Patellar fracture fixation: biomechanical characteristics of static and dynamic compression

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Abstract

BACKGROUND: Static compressure effect between the fracture fragments was generated by fixation itself (tension band wire and screw), but dynamic compression effects were generated during flexion. Mechanical strength and stability of patellar fracture fixation have obvious advantages. However, there are lacks of quantitative comparative studies on static and dynamic compression effects of these fixation methods.
OBJECTIVE: To observe strength changes and clinical significance of static and dynamic compression using four fixation techniques.
METHODS: Standardized transverse patellar fracture models were created with fresh cow patellas. The patellas were randomly divided into four groups: fixation was accomplished with modified tension band wiring (wire group); modified tension band with braided cable (cable group); interfragmentary screws (screw group); cannulated screw tension band with wire (cannulated screw group). Before fracture fixation, Fuji pressure-sensitive film was laid among fracture fragments to measure the pressure among fracture fragments after fixation, *i.e.*, static and dynamic compression. Model of each group was measured as follows: (1) after fixation, the fixation was removed, and the Fuji pressure-sensitive film was taken out; (2) after fixation, material testing machine was used. Samples underwent a three-point bending test with a 5 000 N load, simulating dynamic compression during knee flexion. Subsequently, Fuji pressure-sensitive film was taken out. Each Fuji pressure-sensitive film was tested using prescale FPD-8010E software. Thus, average pressure among broken bone ends was obtained, and statistical analysis was performed. Static and dynamic compression among broken bone ends was compared in each group.
RESULTS AND CONCLUSION: Average static compression was significantly lower in the wire group than in the cable group, screw group and cannulated screw group ($P < 0.05$). Under 5 000 N load of dynamic compression, similar compression among broken bone ends was visible among wire group and cable group, screw group and cannulated screw group ($P > 0.05$). Dynamic compression was higher than static compression in the wire group ($P < 0.05$). Results verified that compared with modified tension band wire fixation technique, cable or screw could evidently increase static compression among broken bone ends, but simultaneously weaken dynamic compression among broken bone ends.

Subject headings: biomechanics; patella; fractures, bone; fixed
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INTRODUCTION

Early concepts of load transfer in bone were developed and described by Pauwels[1], who showed that a curved tubular structure placed under an axial load had a tension side and a compression side. Based on this theory, he described the application of internal fixation on the tension side to convert tensile force (caused by attached muscle pulling) into compressive forces at the fracture site (**Figure 1**). This conversion of forces is called dynamic compression. When static compression is directly applied by the implant (*e.g.*, creating compression with a screw or wires) without external loading, dynamic compression develops during joint flexion, as with a patellar fracture.

During the 1970s, the AO Group modified and recommended the tension band wiring technique, which has proved to be the most common method of transverse patellar fracture fixation[2]. Today, however, many new internal fixation materials are widely used for the tension band technique: Carpenter *et al* [3] combined interfragmentary/cannulated screw fixation with the tension band principle; Scilaris *et al* [4] and Prayson *et al* [5] used braided cable tension loop, instead of monofilament wire. Tian *et al* [7] applied the titanium cable-cannulated screw tension band technique. Burvant *et al* [8] and Dargel *et al* [9] confirmed that mechanically, the addition of the screws to the tension band techniques was superior to the tension band wiring technique. Schnabel *et al* [10] suggested that compression staples have a promising potential to treat transverse patella fractures. Wright *et al* [11] demonstrated that fiber wire is a potentially superior alternative to stainless steel wire in tension band fixation of transverse patellar fractures. These new fixation methods are based on the tension band technique.

Many studies have evaluated the fixation stability or stiffness of various patellar fixation techniques by measuring displacement for a given monotonic/cyclic load[4-10, 12-13], or measuring peak load to generate a given displacement[5-6, 9], or measuring the fracture gap during simulated extensions of the knee and the maximum load to failure at a given degree of flexion on a material testing machine, or measuring interfragmentary compression (static compression) with a load transducer[3, 12, 14-15]. Alternatively, samples were subjected to a cyclic loading test using a three-point bending test[11, 15]. Almost all studies declared that the biomechanical performance of those new internal fixation materials was superior to the tension band wiring technique. No study, however, has clarified the changes or the significance of static and dynamic compression associated with the use of these methods. Can these new fixation techniques provide better static compression and/or dynamic compression? Whether or not the increase of static compression would weaken dynamic compression? What does all this mean to tension band technique? To address some of the questions about the effects of these methods, this study conducted biomechanical tests to evaluate static and dynamic compression using four established fixation techniques.

