[DOI]10.12016/j.issn.2096-1456.2024.03.004　· 基础研究 ·

种植钉植入高度对隐形矫治远移下磨牙时应力分布的影响

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【摘要】　目的　探究种植钉不同植入高度对隐形矫治配合颌内牵引远移下磨牙时所产生的生物力分布的影响，寻找有利于保护下前牙支抗的种植钉植入位置，为临床治疗方案的设计提供参考。**方法**　应用Mimics、Geomagic Studio 2017、SolidWorks2016、Ansys workbench建立有限元分析模型并对六种工况进行力学分析。工况一：无种植钉（对照组）；工况二至工况五：种植钉植入于下颌第一磨牙和第二磨牙之间的颊侧骨皮质，距离牙槽嵴顶分别为10 mm、7 mm、4 mm、1 mm；工况六：种植钉植入于下颌升支前缘颊舌向居中，高于𬌗平面5 mm的位置。**结果**　矢状向，种植支抗使所有牙齿均产生远中向位移；相较于对照组，种植钉组前磨牙远中位移量超过第二磨牙。垂直向，对照组（无种植钉）为类似后倾弯对下颌牙列产生的作用；种植钉组侧切牙、尖牙压低，中切牙、第一前磨牙伸长。冠状向，对照组（无种植钉）第二前磨牙、第一磨牙为舌向位移，种植钉组仅前磨牙及第一磨牙出现了舌向位移；所有牙齿中，尖牙的位移量受种植钉植入高度变化影响最大。**结论**　种植钉植入位置越高，保护前牙支抗的效果越强。方案设计时应根据种植钉植入高度，适当使下颌牙弓缩窄，中切牙、第一前磨牙压低及侧切牙、尖牙伸长。

【关键词】　下颌骨；　错𬌗畸形；　正畸；　无托槽隐形矫治器；　支抗；　微螺钉种植体；　牙齿应力分析；　有限元分析

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Effect of miniscrew placement height on the distribution of biological forces produced by clear aligner for mandibular molar distalization

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【Abstract】　Objective　To explore the effect of different miniscrew placement heights on the distribution of biological forces produced by clear aligner combined with intramaxillary traction for mandibular molar distalization, to identify the miniscrew location that is conducive to the protection of lower anterior tooth anchorage and to provide a reference that can be used when designing clinical treatments. **Methods**　Mimics, GeomagicStudio 2017, SolidWorks 2016, and Ansys workbench were used to establish finite element analysis models and perform mechanical analysis under the following six working conditions: working condition 1 was the control group without miniscrews; working conditions 2 to 5 had miniscrew in the buccal bone cortex between the first and second molars of the lower jaw 10 mm, 7 mm, 4 mm, and 1 mm from the top of the alveolar crest, respectively; working condition 6 had the miniscrew in the center of the buccal tongue at the anterior edge of the ascending branch of the lower jaw 5 mm above the occlusal plane. **Results**　On the sagittal axis, miniscrew anchorage caused distal displacement of all teeth. Compared to the control group, in the miniscrew group, the displacement of the anterior molars exceeded that of the second molars. On the vertical axis, the

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result in the control group was similar to backward bending; the results in the miniscrew groups resembled the effect of a lever, lowering the lateral incisors and canines and raising the central incisors and first premolars. On the coronal axis, the second premolars and the first molars showed lingual displacement in the control group, and only the premolars and first molars showed lingual displacementin the miniscrew groups. The canines were the teeth that were most strongly affected by the change in miniscrew placement height. **Conclusion** The higher the miniscrew position is, the stronger the protective effect on the anterior anchorage. According to the miniscrew placement height, the mandibular arch should be properly narrowed, the central incisors and first premolars should be lowered, and the lateral incisors and canines should be raised when designing clinical treatments.

