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生物力学与材料

有限元分析髓芯减压并同种异体植骨治疗股骨头缺血性坏死的生物力学改变

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【摘要】目的:分析髓芯减压并同种异体植骨治疗早期股骨头缺血性坏死的临床应用。**方法:**选取收治的1例早期股骨头缺血坏死男性患者,入院后术前对患侧股骨头行多层螺旋CT扫描,然后将CT扫描的图片资料导入专业的有限元分析软件,建立股骨头缺血坏死的有限元模型,在有限元模型上模拟进行髓芯钻孔减压术,隧道植入骨块到软骨下骨约0~6 mm处,自体松质骨夯实。双足站立位为股骨头的模拟受力体位,髋关节的负荷条件为:外展肌合力M、髂胫束力T以及髋关节接触力J分别为1 060、1 721、1 621 N,选取90°、120°以及150°的坏死角度,分别计算未处理过的股骨头坏死模型的塌陷值、行单纯髓芯减压以及行髓芯减压加植骨时的塌陷值。**结果:**股骨头的正常骨质杨氏模量高于坏死骨的杨氏模量,正常骨质的横向变形系数低于坏死骨。行股骨头髓芯钻孔减压术后,股骨头的塌陷值显著增加,而减压隧道植入同种异体骨后,其塌陷值显著减低,但高于正常的股骨头。同时,由于股骨头坏死角度的增加,其塌陷值也明显增加。**结论:**髓芯钻孔减压并同种异体植骨术能有效增进坏死区的骨质修复,加强减压通道所致股骨头支撑结构的改变,防止股骨头关节面的塌陷。

【关键词】股骨头;缺血性坏死;有限元分析;髓芯减压;同种异体植骨;生物力学
【中图分类号】R318.01 **【文献标志码】**A **【文章编号】**1005-202X(2020)02-0243-06

Biomechanical changes of avascular necrosis of the femoral head treated by core decompression and allogeneic bone grafting: a finite element analysis

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Abstract: Objective To analyze the clinical application of core decompression combined with allogeneic bone grafting in the treatment of early avascular necrosis of the femoral head. **Methods** A patients with early avascular necrosis of the femoral head was enrolled. Multi-slice spiral CT scan was performed on the affected femoral head before operation, and the obtained CT image was then imported into a professional finite element analysis software for establishing a finite element model of avascular necrosis of the femoral head. The simulation of core decompression was conducted on the finite element model. The allogeneic bone was grafted to the subchondral bone at about 0-6 mm through compression channel, and the autologous cancellous bone was compacted. Biped standing position was adopted as the simulated force position of the femoral head. The load-bearing conditions of the hip joint were as follow: the abductor muscle force M, iliotibial tract tendon force T and hip joint contact force J were 1 060, 1 721 and 1 621 N, respectively. The necrosis angles of 90°, 120° and 150° were used to calculate the collapse value of the untreated femoral head necrosis model and the collapse values after treatments with core decompression only or core decompression combined with bone grafting. **Results** The Young's modulus of the normal bone of the femoral head was higher than that of the necrotic bone, while the lateral deformation coefficient of the normal bone was lower than that of the necrotic bone. After the femoral head core decompression, the collapse value of the femoral head was obviously increased, and after that the allogeneic bone was grafted in the decompression channel, the collapse value was remarkably reduced, but still higher than that of the normal

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femoral head. Meanwhile, due to the increase in the necrosis angles of the femoral head, its collapse value was also significantly increased. **Conclusion** Core decompression combined with allogeneic bone grafting can effectively improve the bone repair in the necrotic area, strengthen the deformation of the femoral head support structure caused by the decompression channel, and prevent the collapse of the femoral head joint surface.

