

骨折愈合的应力适应性研究

——功能活动时兔胫骨断端应力状态的动态观察

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摘要 设计了生物适应性很强的力学控制装置——滑动机械加载控制器,对骨折断端没有应力遮挡,把肌肉动力与肢体负重力作为执行力学加载的源动力,通过压力传感器、多导传感放大器动态记录生理活动状态下断端受力情况及愈合过程中断端的应力状态。结果表明,同一时期内骨折断端压力随肌肉收缩及步态发生变化,不同愈合时间断端压力均值随时间的增加而逐渐增加,而滑动机械加载控制器上承载由术后当日平均 2.4kg 逐渐变小至术后五周平均 0.78kg。同时,通过解剖显微镜进行断端骨痂显微观察,显示断端完全由外骨痂包绕,从而认为骨折断端压力变化是肢体功能恢复,断端骨痂承受载荷的表现,提示临床骨折固定后应适时地进行功能锻炼,肌肉收缩、患肢负重可为断端提供最好的力学环境——生理应力状态。

关键词 骨折愈合 生物力学

骨折的整复、固定只是为骨折愈合创造条件,骨折能否较快的愈合,关键在于活动。问题是固定以后何时开始活动,骨折断端需要什么形式的应力分布,有多大应力范围才最适合刺激外骨痂形成,而又不导致骨折不愈合。为了定量表达局部应力状态与时间及固定条件的关系,就需要一个很强的生物适应性的力学控制系统,观察生理状态下肌肉活动、肢体负重对骨折断端位移及断面应力的影响,为骨折治疗及临床患者进行功能锻炼提供一个量的概念。

材料与方 法

1. 滑动机械加载控制器:采用铝合金材料,由两个主固定臂和大小各两对副固定臂组成。主固定臂分上下两层,分别安装滑轨,滑槽相对,借助滚珠可以无阻力的滑动。每一副固定臂上安装一个锁针臂,其在副固定臂上可以上下左右转动,增加了定位自由度。远近骨折段用 1.5mm 的克氏针穿过骨干后,针孔两边用套筒顶住,螺母锁紧,限制骨在针上的侧向滑动,从而完成器械与骨的连接。在滑动方向上选择骨轴向,肌肉活动使骨断面受正压力,滑动主要是为了不替代断面承受纵向载荷。

2. 压力传感器:采用不锈钢板设计成悬

臂梁作为弹性元件,当悬臂梁受压力而弯曲后,贴在悬臂梁两侧对称部位的电阻应变片 R_1 、 R_2 、 R_3 、 R_4 将出现抗压应变而有相应的电阻改变。四枚应变片组成全桥,可以抵消力偶的影响及起温度补偿作用。

3. 多导传感放大器:为了将输出信号放大,自制了八导微伏放大器,由 OP10+OP07 组成,无需调整和补偿就可方便地使用,温漂 $<1.5\mu\text{V}/\text{C}^\circ$ 。

4. 动物模型的建立:选用健康成年大耳白家兔 14 只,体重 2.7~4kg,采用颗粒型标准饲料喂养。用 3% 戊巴比妥按每 kg 体重 1ml 耳静脉麻醉。取右下肢,剪毛后常规无菌手术操作,在胫骨上闭合穿过四根平行针,固定臂间针距 2.5cm,截骨间针距 3cm。然后安装带传感器的滑动机械加载控制器,并在胫骨中段用低速牙科金刚石锯横行截断,断端对位良好。冲洗伤口,置入 40 万单位青霉素于伤口内,依层缝合,无菌纱布包扎。动物麻醉清醒后,即放回笼内饲养。实验过程中由于腹泻、再骨折等原因去除 5 只,共有 9 只用于实验。

