averaged to model the dentition as one solid structure. The periodontal ligament was not modelled because this would not be present in the implant models. The implants were designed with two major components: the fixture and the crown. Most fixtures used in UK dentistry are titanium or Ti-6Al-4V, both of which have similar material properties (Lee et al., 1991; Osman & Swain, 2015). A preliminary sensitivity study displayed no major stress or strain differences within the model by changing material properties, so a titanium fixture and zirconia cusp was chosen due to being the most common choice in dentistry (Ban, 2021).

Muscles forces for four muscles of mastication (masseter, temporalis, medial pterygoid, and lateral pterygoid) were assigned to the model across their insertion sites and directed to the centre of the origin on the cranium with a local co-ordinate system (Fig. 1). Estimated muscle forces were simplified from Gröning et al. (2011), which calculated muscle forces for individual functional parts from the physiological cross-sectional area of each muscle and scaled these for activation of a right unilateral molar bite (Table 2).

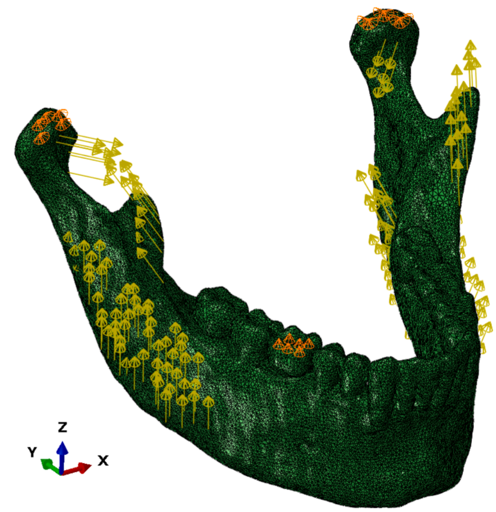


**Fig. 1. Finite element model.** Model construction in Abaqus CAE software, showing loads (yellow arrows) and constraints (orange cones).

Constraints were applied at contact points to restrict movement of the model (Fig. 1). To distribute the constraints more evenly across a surface, and to avoid the high stress artefacts generated due to single-node constraints, five nodes were selected on the left and right TMJs and six were placed on the RM1. The left TMJ was constrained against motion in all degrees of freedom and the right TMJ was constrained in the sagittal plane, enabling medial and lateral movement in line with the action of masticatory muscles, without influencing the occlusive loads on the contralateral side. This avoids over-constraining the mandible and maintains natural deformation. The RM1 was constrained in the occlusal plane only.

### 2.4. Data analysis

To assess the structural performance of the tooth crown and roots, we report a combination of stress and strain. Von Mises stress and principal strains were exported from Abaqus. Von mises stress determines the potential for a material to yield; a higher value will result in an increased likelihood of a material fracturing. Principal strain quantifies the greatest material deformation within a material. This can determine the likelihood of a material fracture or failure (Albogha et al., 2015) and, in biological materials such as bone, acts as a mechanical stimulus that influences growth, remodelling or resorption. Higher von Mises stress and strain can lead to fracture, whereas lower mechanical strain can affect biological materials by inducing atrophy, therefore, the mandible requires an optimum distribution to facilitate osseointegration and minimise bone degradation or fracturing. Comparisons were made against the original tooth due to the assumption that the natural dentition will optimise this distribution.

**Table 1**
Material properties assigned to regions of the finite element models.

| Material | Young's modulus (GPa) | Poisson's ratio |
|---|---|---|
| Bone | 17 | 0.30 |
| Teeth | 53 | 0.30 |
| Implant fixture | 110 | 0.35 |
| Implant crown | 210 | 0.25 |

**Table 2**
Muscle forces applied to each model for a unilateral molar bite.

| Muscle | Force applied (N) | |
|---|---|---|
| | Left | Right |
| Lateral Pterygoid | 27.00 | 58.50 |
| Masseter | 198.00 | 237.60 |
| Medial Pterygoid | 115.20 | 161.28 |
| Temporalis | 284.08 | 279.84 |

## 3. Results

### 3.1. Bite force

Maximum bite reaction forces ranged between 869 N in the original model, to 1268 N in the model with the custom implant (Table 3).