【**Key words**】 mandible; malocclusion; orthodontics; clear aligner; anchorage; miniscrew implant; dental stress analysis; finite element analysis

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隐形矫治器远移磨牙具有优势，其表达率高达70%[1]，远高于隐形矫治器的平均表达率50%[2]，且较固定矫治器效果更佳。高效远移无法避免引起前牙支抗的丢失[3]。尤其在下颌，由于下颌骨骨皮质较厚，骨质致密，磨牙远移阻力大，临床可见下颌磨牙远移表达率低于上颌：在不设计额外支抗的情况下，上颌第二磨牙远移表达率为83.4%[4]，而下颌第二磨牙远移表达率仅为74%[1]，同时切牙区发生骨开窗的风险增高[5]，所以决定下颌磨牙远移时往往需更加谨慎，常需特殊设计以保护前牙支抗[6]。临床使用种植钉推下颌磨牙向后时观察到较好的疗效[7]，但其生物力学机制尚不十分清楚。因此，本研究主要通过有限元分析，探究种植钉不同植入高度在下颌磨牙远移时对应的生物力分布，尝试寻找规律，以期获得保护支抗的有利位置，并为治疗方案的设计提供帮助。

1　资料和方法

本研究已获得吉林大学口腔医院伦理委员会审批（批号：2022LSno.43），已获得志愿者知情同意。

1.1　建模材料

以正畸科1名健康成年志愿者为研究对象。要求研究对象为个别正常颌，下颌牙列完整、牙齿解剖形态正常，左右基本对称，且下颌牙弓远中有足够的空间实现双侧下颌第二磨牙远移。拍摄CBCT（普兰梅卡 Pro-Max 3D，芬兰）并导出患者DICOM格式文件。

1.2　有限元模型的建立及分析

将DICOM格式文件导入Mimics 21.0，设置阈值，编辑、分割和修补图像以初步得到下颌骨和下牙列的三维模型，分别导出Stl格式文件。将Stl格式文件导入Geomagic Studio 2017中，经过去除孤立点、减噪、填充、曲面化等操作后形成封闭的下颌骨及牙列的实体模型。将牙根向外扩展0.2 mm后与原牙根模型使用布尔运算减法以生成牙周膜模型。将下颌骨模型向内扩展2 mm生成皮质骨，余为松质骨。将原始牙列中的第二磨牙向远中移动0.2 mm后，沿牙颈部边缘修剪牙冠表面，均匀向外扩展0.75 mm以产生隐形矫治器模型。为抵抗推磨牙时矫治器对前牙施加的向前的反作用力，决定将颌内牵引力施加在矫治器上[4]，于下颌矫治器尖牙位置设计精密切割作为施力点。种植钉模型在SolidWorks2016中设计并导出为STL格式。将下颌骨、下颌牙列、牙周膜、隐形矫治器及种植钉模型导入Solidworks软件中装配后划分网格，总网格数为507 400，随后导入Ansys workbench软件中进行各种工况下的三维有限元分析[8]。有限元模型及有限元模型所涉及的各材料的属性如图1和表1所示。

1.3　计算条件、参考点及坐标系设定及三维向移动量分析

隐形矫治器未加载荷条件和约束。设置隐形矫治器与牙齿之间为Frictional接触关系，牙齿-牙周膜-牙槽骨之间为Bond接触关系，牙槽骨周围设置固定约束，摩擦系数设为0.2。在精密切割及种植钉间施加200 g力[9]。以后牙颊向为X轴的正

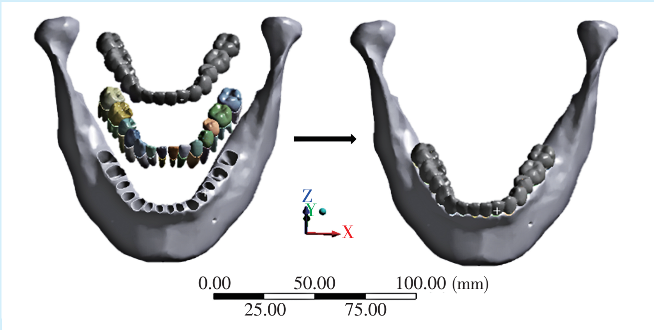


Figure 1 Three-dimensional finite element model assembly and coordinate system setting for the mandible, mandibular dentition and clear aligner