Keywords: femoral head; avascular necrosis; finite element analysis; core decompression; allogeneic bone grafting; biomechanics

前 言

成年人发生股骨头缺血性坏死的年龄多为中青年，既往由于诊疗技术水平不高及患者个人忽视，在早期发病时往往漏诊与误诊，直至患者出现明显症状就诊时多为中晚期，此时股骨头骨质坍陷并导致髋关节的软骨磨损与破坏，需行全髋关节置换，严重影响患者的生活质量[1]。随着磁共振成像技术不断的发展，早期股骨头缺血坏死的检出率不断增高，积极的干预以及尽可能保留患者自身的股骨头以延缓人工髋关节的置换是早中期股骨头坏死总的治疗原则[2-3]。目前，临床上对早期股骨头缺血坏死应用较广的治疗方法有髓芯钻孔减压、同种自体或异体植骨术以及截骨手术，其中以髓芯钻孔减压术应用最广。股骨头内压力增高是导致骨坏死的原因，髓芯钻孔减压术的基本机理为通过钻孔来减低股骨头骨髓腔内压力，使得坏死区的血流阻力降低而恢复其血液供应，从而减轻临床症状或者延缓坏死区骨坏死的进度。但是，髓芯钻孔减压术改变了股骨头骨皮质下的正常骨质支撑结构，容易发生医源性股骨颈骨折或导致股骨头骨质塌陷的风险增加。有学者依据生物力学原理对髓芯钻孔减压术进行改良，经钻孔减压清除死骨后，经钻孔通道向清除了死骨的坏死区植入同种异体或自体骨，使得其类似正常骨质的支撑结构，从而预防股骨头软骨下或股骨颈发生骨折[4]。本研究为明确髓芯钻孔减压术并同种异体植骨术在股骨头缺血坏死早期临床治疗中具体的应用效果与价值，建立股骨头坏死的有限元模型并进行分析，现将相应结果报告如下。

1 资料与方法

1.1 一般资料

研究对象为东南大学附属中大医院2018年8月收治的1例早期股骨头缺血坏死男性患者，年龄49岁，身高167 cm，体质量71 kg，有长期饮酒及吸烟史，有三高（糖尿病、高血脂及高血压病）病史。

1.2 数据采集方法

本研究中股骨头三维重建的原始数据采集在病人术前进行，对术后的股骨头进行多层螺旋CT行薄层扫描，扫描范围从股骨上段至股骨头。扫描参数：管电流420 mA，管电压120 kV；不同节段其层厚不同，从股骨头近端到小转子这一节段的扫描层厚为0.2 mm，从转子到股骨中部这一节段的扫描层厚为5 mm，扫描完成后将DICOM格式的CT图像导入MIMICS软件，提取可以反映轮廓的每个关键层的坐标值，并组合图层距离以获得该点的坐标值，后根据图像所提供的边缘轮廓数据建立股骨头骨骼3D模型。

1.3 建立有限元模型与方法

把重建后的股骨头3D模型导入专用的Abaqus有限元软件，以四面体单元对重建后的股骨头3D模型进行网格划分以建立有限元网格模型。依据股骨头的力学特点对3D模型进行适当的简化处理及对模型的表面进行网格化处理，然后应用三维有限元网格自动生成软件分别生成4节点的四面体和10节点的四面体模型。参考文献将正常股骨头、死骨及植入松质骨的杨氏模量分别设置为13 800、52及700 MPa，横向变形系数为0.2[5]。仿照髓芯减压术和髓芯减压并同种异体植骨术这两种不同处置方式的生物学状态，然后，取双足站立位为股骨头的模拟受力体位，髋关节的负荷条件为：外展肌合力M、髂胫束力T以及髋关节接触力J分别为1 060、1 721、1 621 N，选取90°、120°以及150°的坏死角度，分别计算未处理过的股骨头坏死模型的塌陷值、行单纯髓芯减压以及行髓芯减压加植骨时的塌陷值[6]。

2 结 果

2.1 股骨头的塌陷值的有限元分析

依据股骨头（图1~图4）的不同组成成分杨氏模量及横向变形系数（表1），在股骨头三维有限元模型上方承重部位病理发生变化的地方，随机选取分散均匀8个负重区节点为2603、2604、2605、2606、2627、2628、2629、2630，其对应塌陷值为0.069 7、0.067 3、0.067 4、0.069 2、0.068 0、0.070 4、0.070 5、0.079 3 mm，平均值塌陷值为0.069 3 mm。