### 3.2. Stress and strain

All six models had near identical stress distribution (Fig. 2), with only slight differences in stress magnitude in localised areas around the RM1 root. The highest von Mises (VM) stresses occur around the alveolar socket of the loaded tooth, the mandibular notch on the ipsilateral side, the anterior edge of the ramus and the oblique line on the contralateral side, and the pterygoid favea on the contralateral side. There are mid-ranges of stress around the mental and body of the mandible on the contralateral side, but lower stress along the body on the ipsilateral side apart from directly inferior and posterior to the RM1.

Similar to the VM stress, the distribution of maximum principal strain (predominately tensile strain; Fig. 3) in the mandible was near identical between the models, with only local differences around the tooth root. Around the alveolar socket we see higher tensile strain (red colours) in the single root models (canine, incisor, and standard implant) compared to the original, taurodont, and custom implant models. The high VM stress at the anterior edge of the ramus and the oblique line on the contralateral side can be attributed to high tensile strain in this area. There is also high tensile strain on the anterior edge of the ramus on the ipsilateral side. The original model and custom implant model also have high tensile strain at the mandibular notch on the contralateral side, but this is lower in the other four models. The highest peak values of tensile strain were observed in the original and custom implant models (7800 and 7400 με respectively), whereas the other models ranged from 3700 to 4400 με.

For minimum principal strain (predominately compressive strain; Fig. 4), we also see closer similarities between the original model and the custom implant model, particularly around the body of the mandible; however, this is very minimal. For compressive strain, we can observe higher values around the mandibular notch on the ipsilateral side, and pterygoid favea on the contralateral side. In terms of peak compressive strains, the original and custom implant model are more similar to each other (both 12000 με) compared to the other models (ranging from –6000 to −8000 με).

In terms of the RM1 itself, VM stress is higher and peak principal strains are lower in both the implant models. For all models, the highest stress and strains occur at the boundary between the cusp and root, or fixture; however, stress is greater in the implants and propagates further down the fixture. The impact of tooth root variation on the surrounding teeth is most evident when comparing the single roots to the multiple root models, where the original, taurodont and custom implant produce more stress in the second premolar compared to the other models.

## 4. Discussion

Tooth root shape, orientation and number are variable between individuals and species and can be correlated with the forces experienced during mastication. However, the biomechanical impact of individual variation and what relevance this may have in the design and success of dental implants is not well understood. This study sought to look at the mechanical effect of varying the root morphology of one tooth under identical loading scenarios. We compared six finite element models, each with a different root morphology at RM1: the original molar dentition with multiple roots, an incisor tooth root, a canine tooth root, a taurodont root, a standard dental implant, and a custom root-analogue implant with the original RM1 root morphology. We found that stress distributions and strain magnitudes within the mandible were more similar between the original model and the custom implant model compared to the other models (Figs. 2–4). Specifically, the maximum tensile and compressive strain values in the mandible of the custom implant model reach 94.89 % and 99.15 % of those in the original tooth root model. In contrast, the other models show less than 55.68 % similarity. This is likely due to shape differences, since these models have the same loading scenarios and RM1 crown shape, despite the dental implant being made of a stiffer material. However, the reported strain values here are purely for comparison only, they likely do not reflect realistic values due to our simplification of muscle forces, material properties and lack of other tissues such as the periodontal ligament.

**Table 3**
Bite reaction forces (N).

| Original root | Standard implant | Custom implant | Taurodont root | Canine root | Incisor root |
|---|---|---|---|---|---|
| 869 | 1153 | 1268 | 962 | 979 | 932 |

### 4.1. Bite force

There was variation in the predicted bite forces for each model. These predictions are within the range of published molar bite forces (O'Connor et al., 2005), and the upper end of the range published for men who experience bruxism (Ikebe et al., 2005; Pellizzer et al., 2011; Waltimo et al., 1994). However, our estimates are relatively high compared to other studies (Stansfield et al., 2018; Toro-Ibacache & O'Higgins, 2016). This is likely due to a variety of modelling factors: we have applied estimated maximum muscle forces, the models do not feature periodontal ligaments, and the material properties for the implants are stiffer than natural dental material properties. Stiffer material properties for both implant models lead to higher resultant bite forces due to the transmission of muscle force to the biting tooth with less deformation of the implant. Furthermore, a much higher resultant bite force is consistent with research that has found that loads have been reported up to nine times higher on dental implants (Graf et al., 2022).