MATERIALS AND METHODS

Design

A single-factor and four-level completely random control experiment.

Time and setting

The experiment was conducted in the Laboratory of Orthopaedics and Traumatology, Peking University People's Hospital in China from October 2012 to March 2013.

Materials

Materials and equipment used in this study are listed as follows:

Materials and equipment	Source
2.0-mm Kirschner wires; 1.0-mm stainless steel monofilament wire	Siya Longling Trading Co., Ltd., Beijing, China
1.3-mm braided cable	Cable-Ready System; Zimmer, Warsaw, IN, USA
4.5-mm interfragmentary screws; 4.0-mm cannulated lag screws	Synthes, West Chester, PA, USA
Fuji Prescaler Pressure-Sensitive Film	Fuji Film, Tokyo, Japan
Material Testing Machine	AG-100kNXplus; Shimadzu, Kyoto, Japan

A total of 48 fresh cow patellas were obtained from the local slaughter house, and all of soft tissues were removed. All the patellas were similar in size and weight. Specimens were stored at −20 ℃ until use.

Methods

Experimental groups and interventions

In each specimen, 2-mm drill holes were made at 2.0-cm intervals for placement of Kirschner-wires or screws. A standardized transverse fracture was then created in the middle of the patella using an electric motor saw. All patellas were randomly divided into four equal groups. Each group was performed with one of four internal fixation techniques (**Figure 2**).

Wire group: Modified tension band wiring technique: 2.0-mm Kirschner wires and a 1.0-mm stainless steel monofilament wire;
Cable group: Modified tension band with braided cable: two 2.0-mm Kirschner wires and a 1.3-mm braided cable;
Screw group: Fixation with two AO 4.5-mm interfragmentary screws;
Cannulated screw group: Cannulated screw tension band with wire: two AO 4.0-mm cannulated lag screws plus a 1.0-mm stainless steel wire through the screws.

Cow patella transverse fracture fixation

Twelve specimens were fixed by each technique, with six samples tested for dynamic compression and six for static compression. For the modified tension band technique, two 2.0-mm Kirschner wires were placed longitudinally across the fracture site, and a 1.0-mm wire or 1.3-mm braided cable was secured around the Kirschner wires anteriorly in a horizontal figure-of-eight pattern. For the wire group, the wire bands were twisted at two adjacent corners to provide even tension (**Figure 2A**).

For the cable group (**Figure 2B**), a cable pin was available with the Cable-Ready Cable Grip System. The cable was inserted into the crimper tensioning handle, which was keyed into a hex on the cable pin crimper. The cable was tensioned by turning the handle. A scale on the crimper handle indicated the tension. To adjust the tension when the same scale (highest tension) had been achieved, the handles of the crimper were squeezed until a click was heard. The handles then automatically opened.

Fixation in the screw group was accomplished using two parallel 4.5-mm cortical screws (**Figure 2C**). The proximal pole was overdrilled so the screws acted as lag screws, providing compression across the fracture site. Cannulated screw group combined features of the first and third techniques (**Figure 2D**). The fracture was first fixed with two parallel 4.0-mm cannulated screws lagged across the fracture site. A 1.0-mm stainless steel wire was then threaded through the cannulated screws to create a horizontal figure-of-eight pattern tension band across the anterior surface of the patella, with two twists of the wire placed at adjacent corners of the samples.

All screws were twisted into the fracture models until the screws could not be screwed any further. The wires were twisted until they broke to reach the maximum interfragmentary static compression force of each mode[15], or they were twisted as tightly as possible (and were replaced with a new wire if they broke) before testing the dynamic compression. All operations were performed by the same person.

Fuji prescaler pressure-sensitive film was used with the following parameters: 5 cm × 4 cm; two-sheet type; measurement range 0.5–2.5 Mpa (0.5–2.5 N/mm^2)[16-17]. The time of retention at the pressure to be measured was 2 minutes. Pieces of this film were placed between the fragments before fixing the fracture. Half of the fixation of each technique was removed, and the Fuji films were removed for static compression evaluation. The other half of the fixed samples were placed in the material testing machine[14-15]. A three-point bending test was then performed with a load of 5 000 N, which was derived from pre-experiment testing so it would not lead to compression fracture or wire breakage. It simulated the dynamic compression that develops during knee joint flexion. The Fuji film pieces were then removed for evaluation of dynamic compression.