5. 骨断端应力动态观测:将传感器的引线通过放大器连接 x-y 函数记录仪,调平衡后开始记录。观察时尽量保持动物自然活动,测

试结束前记录传感器不受力时的曲线。术后第一天及每周一次作连续动态观测,共 5 周。每次测试不少于 30 分钟。

6. 断端骨痂显微观察:借助解剖显微镜(日产 Nikon SMZ—10 型)观察骨折断端骨痂分布情况及骨折间隙。

结 果

动物于术后 24 小时内可以行走,但患肢不敢负重或负重很少,也不愿意活动,以静卧为主。术后一周活动接近正常,活动范围也增大,二周时则跑跳自如,患肢正常负重,活动次数也较频繁。

1. 骨折端压力与时间的关系:在功能活动情况下,骨折断端压力的均值随着时间的增加而逐渐增加,而滑动机械控制器上承载由术

后当日平均 2.47kg 逐渐变小至术后 5 周平均 0.78 公斤,表明断端受力由外骨痂承担。为此,计算了骨折端压力与时间的回归系数。(见表)。

ROW	0	1	2	3	4	5
1	3.08	1.96	1.60	1.41	0.95	0.55
2	1.33	1.34	1.14	1.15	0.74	0.52
3	2.14	2.08	1.17	0.78	0.72	0.69
4	2.05	2.94	1.91	1.07	0.89	0.47
5	3.05	2.23	2.13	1.59	1.00	0.98
6	2.65	2.80	2.76	1.66	1.54	1.47
7	3.33	3.47	2.75	1.81	0.68	0.79
8	1.69	—	1.16	—	—	—
9	2.95	—	1.36	1.13	—	—
Mean	2.47	2.40	1.78	1.32	0.93	0.78
SD	0.70	0.71	0.65	0.35	0.29	0.35



图 术后第一周骨折端压力曲线变化

直线回归方程:

$$GaP = 2.57 - 0.38 \cdot (\text{Date})$$

2. 骨折端压力曲线变化:骨折愈合的不同时期,骨断端压力是有变化的。即使同一时间内,断端压力也不是恒定不变的,表现时大时小,时有时无(见图)。

3. 骨折断端显微观察:在解剖显微镜下可见肥厚的外骨痂桥架于骨折断端。断面间没有连接,有的仍可见断端间隙。

讨 论

1. 骨折愈合时间与断端应力曲线:骨折部位的应力应变由加于断端的载荷和骨折端组织特性所决定。试验中采用滑动机械加载控制器及传感器测量技术,连续动态观察记录骨折断端压应力的变化情况,结果显示骨折端压应

力在整个愈合过程中随时间推移而逐渐增加,这主要与骨的功能适应性有关,即断端骨痂的结构、机能与周围力学环境相关,这也正反映了骨折愈合的生物力学特性——骨折愈合的关键是建立骨折端间的完整骨桥,一旦骨桥建立,便能提供合适的机械力保护。其它进程如骨痂增殖和重建活动才能进行。

骨端受力曲线表明,断端应力状态是随着每一步态发生变化的,与负重及肌肉收缩活动有关,安静时断端力恒定不变,活动时呈波峰状,并随着动能恢复、骨愈合时间而受力频率加快。提示生理压应力刺激和良好的血液供应是促进细胞分化,加速骨折愈合的内因,固定形式是保证愈合过程顺利进行的外因。临床应采用相对的局部弹性固定,尽量不要干扰骨折

周围生理状态下的力学环境,应充分发挥人的主观能动性,使骨折部承受一定压应力,并适时地去除固定物。

2. 骨痂形成钙化与断端应力改变:生物组织在每个水平上都具有复杂的内部调节机制和调整生物体与环境之间关系的反馈系统。骨折早期,外骨痂增生起稳定骨断端的作用,为骨折愈合创造条件。随着时间的推移,不断向受力最大的方向增加骨的质量,骨结构强度增加,使骨折部能较早承受较大的载荷。

