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· 综述 ·

打开咬合的三维有限元分析的研究进展

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【摘要】 深覆殆是临床常见的错殆畸形,对患者颜面、咬合功能都有较大影响。打开咬合是治疗深覆殆的关键步骤,对下颌骨的正常发育和治疗的顺利进行有决定性作用。如何在打开咬合的同时兼顾前后牙转矩、轴倾度的控制是正畸领域的热点。三维有限元方法可以精确模拟临床现象并进行动态受力分析。微种植体为打开咬合中支抗控制等问题提供了新的思路,有限元分析发现高位微种植体更易整体压入前牙。对于摇椅弓的有限元模拟则发现其对前牙的压低及唇倾作用随着弓丝角度的增加而增加。隐形矫治器在打开咬合中的应用也日渐受到重视,但其作用力尚难以有效控制,关于其附件设计及相应牙齿移动方式的有限元研究有助于快速有效地打开咬合。但现有的有限元建模精确性不够,研究多针对于初始位移,缺乏对于骨改建后的长期牙移动的研究,未来有待进一步研究和完善。

【关键词】 深覆殆; 错殆畸形; 打开咬合; 正畸牙移动; 三维有限元分析; 生物力学; 微种植体; 摇椅弓; 隐形矫治器; 转矩

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Research progress on the three-dimensional finite element analysis of bite opening CHENG Lanxin, LIU Jun.
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【Abstract】 Deep bite is a common clinical malocclusion that has a great impact on patients' facial aesthetics and oral function. Bite opening is the key step in the treatment of deep bite, playing a decisive role in the development of mandible and the progress of orthodontic treatment. Torque and tip control during the correction of deep bites is a hot topic in orthodontics. The three-dimensional finite element method can accurately simulate clinical processes and conduct dynamic stress analysis, which provides the basis of the biomechanical mechanism. This paper reviewed the finite element analysis of various orthodontic systems for bite opening to provide a reference for clinical application. The emergence of mini-implants provided a new idea for anchorage control in bite opening. Finite element studies found that high-positioned mini-implants are beneficial for bodily tooth intrusion and proposed the ideal position for force application. For the finite element simulation of the reverse curve archwire, it was found that the intrusion and inclination of the anterior teeth increased with the curve depth of the archwire. The application of clear aligners has also been flourishing, but these forces are still difficult to effectively control. Finite element studies on their attachment design and corresponding tooth movement may be helpful to open the bite quickly and effectively. However, the existing studies still have modeling limitations. The structural simplification, linearization and nonstandard parameter definition of the model reduce model accuracy. Additionally, the existing research mostly focused on initial tooth movement, and studies on long-term tooth movement after bone remodeling are lacking. These studies are needed in the future.

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【Key words】 deep bite; malocclusion; bite opening; orthodontic tooth movement; three-dimensional finite element method; biomechanics; mini-implant; reverse curve archwire; clear aligner; torque

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深覆殆是临床常见的一种错殆畸形,表现为上前牙覆盖下前牙冠长的1/3以上或下前牙咬合在上前牙舌侧且1/3以上。深覆殆的矫治是大多正畸患者矫治过程中的首要步骤,而在深覆殆的矫治过程中,打开咬合是关键的一步。前牙间紧密咬合的关系限制了下颌的位置,并抑制了生长期患者的下颌生长,成功打开咬合对下颌骨的正常生长发育和矫治的顺利进行起到决定性作用,而这一时期也需要在控制前后牙垂直向高度的同时兼顾到转矩、轴倾度,以获得最佳的咬合、唇齿关系。常用的打开咬合途径有上下颌前牙的压入、唇倾,后牙的升高,以及正颌手术增加下前面高等^[1]。传统的打开咬合的方法有摇椅弓、压低辅弓等,但在临床中常出现前牙转矩丢失等现象,完善的生物力学研究有助于力系的合理应用。近年来,微种植体支抗应用日益广泛,对打开咬合的牙齿移动方式及支抗控制产生了重要影响。隐形矫治技术对压低前牙效果较好,但应用于临床时间尚短,其作用力复杂,常会出现不受控制的牙齿移动。三维有限元分析通过把研究对象看作是由有限个单元相互连接而成的离散体,建立数学平衡方程,可对物体密度、形状等各数据进行精确还原并进行受力分析^[2],已成为口腔生物力学研究领域的重要分析工具。三维有限元分析是体外应力分析中唯一将牙周膜纳入研究的方法,模型构建的生物相似性较高^[3]。本文对打开咬合的各装置相关的三维有限元分析研究作一综述,分析各装置作用下牙齿的应力变化及位移趋势,为临床应用提供参考。