图1 下颌骨、下颌牙列及隐形矫治器的三维有限元模型装配及坐标系设定示意图

表1 有限元模型所涉及的各材料的属性

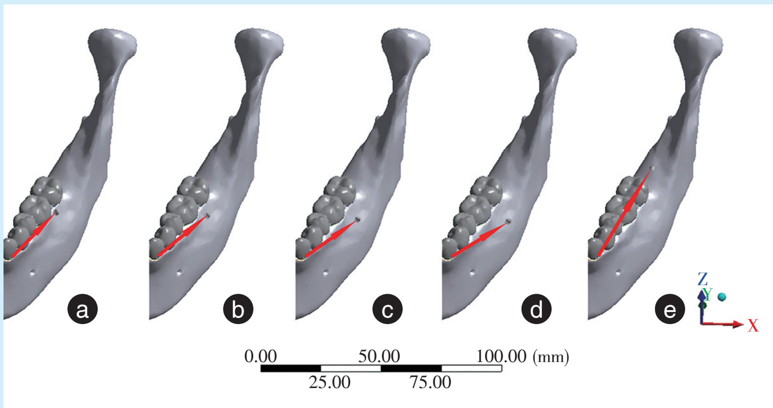
Table 1 The properties of each material involved in the finite element model

Material	Elastic modulus/MPa	Poisson´s ratio
Teeth[8]	18 600	0.31
Periodontal membrane[8]	0.68	0.48
Cortical bone[8]	13 700	0.30
Cancellous bone[8]	1 370	0.30
Clear aligner[8]	816.31	0.30
Miniscrews[8]	11 400	0.34

向,以后牙远中向为Y轴的正向,以𬌗向为Z轴的正向建立坐标系。以中切牙、侧切牙切缘中点,尖牙牙尖点,第一、第二前磨牙颊尖点,第一、第二磨牙的近中颊尖点为标志点观察各个牙齿的三维向移动量。

1.4 实验分组

本实验共设计六种工况。工况一为无种植钉对照组,不设种植钉及颌内牵引,仅使用隐形矫治器。工况二至工况五:种植钉植入于下颌第一磨牙和第二磨牙之间的颊侧骨皮质,距离牙槽嵴顶分别为10 mm、7 mm、4 mm、1 mm;工况六:种植钉植入于下颌升支前缘颊舌向居中,高于𬌗平面5 mm的位置。工况二至工况六中种植钉位置及施力方向如图2所示。



a-d: working conditions 2 to 5, the miniscrews were in the buccal bone cortex between the first and second molars of the mandible, 10 mm (a), 7 mm (b), 4 mm (c), and 1 mm (d) from the top of the alveolar crest, respectively. e: working condition 6, the miniscrew was in the center of the buccal tongue at the anterior edge of the ascending branch of the mandible, 5 mm above the occlusal plane. The red arrow starts from the tight cut on the clear aligner and points to the miniscrew, which indicate the direction of 200 grams of intramaxillary traction

Figure 2 Schematic diagram of miniscrew position and intramaxillary tractive force under working conditions 2 to 6

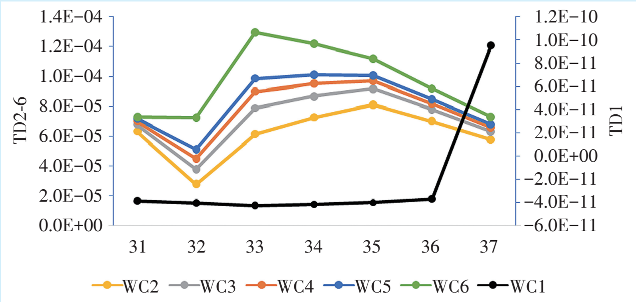
图2 工况二至工况六种植钉位置及颌内牵引力示意图

2 结 果

2.1 Y轴方向(矢状向)

对照组中左下颌第二磨牙产生远中向位移,其余牙齿均出现近中向(后牙)/唇向(前牙)位移,位移量相似且小于第二磨牙的位移量。种植钉组与对照组比较,第二磨牙的远中位移量显著增加,甚至产生全牙列远中向/舌向位移。