2.2 塌陷数值数据的有限元分析

在选取的三维有限元模型上，股骨头坏死的部位类似于管锥体，其顶端在股骨头的中央部位，用圆

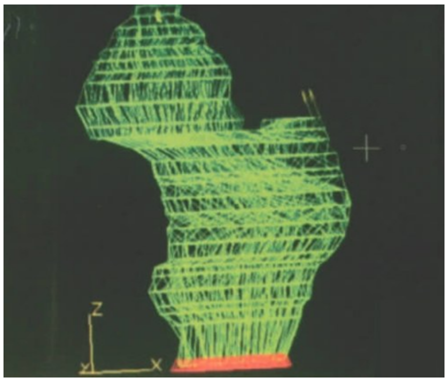

图1　三维有限元模型的建立
Fig.1 Establishment of three-dimensional finite element model

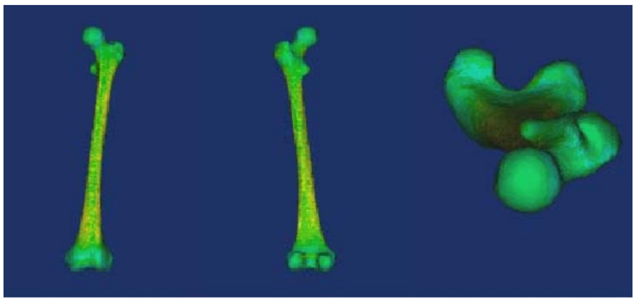

图2　股骨三维有限元模型（MIMICS 多角度观）
Fig.2 Three-dimensional finite element model of the femoral head (MIMICS multi-angle view)

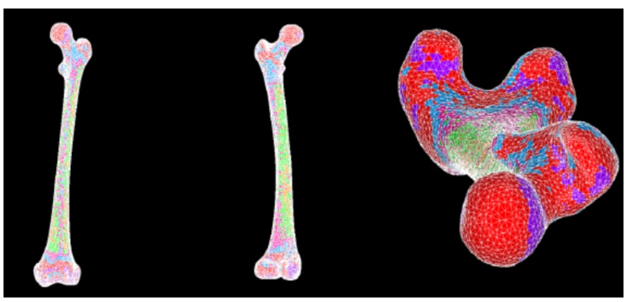

图3　股骨三维有限元模型（ANSYS 多角度观）
Fig.3 Three-dimensional finite element model of the femoral head (ANSYS multi-angle view)

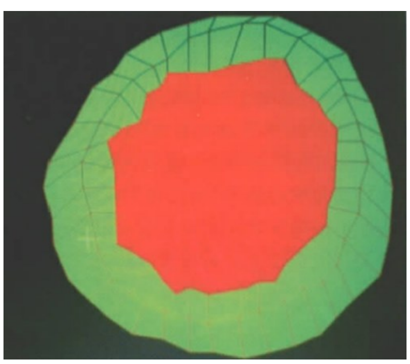

图4　正常股骨头模型的横断面（红色区域代表骨松质，浅绿色区域代表骨皮质）
Fig.4 Cross section of the normal femoral head model (red represents cancellous bone and light green represents bone cortex)

表1　股骨头不同组成成分的杨氏模量与横向变形系数数据比较
Tab.1 Comparison of Young′s modulus and lateral deformation coefficient of different components of the femoral head

组别	杨氏模量	横向变形系数
皮质骨	16.8 GPa	0.20
松质骨	700 MPa	0.40
正常骨	13.8 GPa	0.25
坏死骨	0.052 GPa	0.45

锥体的张角表示股骨头坏死部位的规模，张角度数为90°、120°（图5）、150°，分别推算各种坏死角度下，股骨头压力降低时的塌陷数值（表2~表4、图6）。

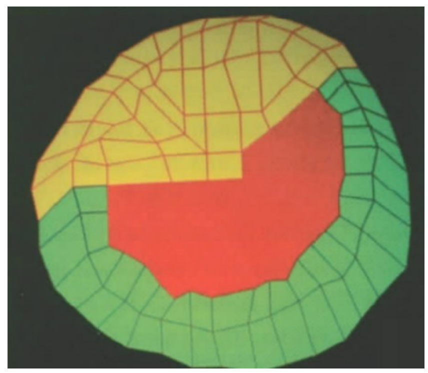

图5　股骨头坏死模型横断面（黄色区域表示坏死角度120°的坏死范围）
Fig.5 Cross section of the femoral head necrosis model (Yellow represents necrosis region with a necrosis range of 120°)

