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Biomechanical investigation into the role of the periodontal ligament in optimising orthodontic force: a finite element case study

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ABSTRACT

Objectives: This paper aimed to precisely locate centres of resistance (CRe) of maxillary teeth and investigate optimal orthodontic force by identifying the effective zones of orthodontic tooth movement (OTM) from hydrostatic stress thresholds in the periodontal ligament (PDL).
Methods: We applied distally-directed tipping and bodily forces ranging from 0.075 N to 3 N (7.5 g to 300 g) onto human maxillary teeth. The hydrostatic stress was quantified from nonlinear finite element analysis (FEA) and compared with normal capillary and systolic blood pressure for driving the tissue remodelling. Two biomechanical stimuli featuring localised and volume-averaged hydrostatic stresses were introduced to describe OTM. Locations of CRe were determined through iterative FEA simulation.
Results: Accurate locations of CRes of teeth and ranges of optimal orthodontic forces were obtained. By comparing with clinical results in literature, the volume average of hydrostatic stress in PDL was proved to describe the process of OTM more indicatively. The optimal orthodontic forces obtained from the in-silico modelling study echoed with the clinical results in vivo.
Conclusions: A universal moment to force (M/F) ratio is not recommended due to the variation in patients and loading points. Accurate computational determination of CRe location can be applied in practice to facilitate orthodontic treatment. Global measurement of hydrostatic pressure in the PDL better characterised OTM, implying that OTM occurs only when the majority of PDL volume is critically stressed. The FEA results provide new insights into relevant orthodontic biomechanics and help establish optimal orthodontic force for a specific patient.

1. Introduction

Orthodontic tooth movement (OTM) has been widely thought to occur due to compression and tension within the surrounding tissues generated by orthodontic appliances, which was traditionally documented as the classic "pressure-tension" theory (Schwarz, 1932). In this physiological process, the periodontal ligament (PDL) plays a crucial role in regulating OTM as the microvasculature and blood flow contained within the PDL may be partially or completely occluded due to its exposure to certain level of pressure, hence adjusting the periodontal interstitial fluid (Jones, Hickman, Middleton, Knox, & Volp, 2001; Middleton, Jones, & Wilson, 1996). This can cause the dysfunction or necrosis of PDL tissue, followed by a cascade of events directing OTM via recruitment of osteoclasts and osteoblasts and release of RANKL, TGF-β and OPG (Meikle, 2006; Roberts-Harry and Sandy, 2004). There have been a number of clinical studies addressing the challenges of obtaining the "ideal" orthodontic forces for OTM (Boester & Johnston, 1974; Storey & Smith, 1952). However, no general consensus has been available to date, particularly with the associated fundamental biomechanics.

It has been proposed on the basis of several clinical experiments and biomechanical studies that external pressure comparable to capillary blood pressure of 4.7 KPa (35 mmHg) can be a stimulus to initiate OTM and root resorption (Chen, Li, Swain, Darendeliler, & Li, 2014; Dorow & Sander, 2005; Hohmann et al., 2009; Hohmann et al., 2007), while other studies adopted a higher pressure of 16 KPa (120 mmHg), namely the human systolic pressure, as an indicator for predicting PDL tissue necrosis and hyalinisation (Choy, Pae, Park, Kim, & Burstone, 2000; Rygh, 1973). It has also been hypothesised that hydrostatic stress higher than the capillary blood pressure may start to induce PDL occlusion and dysfunction to some degree (Chen et al., 2014; Field et al., 2009; Hohmann et al., 2007). Nevertheless, the capillary blood vessels may not collapse completely under this pressure. When the pressure rises to the systolic pressure, it exceeds the physiological upper limit and can

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lead to complete occlusion (Choy et al., 2000; Hohmann et al., 2009; Kondo, 1969). When the pressure rises to a certain level, the rate of OTM can possibly be plateaued or even decreased (Choy et al., 2000; Rygh, 1973; Storey & Smith, 1952). However, there has been no exact quantitative linkage and correlation between the turning point of OTM deceleration and the stress or pressure state in the PDL. It is therefore imperative to introduce such a quantitative reference for orthodontic therapies. The abovementioned thresholds, i.e. 4.7 KPa (capillary blood pressure) and 16 KPa (human systolic pressure) were adopted herein as the hypothesised simulative quantities that act as the lower and upper thresholds for suggesting an optimal level of orthodontic force.