### 4.2. Tooth root variation and biomechanics

The overall stress and strain distributions across different models appear similar when comparing across the whole mandible (Fig. 2). However, our results highlight how subtle variations in root structure can affect strain magnitudes and stress distribution in localized areas, particularly around the tooth root. The original molar root model and the custom root-analogue implant demonstrated higher tensile and compressive strains in the mandible, but the distribution was more evenly spread and not as concentrated around the alveolar socket compared to the single root models. These findings support the hypothesis that multi-rooted teeth like molars are biomechanically optimized for resisting high masticatory forces, as the multiple roots help distribute stresses more effectively throughout the surrounding bone due to the increased surface area and more complex root architecture (Najafzadeh et al., 2024; Spencer, 2003). These results align with other findings that multi-rooted molars provide enhanced stability and load distribution under functional loads compared to single-rooted teeth like incisors and canines (Kupczik et al., 2005, 2018; Tokmakidis et al., 2009). The localized differences in stress magnitude observed around the RM1 root in all our models suggest that even minor variations in root form, such as those seen in taurodont teeth, can lead to changes in the mechanical environment of the mandible, with potential implications for both dental evolution and clinical practice.

An individual bones shape is, at least in part, determined by the mechanical environment that it is placed under over time (Frost, 2003). Furthermore, it has been shown that, not only can the alveolar process "follow" the movement of the teeth (as in orthodontic braces) but has the highest bone turnover in the skeleton (Jonasson et al., 2018). Therefore, we can assume that the mandible in individuals who have