种植钉植入位置升高,所有牙齿远中向/舌向位移量越大,其中前磨牙远中位移量甚至超过第二磨牙(图3),远中位移增量变化尖牙 > 第一前磨牙 > 侧切牙 > 第二前磨牙 > 第一磨牙 > 第二磨牙 > 中切牙(表2)。



TD2-6: tooth displacement of working condition 2 to 6. TD1: tooth displacement of working condition 1. The horizontal coordinate is the tooth position of left mandibular. WC: working condition. The higher the implantation position of the miniscrew, the greater the displacement of all teeth in the distal (posterior)/lingual (anterior) direction

Figure 3 Line chart of the Y-axis displacement of each tooth in the left mandible with different miniscrew placement heights

图3 不同种植钉植入高度下左下颌各牙齿Y轴位移量折线图

表2 不同种植钉植入高度下左下颌各牙齿Y轴位移量

Table 2 Y-axis displacement of each tooth in the left mandible with different miniscrew placement heights

Tooth position	Working condition					
	1	2	3	4	5	6
31	-3.86E-11	6.31E-05	6.78E-05	7.00E-05	7.16E-05	7.27E-05
32	-4.05E-11	2.75E-05	3.75E-05	4.47E-05	5.09E-05	7.23E-05
33	-4.29E-11	6.13E-05	7.88E-05	8.99E-05	9.86E-05	1.29E-04
34	-4.20E-11	7.26E-05	8.67E-05	9.49E-05	1.01E-04	1.22E-04
35	-4.03E-11	8.09E-05	9.16E-05	9.69E-05	1.01E-04	1.12E-04
36	-3.71E-11	7.00E-05	7.78E-05	8.17E-05	8.45E-05	9.20E-05
37	9.54E-11	5.76E-05	6.30E-05	6.57E-05	6.77E-05	7.26E-05

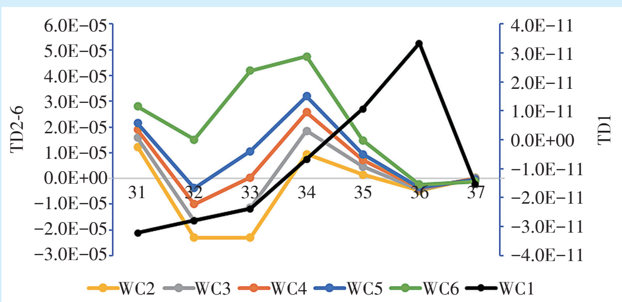
Working condition 1 was the control group without miniscrews; working conditions 2 to 5 had miniscrew in the buccal bone cortex between the first and second molars of the lower jaw 10 mm, 7 mm, 4 mm, and 1 mm from the top of the alveolar crest, respectively; working condition 6 had the miniscrew in the center of the buccal tongue at the anterior edge of the ascending branch of the lower jaw 5 mm above the occlusal plane

2.2 Z轴方向(垂直向)

对照组中左下颌第二磨牙产生龈向位移,第二前磨牙、第一磨牙产生𬌗向位移,第一前磨牙、尖牙、侧切牙、中切牙龈向位移量逐渐增大。种植钉组与对照组比较,各牙齿位移量均显著增加。主要表现为中切牙、前磨牙升高,侧切牙、尖牙、第一磨牙压低。种植钉植入位置升高,第二磨牙反而压低,其余牙齿则有升高的趋势(图4)。其中尖牙的位移量变化最大,磨牙最小(表3)。