The incorporation of 3D finite element (FE) method enables to quantify important biomechanical data for more accurate analysis of dental structure and manipulation of OTM that may be hardly achieved from clinical studies (Field et al., 2009; Jones et al., 2001; Knox, Jones, Hubsch, Middleton, & Kralj, 2000; Middleton et al., 1996; Middleton, Jones, & Wilson, 1990; Rungsiyakull et al., 2014; Rungsiyakull, Li, Sun, Li, & Swain, 2010). For example, precise localisation of the centre of resistance (CRe) and the centre of rotation (CRot) for a required tooth movement may not be easy due to considerable variation in individual tooth and bony anatomy. A CRe is an important reference point through which a force is applied so that the tooth moves without rotation (i.e. pure translation). A CRot is the point with respect to which the rotation occurs. Simulation and clinical conduct of a pure translation of tooth without tipping remain a demanding task in orthodontics and largely rely on clinical experience or the estimation of CRe by approximating 40% from the alveolar crest to the length of tooth root (Burstone, 1982; Provatidis, 1999). For this reason, several computational modelling methodologies have been introduced to estimate the locations of CRe and CRot, thereby helping achieve desirable OTM in an effective way (Burstone, 1982; Provatidis, 1999; Vollmer, Bourauel, Maier, & Jager, 1999). Although it has been educated and reported that the estimation of CRes and hence moment to force (M/F) ratio should be based on tooth movement type and morphological variation of teeth (Choy et al., 2000; Lindauer, 2001), very few systematic and widely-used method of accurate CRe estimation was provided. To date, no general agreement in terms of accurate or universal CRe for each tooth has been made owing to the variation of the teeth morphology from patient to patient. As a result, it is challenging to provide a universal or general range of optimal orthodontic forces determined by considering detailed biomechanical responses in the PDL and alveolar region. Therefore, from biomechanical perspective, precise localisation of CRe in a patient-specific manner is considered critical to estimating the optimal orthodontic forces.

This paper aims to construct an anatomically accurate 3D human maxilla model based on clinical CT images and computationally investigate the optimum orthodontic forces in mesiodistal tipping and translational directions on maxillary teeth, via introducing an active spectrum of orthodontic force in relation to the mechanical stimulus namely hydrostatic stresses for OTM.

2. Materials and methods

2.1. Finite element modelling

An anatomically accurate maxilla model was constructed based on CT images of an average subject with a resolution of approximately 0.2 mm/pixel. ScanIP 4.3 (Simpleware Ltd., Exeter, UK) was utilised to process the CT images. The CT images were segmented by defining thresholds for different tissues in terms of the greyscale values, and then refined and contrasted by applying filters. The resultant maxilla model comprised a full set of maxillary teeth, adjacent PDLs with thicknesses ranging from 0.2 mm to 0.4 mm (Chandra et al., 2007), sectioned alveolar bone and surrounding cortical bone, as displayed in Fig. 1a. Two unerupted wisdom teeth of the subject were not included in this model for simplicity (Sarrafpour, Swain, Li, & Zoellner, 2013).

The surface models were imported into Rhinoceros (Robert McNeel & Associates, Seattle, US) for further processing. The patch boundary structures were generated from contour and boundary lines, based on which the ordered grids were created within every patch on the object, leading to the creation of non-uniform rational basis spline (NURBS) surfaces (Fig. 1c). The processed surfaces

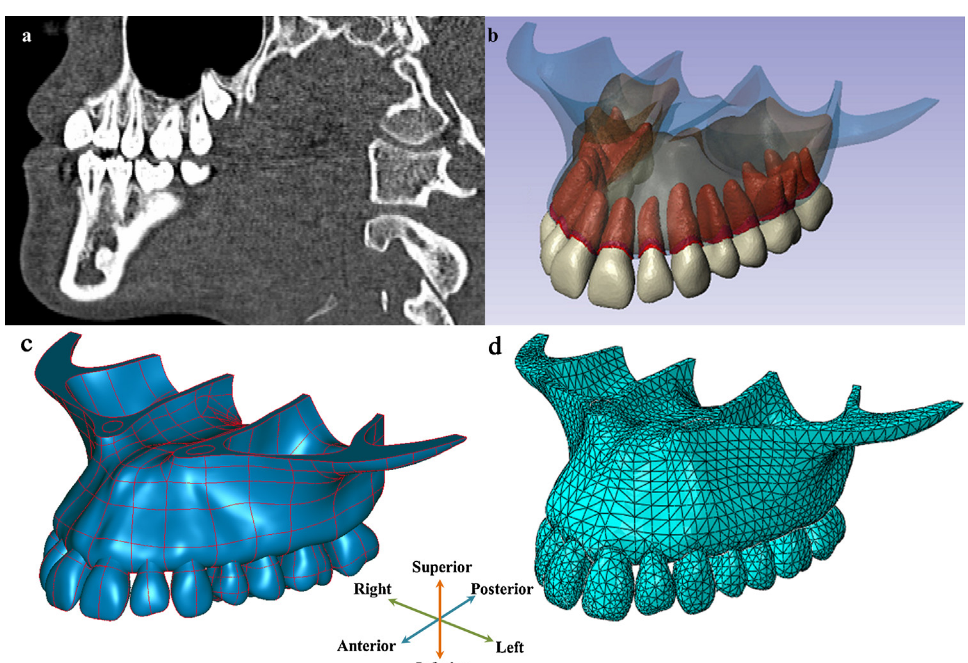

Fig. 1. CT based maxillary modelling: (a) DICOM images processed and segmented in ScanIP; (b) Masks generated for dental each dental material in ScanIP; (c) NURBS surfaces created in Rhinoceros; (d) Full meshed FE model in Abaqus.