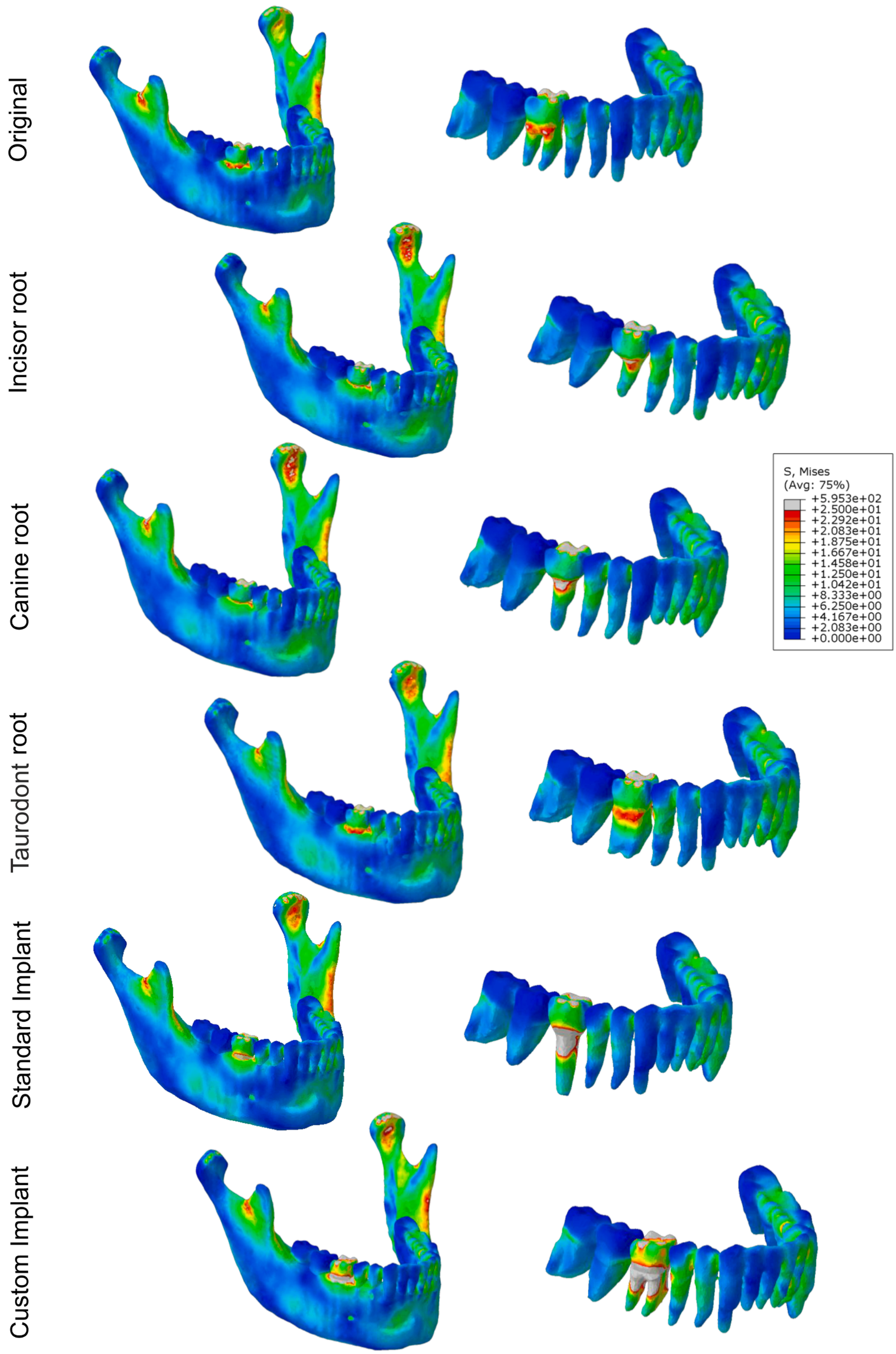


**Fig. 2. Von Mises stress distribution plots.** Full mandibles are shown on the left and isolated teeth showing the tooth roots are viewed on the right. Low areas of stress are coloured in blue and high areas are red; grey is beyond the maximum set with the scale.