2.3 X轴方向(冠状向)

对照组中左下颌第二磨牙有较大的颊向位移量,第二前磨牙、第一磨牙为舌向位移,其余牙齿颊向移动相对不明显。种植钉组与对照组比较,尖牙及其邻牙颊向位移量显著增加。种植钉组切牙、尖牙、第一前磨牙、第二磨牙有颊向位移,第二



TD2-6: tooth displacement of working condition 2 to 6. TD1: tooth displacement of working condition 1. The horizontal coordinate is the tooth position of left mandibular. WC: working condition. With the miniscrew position raising, the second molar is actually depressed, while the other teeth show a trend of elevation

Figure 4 Line chart of Z-axis displacement of each tooth in the left mandible under different miniscrews placement heights

图4 不同种植钉植入高度下左下颌各牙齿Z轴位移量折线图

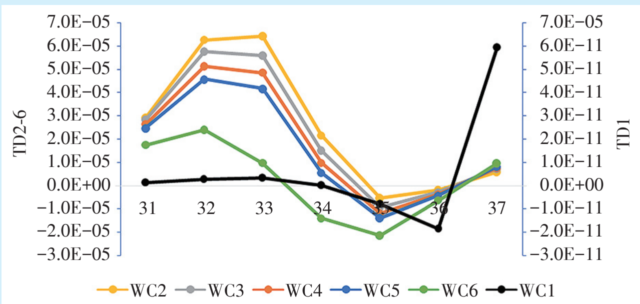
表3　不同种植钉植入高度下左下颌各牙齿Z轴位移量

Table 3　Z-axis displacement of each tooth in the left mandible under different miniscrews placement heights

Tooth position	Working condition					
	1	2	3	4	5	6
31	−3.22E−11	1.23E−05	1.58E−05	1.89E−05	2.15E−05	2.80E−05
32	−2.78E−11	−2.30E−05	−1.66E−05	−9.90E−06	−3.80E−06	1.51E−05
33	−2.38E−11	−2.30E−05	−1.14E−05	3.43E−07	1.05E−05	4.20E−05
34	−6.68E−12	9.44E−06	1.85E−05	2.58E−05	3.21E−05	4.74E−05
35	1.07E−11	1.52E−06	4.62E−06	7.14E−06	9.44E−06	1.49E−05
36	3.34E−11	−4.70E−06	−4.38E−06	−3.90E−06	−3.50E−06	−2.30E−06
37	−1.54E−11	2.04E−07	1.66E−07	−1.40E−07	−2.80E−07	−1.10E−06

Working condition 1 was the control group without miniscrews; working conditions 2 to 5 had miniscrew in the buccal bone cortex between the first and second molars of the lower jaw 10 mm, 7 mm, 4 mm, and 1 mm from the top of the alveolar crest, respectively; working condition 6 had the miniscrew in the center of the buccal tongue at the anterior edge of the ascending branch of the lower jaw 5 mm above the occlusal plane

前磨牙、第一磨牙有舌向位移。随着种植钉植入位置升高，所有牙齿位移量均有颊向减少的趋势。种植钉位置较高时，侧切牙、尖牙的颊向位移量甚至会超过远中位移量（图5）。其中尖牙位移量的变化幅度最为明显，相较之下磨牙变化很小（表4）。



TD2-6: tooth displacement of working condition 2 to 6. TD1: tooth displacement of working condition 1. The horizontal coordinate is the tooth position of left mandibular. WC: working condition. With the miniscrew position raising ,buccal displacement decreased or lingual displacement increased in all teeth

Figure 5　Line chart of X-axis displacement of each tooth in the left mandible under different miniscrews placement heights

图5　不同种植钉植入高度下左下颌各牙齿X轴位移量折线图

表4　不同种植钉植入高度下左下颌各牙齿X轴位移量

Table 4　X-axis displacement of each tooth in the left mandible under different miniscrews placement heights