本试验结果可以看出,早期血肿、骨膜掀起、断端微动,骨折局部呈液相,很不稳定,但由于动物术后的应激保护反应,以静止为主。骨折后显微内环境及应力状态的轻微改变,迫使局部出现生物学反应,细胞侵入血肿,很快形成骨痂。这些大量纤维骨痂只是包绕骨折端,在短时间内使之趋于稳定,但不能承受较多的载荷。随着功能锻炼,断端承担较多压应力,骨痂逐渐钙化,由胶冻样物质转化为有结构的骨样组织,力的作用促进成骨细胞转变为骨细胞,使骨小梁形成并矿物质沉积,也就完成了骨折端由液相向固相的转化。钙化的骨痂承担更多的载荷,外骨痂在功能上与内固定物起着相同的作用,这是一个新的功能适应过程。

同样,断端骨痂显微观察及 X 线片也可以看出,骨折愈合均是通过桥梁外骨痂架于骨折端,以后骨桥肥大及再塑形而逐渐恢复其力学性能及完整性。但骨痂生长不是向任何方向无控制地扩张,也不是无限制的繁殖,而是力学性能最差的位于中心,力学性能最好的位于外周,外骨痂生长或抑制,骨痂分布与骨痂量的控制,与局部应力状态有关。由外骨痂桥架于骨断端的骨折“二期愈合”,有效的增加了骨外径和惯性矩,使骨有最大的负重能力,加快了骨折愈合。

3. 肌肉动力系统与断端应力状态:固定是非自然的,功能活动是自然的,在实验控制模型中应用滑动机械加载控制器,保证肌肉收缩

时,只能进行一维的骨干纵轴方向的滑动,并且滑动时没有功能替代,骨断面完全承受纵向载荷。实验过程中,充分发挥兔自身的活动能力,使断端的力学环境保持接近自然活动的稳定状态。这样,有控制的轴向显微活动,周期性刺激,早期便有丰富的外骨痂生长,骨痂在抗扭转能力增高,提示早期主动的功能活动为骨折端可提供一个合适的力学刺激。

“骨为干”、“筋为刚”、“宗筋主束骨而利机关”,每块肌肉的起止点不同,体积大小、收缩强度等也独立变化,但最终肌肉动力都要作用到骨折断端,所以采集断端的应力状态可以部分地认识骨折肢体的肌力情况。

其一,生理状态下,骨折肢体关节屈伸,肌肉舒缩,骨折断端的受力形式表现为间断性应力,时大时小,时有时无,提示临床固定后,患肢要“或屈或伸,时时为之”。

其二,骨折早期,肌肉表现为静力性紧张,主要通过肌肉间隔“不可压缩液体效应”的作用,使肌肉包绕在骨折端达到相对稳定状态。提示临床骨折早期即可活动,但主要是肌肉静力性收缩紧张,即“筋束骨”的作用。

其三,骨折愈合过程中,断端受力不是恒定不变的,这主要是骨折端周围骨痂承担肌肉动力载荷的能力逐渐增大,是肢体功能恢复的表现,其应力范围是最佳的,从而证实了 Eggers 的推测,骨愈合的最佳压应力是该部生理状态下所承受的肌力。

小 结

滑动机械加载控制器对骨折断端没有功能替代,可以测量骨断端功能活动状态下肌肉收缩、患肢负重的压应力。通过动物实验记录发现,断端应力状态随着每一步态发生变化,与负重及肌肉收缩活动有关,在整个愈合过程中,断端压应力随时间推移而逐渐增加。显微观察显示断端完全由桥梁外骨痂包绕,提示临床骨折固定后要适时地进行功能练习,包括肌肉收缩活动和负重。

Abstract of Original Articles

Study on pathogenesis of derangement of lumbar posterior intervertebral facet joint and biomechanics of manipulative treatment

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A microsensor was embedded to detect the displacement and receiving forces from lumbar posterior intervertebral facet joints with various postures. The results indicates that the degree and direction of displacement is influenced by morphology of the articular process, during motion of the spine, the intra-pressure of facet joints is concentrated on the superior and inferior ends of the facet joint. During instability of certain segment of the joint, there will be an increasing of around 8 times of intra-pressure within the facet joints. Results of measurement of mimic rotatory manipulative reduction indicate that there are undulant changes within the intra-pressure of posterior facet joints. All-round direction movements of the inferior facet joint toward upward - forward - downward - backward have been found. Based on the viewpoint of bio-mechanics, the pathogenesis of derangement of lumbar posterior intervertebral facet joint and principle of manipulative treatment are explored by authors.