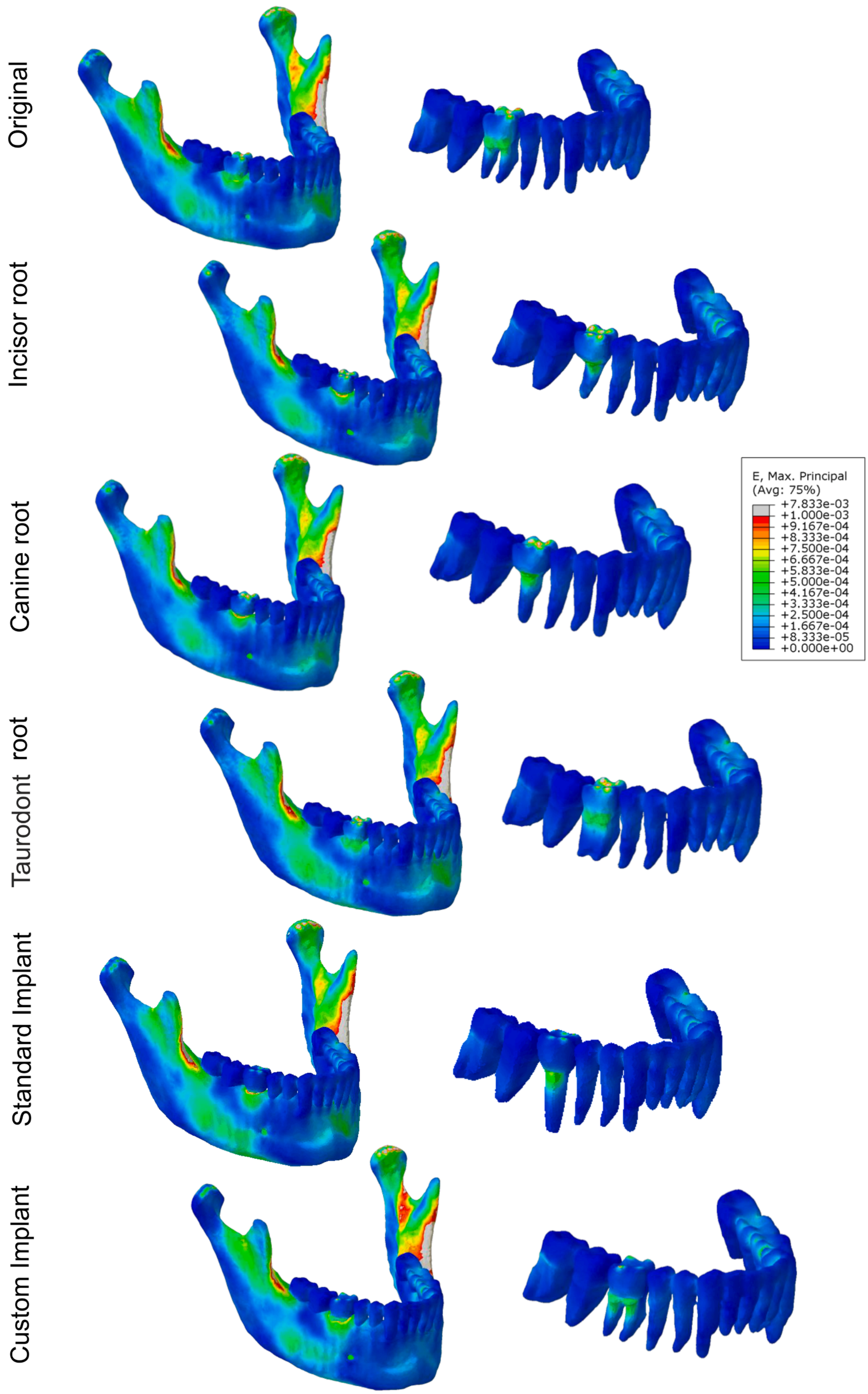


**Fig. 3. Maximum principal strain (predominantly tension) distribution plots.** Full mandibles are shown on the left and isolated teeth showing the tooth roots are viewed on the right. Low values of tension are coloured in blue and high values are red; grey is beyond the maximum set with the scale.