Tooth position	Working condition					
	1	2	3	4	5	6
31	1.40E−12	2.93E−05	2.83E−05	2.65E−05	2.47E−05	1.75E−05
32	2.74E−12	6.27E−05	5.75E−05	5.14E−05	4.57E−05	2.41E−05
33	3.41E−12	6.43E−05	5.58E−05	4.86E−05	4.16E−05	9.80E−06
34	2.12E−13	2.16E−05	1.50E−05	9.77E−06	5.58E−06	−1.39E−05
35	−7.84E−12	−5.36E−06	−9.43E−06	−1.20E−05	−1.38E−05	−2.13E−05
36	−1.85E−11	−1.79E−06	−2.91E−06	−3.69E−06	−4.18E−06	−6.26E−06
37	5.94E−11	5.89E−06	7.15E−06	7.67E−06	8.19E−06	9.65E−06

Working condition 1 was the control group without miniscrews; working conditions 2 to 5 had miniscrew in the buccal bone cortex between the first and second molars of the lower jaw 10 mm, 7 mm, 4 mm, and 1 mm from the top of the alveolar crest, respectively; working condition 6 had the miniscrew in the center of the buccal tongue at the anterior edge of the ascending branch of the lower jaw 5 mm above the occlusal plane

3　讨　论

磨牙远移是临床常用的正畸治疗手段之一，它在获得治疗错𬌗畸形所必须的间隙、调整磨牙中性关系和避免有创性操作等方面具有明显优

势。目前，上颌磨牙远移应用广泛、疗效稳定[10-11]，下颌磨牙远移应用较少、难度较大，这与下颌骨质致密、下磨牙远移难度大有关。下颌磨牙远移量也受第二磨牙远中根与下颌体内舌侧骨皮质之间最短距离限制[12]，患者的垂直骨面型[13]、错䶮畸形类型[14]、第三磨牙状态[15]、磨牙牙根形态[16]都与该距离大小有关。但也有部分病例报告提示：下颌磨牙远移在双颌前突[17]、Ⅲ类错䶮畸形[18]、下颌拥挤[19]等情况下能均够获得较好的效果，但常需配合骨锚装置以保护支抗。

种植钉体积小、植入操作简单、创伤小，是目前临床常用的一种提供支抗的工具。磨牙远移时，种植钉的植入位置应符合以下要求：①能提供足够的稳定性，其中，植入部位有足够的骨量，皮质骨尽可能厚[20]，另外黏膜动度要小；②安全舒适；③最好能不影响下颌磨牙远移，避免在远移过程中更换种植钉位置。Liu等[21]经过对80例患者CBCT的测量，综合考虑牙槽骨厚度及距离下颌神经管的距离，认为下颌第一磨牙的远中根与第二磨牙近中根之间为下颌磨牙远移时植入种植钉位置的首选。Wang等[22]则认为，下颌第二磨牙近中距离牙槽嵴顶6 ~ 8 mm为适宜植入位置，此处颊侧骨皮质最厚，且不影响远移。Ono等[23]测量了43例患者的CT图像，得出下颌第一、二磨牙之间距离牙槽嵴顶1 mm、4 mm、7 mm、10 mm的骨皮质平均厚度分别为2.10 mm、2.26 mm、2.74 mm、3.13 mm，均大于1 mm，能够为种植钉提供足够的骨质支持[24]。Haddad等[25]的研究中则报道了在下颌骨，距离牙槽嵴顶2 ~ 10 mm可以成功植入种植钉。除下颌骨颊侧骨皮质，临床也可见于下颌升支植入种植钉以直立下颌磨牙的病例[26]。本实验为尽可能探究更多施力角度，又综合上述研究结果，设计了种植钉植入于下颌骨颊侧距离牙槽嵴顶1 mm、4 mm、7 mm、10 mm及高于䶮平面5 mm的分组，以便分析种植钉植入高度影响牙齿移动方式的生物力学机制。