表2　各三维有限元负重区节点及其对应塌陷数值（mm）
Tab.2 Three-dimensional finite element load-bearing zone nodes and their collapse values (mm)

D	负重区	负重区内侧0.5 cm	负重区外侧0.5 cm
0 mm	0.850 5	0.101 9	0.088 8
3 mm	0.158 5	0.097 4	0.082 8
6 mm	0.118 7	0.091 2	0.074 8
9 mm	0.105 6	0.080 2	0.070 2

*D*值为股骨头软骨面与减压区表面的距离

表3　120°时不同减压位置股骨头的塌陷数值数据对比（mm）
Tab.3 Comparison of collapse values of the femoral head at different decompression positions and at a necrosis angle of 120° (mm)

D	负重区	负重区内侧0.5 cm	负重区外侧0.5 cm
0 mm	0.891 4	0.127 7	0.113 2
3 mm	0.242 6	0.124 3	0.108 5
6 mm	0.159 7	0.122 6	0.092 9
9 mm	0.154 7	0.113 8	0.092 9

表4 150°时不同减压位置股骨头的塌陷数值数据对比(mm)

Tab.4 Comparison of collapse values of the femoral head at different decompression positions and at a necrosis angle of 150° (mm)

D	负重区	负重区内侧0.5 cm	负重区外侧0.5 cm
0 mm	1.493 4	0.950 3	0.527 6
3 mm	0.509 2	0.703 9	0.408 6
6 mm	0.445 0	0.542 2	0.313 6
9 mm	0.409 4	0.463 2	0.315 3

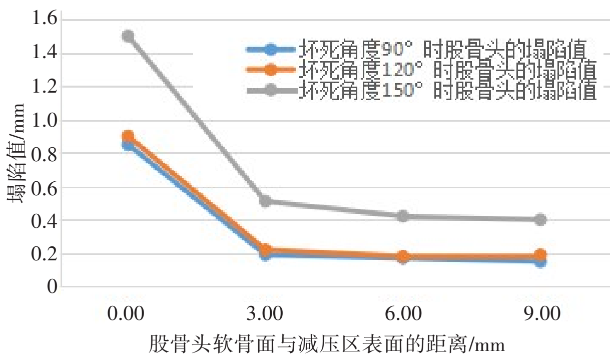

图6 不同角度不同减压位置股骨头的塌陷值

Fig.6 Collapse values of the femoral head at different decompression positions and at different necrosis angles

2.3 髓芯减压并植骨后股骨头的塌陷数值的有限元分析

在选取的三维有限元模型上，选取股骨头坏死承重部位，开展直径为1.0 cm的减压植骨，放入骨块后再计算坏死角度股骨头的塌陷数值，计算结果表明，在医治不同规模的股骨头坏死时，植骨放置后可改善塌陷状况(表5，图7~图8)。

表5 髓芯减压+植骨后在不同的负重区股骨头塌陷值的对比(mm)

Tab.5 Comparison of collapse values of the femoral head in different load-bearing areas after core decompression combined with bone grafting (mm)

D	坏死范围90°	坏死范围150°
0 mm	0.056 3	0.055 0
3 mm	0.061 0	0.059 3
6 mm	0.062 3	0.061 5
9 mm	0.064 8	0.065 0

3 讨 论

3.1 髓芯减压对股骨头机械支撑力的影响

当前，髓芯减压+带血运的骨移植的方式是治疗骨头缺血性坏死疾病最常见的治疗方案，但是，由于减压术需要把死骨刮除，这一过程会导致股骨头内部的支撑结构发生改变，更容易导致股骨头发生塌陷。有学者研究报道，在股骨头软骨下行直径10 mm的减压术后，股骨头负重区的塌陷值约为减压术前的10倍，且塌陷值与坏死范围与减压的直径呈正比[6]。这说明髓芯钻孔减压术在清除死骨的同时也破坏了股骨头内部的固有支撑结构，如果清除的死骨范围较广时，需要植骨或者植入钽块以防止股骨头负重区的塌陷[7]。