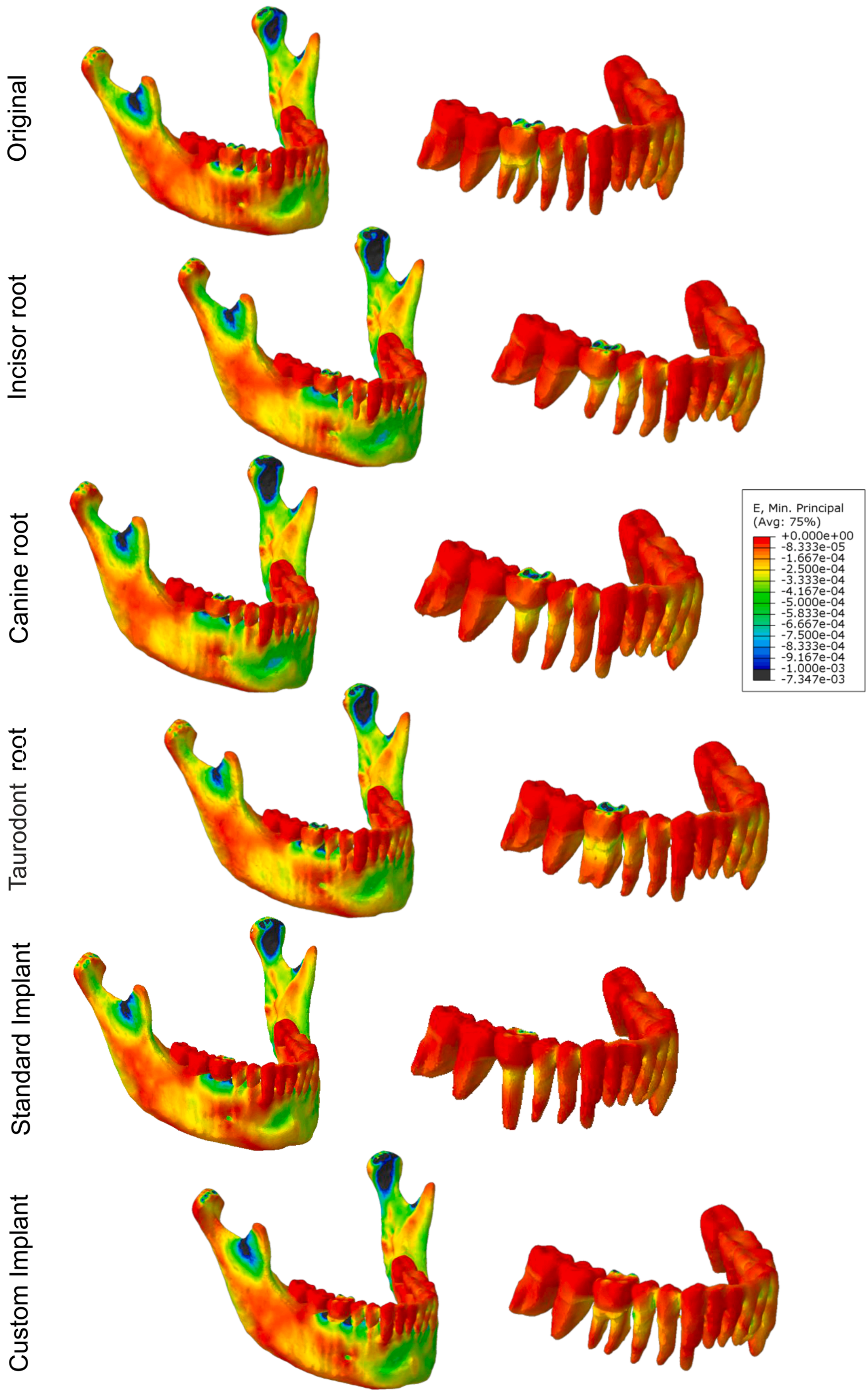


**Fig. 4. Minimum principal strain (predominantly compression) distribution plots.** Full mandibles are shown on the left and isolated teeth showing the tooth roots are viewed on the right. Low values of compression are coloured in red and high values are blue–black.

lived with anatomical variants in their tooth roots (such as taurodontism) is locally adapted to that particular root form. Our work suggests that introducing a root implant shape that does not mimic the original tooth root form may result in a mechanical environment that the mandible is not adapted to.

### 4.3. Dental implants and custom root-analogue implants

Dental implants aim to mimic natural tooth function and structure; however, the standard designs often fail to replicate the complex biomechanical environment created by natural tooth roots, particularly in multi-rooted teeth like molars and premolars. Standard implants typically consist of a single screw-type fixture that resembles the root structure of single-rooted teeth, which may not be well-suited for the posterior dentition where multi-rooted teeth normally exist (Tokmakidis et al., 2009). This could explain the higher failure rates observed in the posterior dentition, where the changes between the implant design and the natural biomechanical environment results in poor load distribution and poor bone remodelling (Fischer et al., 2024; Hossain et al., 2023; Tribst et al., 2024).

Custom root-analogue implants, which are designed to replicate the original tooth root morphology, offer a promising alternative for addressing these biomechanical shortcomings. Our results show that the custom implant model, which replicates the original molar root structure at RM1, exhibited stress distributions and strain magnitudes more closely aligned with the natural tooth model. Notably, both the original and custom implant models showed the highest values of tensile strain in the mandible (7800 με and 7400 με, respectively) and similar compressive strain magnitudes, suggesting that replicating natural root geometry can achieve a more favourable, individualized biomechanical environment compared to standard implant designs (Pessanha-Andrade et al., 2018; Tribst et al., 2024). This is consistent with findings from other studies indicating that custom-made root-analogue implants provide better stress distribution and can reduce the risk of peri-implantitis by promoting a more natural load transfer to the surrounding bone (Lee et al., 2020; Saeidi Pour et al., 2019). Furthermore, the similarity in the strain distribution between the custom and original models suggest that the remodelling environment may be similar between the two, which is a promising outcome when considering bone remodelling around an implant. Although these maximum strains are high, other finite element studies have found similarly high maximum strains (Marcián et al., 2018) and they likely represent a small fraction of overall strain values.