1 微种植体

微种植体支抗是一种近年广泛发展的正畸支抗技术,可作为绝对支抗辅助压低前牙、打开咬合,避免不必要的牙齿移动如倾斜、伸长,实现牙齿垂直向控制^[4]。相比于传统压低上前牙的方法,微种植体支抗疗效好、疗程短、患者依从性高^[5]。Kushwah等^[6]建立微种植体支抗联合舌侧矫治系

统内收压低上前牙的有限元模型,分析不同高度微种植体支抗压低上前牙时其位移趋势及应力变化,发现微种植体支抗作用下前牙仍表现冠舌向的负转矩,微种植体支抗高度的增加有助于消除负转矩。Shyagali等^[7]利用三维有限元分析研究不同长度微种植体支抗辅助舌侧矫治压低上前牙时骨皮质的应力分布,提出6 mm的微种植体支抗在舌侧矫治系统中使用较合适。高位植入的微种植体更有利于上颌前牙的整体压入移动,同时牵引钩高度的变化也对前牙的移动方式有影响^[8]。Kojima等^[9]利用三维有限元分析研究发现,对于低位微种植体支抗,增加牵引钩臂的长度有助于力线通过阻抗中心,牙齿更容易实现整体移动,同时其垂直分力可有效压低前牙。长臂牵引钩和高位微种植体支抗有助于牙齿的整体移动,然而易引起黏膜激惹,造成患者不适。关于微种植体具体位置的制定,Namburi等^[10]提出距牙冠中心10 mm可能是一个合适的高度。Mauricio等^[11]建立了不同位点微种植体支抗内收上前牙的三维有限元分析模型,提出在双侧尖牙远中各植入1枚微种植体支抗即可产生均匀的牙周应力,但具体植入部位应根据临床条件如骨量、牙龈附着水平决定。

Hedayati等^[12]建立微种植体支抗整体内收及压低上颌前牙的全牙列三维有限元分析模型,分析植入不同高度微种植体支抗施加压低力后上颌前后牙的生物力学效应,发现微种植体支抗与牵引钩的相对垂直距离决定了对前牙区的伸长或压低作用,但并未对后牙区的应力、位移等做进一步研究。Ifter等^[13]运用三维有限元分析评估微种植体支抗压低后牙的效应,发现第一前磨牙根尖区和第一磨牙近中根尖区的应力水平较高,这些部位在临床上应被视为易于吸收的部位。Mo等^[14]还应用三维有限元分析研究了仅使用微种植体支抗联用Gable曲,无需在后牙粘接矫治器即可整体内收压低前牙的情况,得到了理想的前牙压入模拟情况,但临床是否可行尚需进一步验证。

2 摇椅弓

摇椅弓通过后牙的伸长及其引起的下颌平面的后下旋转、前牙的压入及少量前倾来打开咬合。Gyawali等^[15]建立摇椅弓施行舌唇侧矫治打开咬合的三维有限元分析模型,发现摇椅弓可很好地完成切牙压入,但会造成磨牙远中斜,牙齿受到的应力随摇椅弓深度的增加而增加,并且舌侧矫治中应力更大,更易造成牙齿创伤,应适当减小曲度。摇椅弓联合微种植体支抗也在临床应用较广。安晓莉等^[16]建立摇椅弓联合微种植体支抗整体内收并压低上颌前牙的三维有限元分析模型,微种植体支抗的支抗保障有利于摇椅弓对上前牙施加冠唇向转矩,从而打开咬合,并减少不利的牙齿旋转倾斜。随摇椅弓角度增加,前牙冠唇向转矩增加,而后牙的升高作用逐渐明显。

3 局部弓加辅弓

局部弓加辅弓是通过在主弓丝上结扎长的辅弓,额外的控制力可控制后牙垂直向支抗,同时持续轻力可将前牙绝对压入来打开咬合,尤其适于露龈微笑的患者,但可能造成前牙转矩的丢失^[17]。Ahuja等^[18]建立了局部弓加压低辅弓的三维有限元分析模型,分析了各部分应力及牙齿各方向位移,发现其产生了较大且均一的压低力,同时产生较大的磨牙后倾移动趋势,能产生较强的支抗作用。但由于辅弓力臂较长,各方向的分力较轻,因此认为唇颊肌的力量在压低前牙过程中的作用也不容忽视,其机理尚需进一步探索。De Brito等^[19]建立了类似三维有限元分析模型,改变压低辅弓悬臂的位置以研究施力点对前牙压入力的影响,发现当施力点位于尖牙牙冠中心远中2 mm时,前牙呈现出单纯的压低,而近远中向移动该施力点则会造成前牙相应的舌向及唇向倾斜;同时发现压低前牙的反作用力主要作用于第一磨牙上,临床上使用片段弓时应关注第一磨牙支抗丢失的情况。