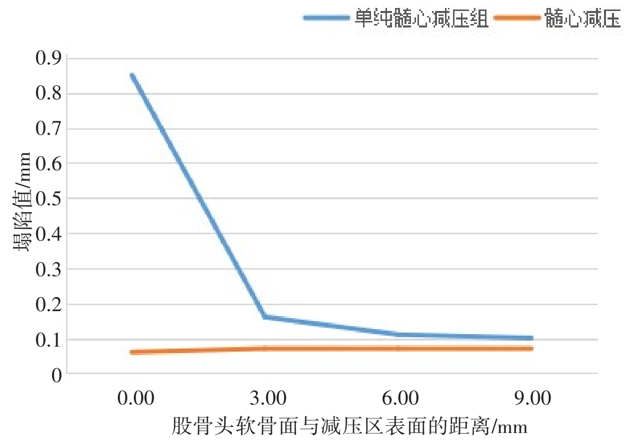

图7 单纯髓芯减压与髓芯减压+植骨术时不同减压位置股骨头负重区软骨下塌陷值的比较(坏死角度90°)

Fig.7 Comparison of subchondral collapse value in the load-bearing area of the femoral head at different decompression positions after core decompression only and core decompression combined with bone grafting (necrosis angle was 90°)

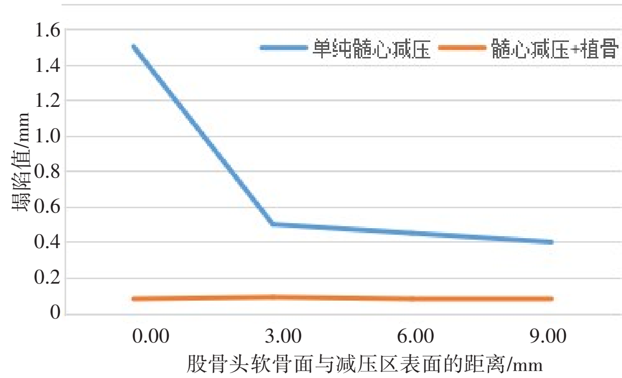

图8 单纯髓芯减压与髓芯减压+植骨术时不同减压位置股骨头负重区软骨下塌陷值的比较(坏死角度150°)

Fig.8 Comparison of subchondral collapse value in the load-bearing area of the femoral head at different decompression positions after core decompression only and core decompression combined with bone grafting (necrosis angle was 150°)

3.2 植骨的结构和治疗股骨头缺血性坏死的力学原理

本研究使用同种异体冷冻干燥骨，其在结构与力学特性上都与自体骨基本一致。髓芯减压术时减压通道通常会到达软骨下的骨质从而导致股骨头支撑结构破坏，这种情况下可通过植入骨块并打压夯

实而恢复软骨下骨的结构支撑，进而使得减压通道获得良好的支撑稳定性，有效地防止股骨头的塌陷[8]。同种异体冷冻干燥骨具有两方面特征：①它与自体骨骼弹性模量基本相同，具有非常强大的支撑作用，能够承担生理负重，避免发生塌陷[9-10]；②另一方面，植入骨块具有与人体良好的相容性和很好的骨诱导活性，能够加速坏死区的再血管化和促进骨组织的修复[11-12]。大量研究结果表明，植入骨块后，加强了股骨头的机械支撑力，并且机械支撑力的大小与骨头形变位移的大小呈正比关系。例如有学者报道当髓芯减压区达软骨下骨并且坏死角度为90°时，股骨头的塌陷值为0.850 4 mm，而植入骨块后，其塌陷值下降至0.056 2 mm，表示其能够有效避免塌陷，并且效果为原来的100倍左右[6,13]。