A factor that should be considered for custom root-analogue implants is the intraspecific variation found in tooth roots, particularly in the molars. Taurodont roots, for example, are relatively rare but are comorbid with a large range of genetic disorders and found in higher percentages in certain genetically isolated populations (Constant & Grine, 2001; Manjunatha & Kovvuru, 2010). The mandible in individuals with these root variations will be adapted to its specific stress/strain environment, which we have shown to be affected by the shape and size of the tooth root. Therefore, it may be more optimal for an individual if an implant mimics the specific tooth root shape they had originally. The implications for implant design are significant. Custom root-analogue implants, fabricated using advanced techniques such as CAD/CAM and 3D printing, can be tailored to the patient's unique anatomy, improving the fit, stability, and long-term success of the implant (Lee et al., 2022; Liu et al., 2020). However, while the custom implants demonstrated more natural stress distributions, similar to the original tooth models, challenges remain in optimizing their clinical application, particularly in ensuring accurate positioning and primary stability, as well as minimizing potential stress concentrations that could lead to bone resorption or implant failure (Tribst et al., 2024). The feasibility of dental implants as a primary treatment option for tooth loss is restricted to cases where the individual is periodontally healthy or is in stabilised periodontal condition (to provide sufficient bone support), is not immunocompromised, allowing for normal bone healing and does not have unfavourable patient habits such as bruxism or smoking (Tolstunov, 2006). Furthermore, in the case of multi-rooted custom implants, tooth extraction would likely become challenging, as there would need to be some congruence with between the socket wall and the implant (Dantas et al., 2020). Further research is needed to refine these designs and better understand how different modifications to root-analogue implants might influence their biomechanical performance and clinical outcomes.

While this study offers valuable insights, it is important to consider several limitations that may inform the interpretation of results. Our models were relatively simple in that they did not distinguish between cortical and trabecular bone or include structures such as cementum, a pulp chamber or a periodontal ligament. These modelling simplifications permitted the comparison of non-implant and implant models by removing structural variables that would not be present in an implant. Although the stress and strain values produced by our models are within ranges found in the literature (Marcián et al., 2018), the omission of these structures may mean that raw values are potentially not realistic, particularly around the tooth socket. Furthermore, the specimen used to generate the models is a healthy, adult male. However, conditions such as osteoporosis and aspects of periodontitis (e.g., clinical attachment loss), which are associated with tooth loss, are more likely to affect aging populations and complicate the implantation of dental prostheses (Billings et al., 2018).

## 5. Summary

The design of dental implants has evolved significantly over the years, moving from standardized, one-size-fits-all solutions to more patient-specific approaches that aim to better mimic the natural anatomy and biomechanics of teeth (Dantas et al., 2021; Figliuzzi et al., 2022; Hossain et al., 2023). This study is the first to analyse the stress and strain of the mandible with different implant designs and root morphologies under loads from the jaw muscles. We conclude that custom-made root-analogue implants, which replicate the natural tooth root's morphology, have distinct advantages over traditional screw-type implants, particularly when replacing teeth in the posterior dentition where multi-rooted molars are important for distributing loads from chewing. By better replicating the natural root morphology and optimizing load distribution, custom implants may overcome the limitations of standard designs by improving force propagation, minimising bone loss and increasing osseointegration of the implant. This study underscores the importance of tooth root variation in understanding mandibular biomechanics and highlights the potential benefits of custom root-analogue implants in improving dental restoration outcomes. Future work should focus on further refining these custom implants, exploring new designs, and validating their clinical efficacy through long-term studies.

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## CRediT authorship contribution statement

**Amber P. Wood-Bailey:** Writing – review & editing, Writing – original draft, Methodology, Investigation, Formal analysis. **Laura C. Fitton:** Writing – review & editing, Supervision, Methodology, Data curation, Conceptualization. **Chris Smith:** Writing – review & editing, Writing – original draft, Formal analysis. **Sharp Alana C:** Writing – review & editing, Writing – original draft, Supervision, Project administration, Methodology, Investigation, Formal analysis, Conceptualization.

## Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

## Data availability

The tooth implant model used for this study is available on Sketch-Fab (Hq3dmod, 2022) for download. All other original data, including finite element models can be requested from the Corresponding Author.

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