Key Words Derangement of lumbar posterior intervertebral facet joint Microsensor
Biomechanics Principle of manipulative treatment

(Original article on page 5)

A retrospective study on the fracture and dislocation of the thoracic and lumbar spine complicated with paraplegia

Xue Dong-lun(薛栋伦) Que Zai-zhong(阙再忠) et al

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Forty three cases of fracture and dislocation of the thoracic and lumbar spine complicated with paraplegia was studied retrospectively by authors. Among them, 15 were complete paraplegia; 28, incomplete paraplegia. The rate of improvement was 26.7% in the former, and 71.4% in the latter. A comment among the relationship of segment of spine, spinal cord and nerve root, determination the nature of spinal cord injury and reduction of internal fixation and route of decompression of the cord were discussed.

Key Words Fracture of thoracic and lumbar spine Dislocation of thoracic and lumbar spine
Paraplegia Integration of traditional Chinese and modern medicinal therapy

(Original article on page 9)

Experimental study and clinical observation on ankylosing spondylitis treated with Chinese drug Feng Shi Ling

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Third Affiliated Hospital, Hubei College of Medical Science (055051)

Animal experiments mimic as ankylosing spondylitis treated with Chinese drug Feng Shi Ling showed that there is an anti-inflammatory action on edematous foot induced by Irish moss glue, and prominent inhibitory action of the allergic inflammatory reaction and inhibiting

hemolysin and reaction with increasing weight of the spleen and thymus produced by late allergic reaction as well. Among 38 cases of patients, the therapeutic results indicated that 10 were alleviated; 17, markedly improved; 9, improved; 2, in effective.

Key Words Feng Shi Ling Ankylosing spondylitis Traditional Chinese medicinal therapy

(Original article on page 12)

A study on stress adaptability of fracture healing

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A sliding mechanical loading controller with strong physiological adaptability was designed without stress shading of the fracture site. The muscle force and body weight exerted on the extremity thus were treated as the dynamic source of the mechanical loading. The force condition of the fracture site during functionally moving and over whole healing progress of the rabbits were recorded with force transducers and related amplifiers etc. The experiments indicated that the compressive force of the fracture site changed in relation with the muscle contraction and moving of the gait, the mean load increased along with the time prolonged, and the loading on the sliding mechanical loading controller gradually decreased from 2.4 kg in average on the day of operation to that of 0.78 kg till 5 weeks on the fractured tibia during healing process. On the other hand, under anatomical microscopic observation, the original fracture site is thoroughly enrolled by external callus, thus it is realized that the force changed on the fracture site indicating functional recovery of the extremity, and a reflection of compressive loading sustained by the callus on the fracture site. It is suggested that the muscle contract during functional training in time and body weight bearing after fixation of the fracture may offer an optimized mechanical environment, a physiological stress condition.

Key Words Fracture healing Biomechanics

(Original article on page 16)

Preliminary study of fracture healing detected by B ultrasonic histogram

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More than 90 tests of 33 places of fracture in 20 patients with B ultrasonic histogram were detected. Echo and morphological changes with various period of bone-healing could be revealed with B ultrasonic examination. Quantitative measurements were undertaken via histogram. The color parameter of early stage of bone healing is processed with international statistical analytical system(SAS) to analyze multivariate and principal component analysis. The results showed that the method provide a scientific quantitative index in bone healing clinically, and it is earlier than X ray and without radiating hazard. It widens B ultrasonic application in the field of orthopaedics.

Key Words B ultrasonic Histogram Bone healing

(Original article on page 37)