目前用种植支抗辅助磨牙远移的力学分析主要局限在固定矫治。它将下颌牙弓作为一个整体，阻抗中心位于下中切牙切缘根尖向13.5 mm、远中向25.0 mm[27]，约在第一磨牙近中根前[28]。当对下颌牙列施力通过阻抗中心时，它将沿力的方向平动[29]。但在隐形矫治系统中，各个牙齿作为相对独立的单元，上述力学规律可能并不完全适用。隐形矫治器主要依赖形变产生矫治力。通过使用多个连续的、形状和牙冠外形不匹配的矫治器，逐渐使牙齿重新定位。在初戴时会产生较大的应力，然后由快到慢逐渐下降至平稳阶段，在2周过后矫治力会衰减到原来的20% ~ 50%[30]。除戴入时因矫治器与牙齿不匹配产生的形变，颌内牵引等其他因素也可能会引起矫治器形变，这些形变一般难以直接观察，目前主要依赖三维有限元的方法[31]对隐形矫治器的力学规律进行分析。从本研究数据折线图中可以看到，颌内牵引的有无会对隐形矫治器产生的生物力分布造成影响；而颌内牵引组中，不论种植钉植入高度如何，生物力分布相似；随种植钉植入位置升高，力的分布又表现出相似的变化趋势；提示隐形矫治器通过形变产生力的规律是有可能被预测的。

本实验通过有限元分析，得出了隐形矫治器在推下颌磨牙向后时矫治器形变产生的力学规律。主要有以下三个方面。第一，推磨牙向后时，隐形矫治器对第二磨牙产生一个远中颊向的压低力。与此同时，作为支抗，第一磨牙受到一个近中舌向的伸长力。在䶮龈向上，第二磨牙被压低，第一磨牙、第一第二前磨牙升高，中切牙、侧切牙、尖牙被压低，表现类似固定矫治中后倾弯的作用。提示隐形矫治器有可能是以材料在第一二磨牙间向䶮方堆积，产生形变，从而产生推力的。第二，实验组受口内牵引力的影响，矫治器在牵引力施力点处下沉；又以侧切牙及尖牙形成支点，使侧切牙及尖牙压低而中切牙和第一前磨牙升高；提示施加颌内牵引力同样会引起矫治器变形。本实验中牵引力的施力点为位于隐形矫治器上的精密切割，这种方式更加有利于磨牙远移[32]。至于使用天使扣或粘接在尖牙唇侧的舌侧扣作为施力点时的生物力学规律，则有待进一步研究。第三，颌内牵引力从施力点开始逐渐向后传递。前磨牙的远中位移量甚至大于第二磨牙的远中位移量。颌内牵引力施力点处有较大的颊向力。三维方向上，尖牙及侧切牙位移量受种植钉植入高度变化影响最大，这与颌内牵引力施力点最靠近它们有关。以上三个规律也与上颌磨牙远移的相关实验结论[33]一致。

本研究结果显示，隐形矫治器配合颌内牵引远移磨牙时似乎也会引起䶮平面的旋转：当种植钉植入位置较低时，有顺时针旋转的趋势；当种植钉植入位置较高时，有逆时针旋转的趋势。这与固定矫治生物力学规律相似[29]：以尖牙托槽远中

为施力点，当力的方向为-23°时通过阻抗中心，若力的角度更低，殆平面将顺旋，若力的角度更高，殆平面将逆旋。固定矫治器推磨牙向后时，若想保持咬合平面不变，往往需要压低远移的磨牙。但使用隐形矫治器时，即便不使用种植钉压低，仍可因殆垫作用较好地维持患者面下1/3高度[34]。本研究结果还提示，种植钉植入位置越高，下颌前牙远中位移量越大，保护支抗的效果越强。除此以外，支抗保护效果还受牵引力大小影响，牵引力力值越大，支抗保护效果越强[35]。选择合适的牵引力大小需要密切观察关注患者下前牙的唇倾度、尖牙的轴倾度，在种植钉承力最大限度（2 ~ 3 N）[9]内调整牵引力为适宜大小。

目前隐形矫治器生物力学相关临床研究较少，希望本实验结果能为临床应用及后续研究提供帮助。

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