3.3 影响植骨置入后股骨头生物力学性能的因素

首先，要使置入骨块的生物力学性能充分发挥出来，行髓芯减压术时候需要把坏死的骨质完全清除干净，这样既可以有效地降低股骨头的骨内压，又可对骨内血液循环的重建和再血管化有促进作用[14]。其次，在扩孔过程中要保证松质骨的新鲜度，然后把这部分松质骨植入彻底刮除死骨后的空腔以及剩余的骨块隧道，因自体松质骨中存在大量的骨髓基质干细胞，可以很好地促进坏死区的减压通道生成新骨，促进骨质修复[15-16]。此外，还要保证植入松质骨的夯实性，为了达到植骨骨块和松质骨成为整体的目的，使骨块和洞壁中间依然存留空隙，并提供股骨头形变的空间，当股骨头的载荷递送到植骨时，植骨的移动可有有效的吸收及分散的作用力。将植骨置入减压洞后，必须消除骨块间的空隙，才能保证骨块的作用发挥到极致。置入骨块时，可以将一定量的新鲜松质骨骨末填入骨块间的空隙中，才能保证夯实骨洞时达到以下作用：(1)能够引导骨组织长入骨块置入物中；(2)借助工程建筑学中的力学原理，将一定量的松质骨粉末填入植骨骨块间，期间增加的压力避免骨块之间间隙的产生，完全避免骨块间出现滑动及空间形变的情况，不仅表现了骨块自身的强度，同时也提高了整体骨块置入物中总的机械支撑力[17-18]。

综上，髓芯钻孔减压并同种异体植骨术能有效增进坏死区的骨质修复，加强减压通道所致股骨头支撑结构的改变，防止股骨头关节面的塌陷。

【参考文献】

[1] 彭帆. 股骨头骨缺损模型打压植骨应力与软骨下骨承受能力的相关性研究[D]. 上海: 第二军医大学, 2017.
PENG F. Study bone on the correlation between impaction grafting stress and subchondral bone bearing capacity in the femoral head bone defect model[D]. Shanghai: Second Military Medical University, 2017.

[2] ROMANOS G E, DELGADO-RUIZ R A, SACKS D, et al. Influence of the implant diameter and bone quality on the primary stability of porous tantalum trabecular metal dental implants: an *in vitro* biomechanical study[J]. Clin Oral Implan Res, 2018, 29(6): 649-655.

[3] BENCHARIT S, BYRD W C, HOSSEINI B. Immediate placement of a porous-tantalum, trabecular metal-enhanced titanium dental implant with demineralized bone matrix into a socket with deficient buccal bone: a clinical report[J]. J Prosthet Dent, 2015, 113(4): 262-269.

[4] BENCHARIT S, BYRD W C, ALTARAWNEH S, et al. Development and applications of porous tantalum trabecular metal-enhanced titanium dental implants[J]. Clin Implant Dent Relat Res, 2013, 16(6): 817-826.

[5] 张怡元, 冯尔宥, 林飞太, 等. 以三维有限元分析多孔钽块植入治疗股骨头缺血性坏死的生物力学改变[J]. 生物骨科材料与临床研究, 2012, 9(1): 4-7.
ZHANG Y Y, FENG E Y, LIN F T, et al. Biomechanicai study and three-dimension finite element analysis on the treatment of the iscbemic necrisis of the femoral head using piece of tantalum[J]. Orthopaedic Biomechanics Materials and Clinical Study, 2012, 9(1): 4-7.

[6] 张怡元, 冯尔宥, 陈日齐, 等. 多孔钽块置入治疗股骨头缺血性坏死的生物力学及三维有限元分析[J]. 中国矫形外科杂志, 2012, 20(12): 1113-1116.
ZHANG Y Y, FENG E Y, CHEN R Q, et al. Biomechanical study and three-dimension finite element analysis on the treatment of the iscbemic necrosis of the femoral head using pieces of tantalum in adult[J]. Orthopedic Journal of China, 2012, 20(12): 1113-1116.

[7] 王岩, 赵德伟, 王继芳, 等. 镍-钛记忆合金网球治疗成人股骨头缺血性坏死初步报告[J]. 中华外科杂志, 2018, 36(10): 579-581.
WANG Y, ZHAO D W, WANG J F, et al. Memorial metal ball for the treatment of avascular necrosis of femoral head[J]. Chinese Journal of Surgery, 2018, 36(10): 579-581.

[8] 方锐, 梁治权, 孟庆才, 等. 多孔钽棒置入治疗股骨头坏死16例[J]. 中国组织工程研究与临床康复, 2011, 15(34): 6445-6448.
FANG R, LIANG Z Q, MENG Q C, et al. Porous tantalum rod insertion for treatment of femoral head necrosis in 16 cases[J]. Journal of Clinical Rehabilitative Tissue Engineering Research, 2011, 15(34): 6445-6448.