4 隐形矫治器

隐形矫治技术(clear aligner therapy, CAT)是基于计算机模拟牙齿各运动阶段,利用一系列透明塑料矫治器逐步引导牙齿排齐,因其美观、方便的特点受到越来越多患者的喜爱。研究发现隐形矫治器擅长深覆殆的矫治,可有效打开咬合^[20]。Gupta等^[21]建立了上颌中切牙的三维有限元分析

模型,研究CAT不同类型移动方式时牙周膜的应力分布情况,发现压入移动时根尖受到较大的应力,有牙根吸收的风险。Kim等^[22]对下颌尖牙进行三维有限元分析,研究不同位置附件压入尖牙的效果,发现舌侧附件更有利于转矩和轴倾度的控制。Hong等^[23]进行相似的研究则发现附件可防止牙冠近远中向的倾斜和轴向的旋转,但对于牙冠的舌倾没有预防作用。Seo等^[24]建立全牙列有限元模型,研究不同厚度隐形矫治器打开咬合时牙齿牙周膜的应力分布情况,发现0.75 mm厚的矫治器较0.5 mm产生的载荷较高,并且更适于整体移动。Liu等^[25]建立拔除第一前磨牙后使用CAT内收压低切牙的模型,对照研究微种植体支抗和弹性牵引的效应,发现CAT在内收前牙的时候可能会造成前牙的舌倾和伸长,而前牙区植入微种植体支抗并配合弹性牵引可以达到前牙的压低和根舌向转矩的控制,并且施加于舌侧的弹性牵引更不易引起前牙的开殆。

CAT尚难以控制牙齿的精确移动,对于前牙转矩和后牙支抗的控制技术始终是难点。Jiang等^[26]对受试者进行上颌骨及牙列的三维有限元重建,并建立隐形矫治器的模型进行前牙的内收及压低,发现前牙出现不受控制的倾斜移动,尖牙伸长而后牙也出现了一定的近中移动,出现了支抗的丢失。

5 上颌平面/斜面导板

低角型患者常采用平面导板打开咬合,而斜面导板还可改善上下颌矢状向不调。过往研究多为头影测量的静态分析^[27],也有建立3D模型用于分析咬合力对导板影响的研究。Dai等^[28]建立三维有限元分析动态咀嚼模型研究不同厚度平面导板对前牙的作用,发现打开咬合时,下切牙受到20 g的压入力最为理想,提出3 mm厚的导板可能较适于临床应用。

6 口外装置

J钩、高位口外弓等口外装置可以绝对压入上前牙,但相关三维有限元分析研究较缺乏。Maruo等^[29]通过三维有限元分析研究头帽作用下牙齿的移动趋势,分析不同高度牵引钩对于牙齿的作用力,发现高位口外弓造成前牙压入量最大,而低位口外弓可能造成前牙伸长。对于后牙则均能造成一定程度的磨牙远移,其中低位口外弓能产生最

大程度的磨牙远移及第一磨牙舌尖及远中颊尖的伸长。

7 现有研究的局限性

7.1 模型的局限性

由于牙列形态复杂,而三维有限元分析受到算法等限制,往往将模型进行简化,而且对于边界条件的定义模糊,文献之间的差异极大,有必要进行相关研究以设计简便但精确的建模方法。现有的三维有限元分析也主要采用线性分析,非线性模型虽然更符合现实情况,真实性、精确性更高,但计算难度大为增加,应用较少^[30]。现有的建模方法对创伤负荷条件下的研究处于空白状态,对于牙齿等结构也常用抛物面、圆柱体等代替,难以精确重建牙齿^[31]。但有学者^[32]也指出,简化的有限元模型也足以满足主要目标。

7.2 初始位移的局限性

现有研究多针对于初始位移,仅考虑牙周膜弹性形变产生的牙齿移动,对于治疗期间长期的牙齿移动反应效果有限。Jang等^[33]通过原位生物力学模拟牙齿的长期位移,研究应力调节下的细胞生化反应,发现牙周膜在其中起到重要的作用。Kojima等^[34]提出一种对继发位移的研究方法,根据骨改建率与牙周膜平均应力成正比,通过单位应力推算骨吸收量、牙移动量,得出牙齿移动前后的位置。

8 小结

三维有限元分析对临床情况的模拟效果较为真实,可准确分析各加力过程中牙齿的移动情况和牙周膜的应力分布特征,从而分析牙齿移动趋势,为探寻打开咬合时更理想的施力方式提供了研究条件。打开咬合相关的有限元研究主要聚焦于各装置作用下牙齿的受力和位移情况,但现有研究仍存在建模的局限性,未来有待进一步完善,为正畸生物力学提供理论基础。

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