[9] 刘文源. 独活寄生汤配合髓芯减压干细胞移植治疗早期股骨头坏死[D]. 郑州: 郑州大学, 2013.
LIU W Y. Chinese medicine cooperate with medullary core decompression and stem cell transplantation in the treatment of early femoral head necrosis[J]. Zhengzhou: Zhengzhou University, 2013.

[10] 巩慧明, 侯亮, 叶桂峰. 髋关节置换的三维有限元分析[J]. 生物骨科材料与临床研究, 2018, 5(5): 43-46.
GONG H M, HOU L, YE G F. Three-dimensional finite element analysis of hip joint replacement[J]. Orthopaedic Biomechanics Materials and Clinical Study, 2018, 5(5): 43-46.

[11] 钟红发, 陈荣春, 朱道信, 等. 多孔钽金属棒植入在早期股骨头缺血性坏死的临床疗效观察[J]. 齐齐哈尔医学院学报, 2011, 32(16): 2593-2594.
ZHONG H F, CHEN R C, ZHU D X, et al. The clinical effect of porous tantalum metal rod implantation in early avascular necrosis of femoral head[J]. Journal of Qiqihar Medical College, 2011, 32(16): 2593-2594.

[12] 杜东鹏, 缪祥文, 姜文雄, 等. 伞状记忆合金股骨头支撑器及器械的设计[J]. 西北国防医学杂志, 2014, 35(2): 124-127.
DU D P, MIAO X W, JIANG W X, et al. Design of femoral head supporting device and corresponding instrument of memory alloy with

umbrella shape[J]. Medical Journal of National Defending Forces in Northwest China, 2014, 35(2): 124-127.

[13] 边卫国, 李涤尘, 连芩, 等. 多孔预置管道股骨头坏死髓芯植入体的设计与制造[J]. 生物医学工程学杂志, 2011, 28(5): 961-967.
BIAN W G, LI D C, LIAN Q, et al. Design & Fabrication of porous core implant with preset channel network for osteonecrosis of the femoral head[J]. Journal of Biomedical Engineering, 2011, 28(5): 961-967.

[14] 蒋羽清, 周栋, 王禹基, 等. 多孔钽棒置入联合髓芯减压治疗早期股骨头坏死中远期疗效的临床评价[J]. 实用临床医药杂志, 2012, 16(11): 43-45.
JIANG Y Q, ZHOU D, WANG Y J, et al. Clinical evaluation of the long- term efficacy of porous tantalum rod implantation combined with core decompression for early-stage femoral head necrosis[J]. Journal of Clinical Medicine in Practice, 2012, 16(11): 43-45.

[15] 庞智晖, 何伟. 基于三维重建和有限元分析的股骨头坏死围塌陷期保髋新技术的临床应用[J]. 中华关节外科杂志(电子版), 2013, 7(3): 301-308.
PANG Z H, HE W. Clinical application of a new technique based on three-dimensional reconstruction and finite element analysis for osteonecrosis of femoral head in peri-collapse stage[J]. Chinese Journal of Joint Surgery (Electronic Edition), 2013, 7(3): 301-308.

[16] 卢岩岩, 翟明玉, 魏宗星, 等. 髓芯减压自体髂骨打压植骨联合骨形态发生蛋白2治疗早中期股骨头坏死疗效观察[J]. 风湿病与关节炎, 2015, 4(9): 42-43.
LU Y Y, ZHAI M Y, WEI Z X, et al. Effect of core decompression of ilium autograft combined with bone morphogenetic protein-2 in the treatment of early and middle femoral head necrosis[J]. Rheumatism and Arthritis, 2015, 4(9): 42-43.

[17] KARASUYAMA K, YAMAMOTO T, MOTOMURA G, et al. The role of sclerotic changes in the starting mechanisms of collapse: a histomorphometric and FEM study on the femoral head of osteonecrosis[J]. Bone, 2015, 81: 644-648.

[18] SARDANA V, PHILIPPON M J, DARREN-DE S A, et al. Revision hip arthroscopy indications and outcomes: a systematic review[J]. Arthroscopy, 2015, 31(10): 2047-2055.

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