Data analysis

Data were quantified using Fuji film pressure distribution mapping software (FPD-8010E). Before scanning the film, a calibration sheet was used to limit scanner-read errors to a fixed range, thereby ensuring the best accuracy from the Fuji Digital Analysis System. The calibration sheet created a correlation between color density and the absolute pressure value. The analysis was performed utilizing FPD-8010E software, which determined the average pressure on a piece of Fuji film.

Main outcome measure

There were mean values for static compression and dynamic compression for the four groups, differences in static compression or dynamic compression between groups, differences in static compression and dynamic compression of each group.

Statistical analysis

The mean values for static compression and dynamic compression were expressed as the mean and standard deviation. Statistical analysis was performed using SPSS 17.0 software (SPSS, Chicago, IL, USA). Differences in static compression or dynamic compression between groups were analyzed with one-way analysis of variance followed by the Bonferroni *post hoc* test. The values for static compression and dynamic compression of each group were analyzed by the unpaired sample t test. A value of $P < 0.05$ was considered statistically significant.

RESULTS

Quantitative analysis of experimental samples

Test results of all the samples were taken into account with their analytics, and no samples were lost or excluded.

Static compression changes after fixation for patellar fracture

There were significant differences between the four groups regarding the mean values for static compression (F=30.128, P=0.000, one-way analysis of variance). Wire group had the least interfragmentary static compression ($P < 0.05$). There were no significant differences between three other groups ($P > 0.05$). Cable group (with braided cable) achieved static dynamic compression similar to that in screw groups and cannulated screw group. Compared with screw group, cannulated screw group (addition of the tension band wire to the screws) did not significantly increase static compression (**Figure 3**).

Dynamic compression after fixation for patellar fracture

A 5 000-N load caused no significant differences in the mean dynamic compression between the four groups (F=2.381, P=0.100, one-way analysis of variance). The dynamic compression of wire group was similar to that of three other groups (**Figure 4**).

Static compression *versus* dynamic compression after fixation for patellar fracture

This 5 000-N load significantly increased the average dynamic compression relative to the static compression only in wire group (P=0.000). There were no significant increases in dynamic compression pressures when compared with static compression in cable, screw and cannulated screw groups ($P > 0.05$; **Figure 5**).

DISCUSSION

A three-point bending test simulated the progress of dynamic compression. In John *et al* 's study[15], samples were subjected to a cyclic loading test using a three-point bending test. Dynamic compression develops with joint flexion, as with a patellar fracture, and the tensile forces (*e.g.*, between the quadriceps muscle and the tibial tuberosity) cannot convert to compressive forces without the support or resistance of the femoral trochlea. That is, the tensile forces must be converted to a compressive articular contact load, effectively putting the entire structure (patella and/or Kirschner wires) in a bending position, which then converts to an interfragmentary compression, a three-point bending test can simulate the progress of converting tensile force into compression force (*i.e.*, dynamic compression) at the opposite cortex during knee joint flexion.

The increased static compression weakened the effective dynamic compression and the process of mechanotransduction. The use of cable in conjunction with Kirschner wires or interfragmentary screws or of cannulated screws with wires provided significantly greater static compression. However, it had less effect on dynamic compression than the classic modified tension band wiring technique consisting of two Kirschner wires and monofilament wire. Dynamic compression can provide additional interfragmentary compression during joint flexion, which can induce osteoblasts to grow,

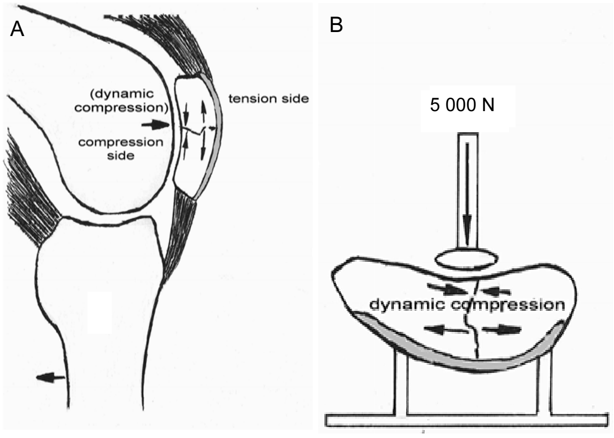

Figure 1 Converting tensile forces into compressive forces

Note: A: The application of internal fixation on the tension side to convert tensile forces into compressive forces at the patellar fracture site, dynamic compression develops during joint flexion. B: A three-point bending test can perfectly simulate the dynamic compression developed during knee joint flexion, with a load of 5 000 N.

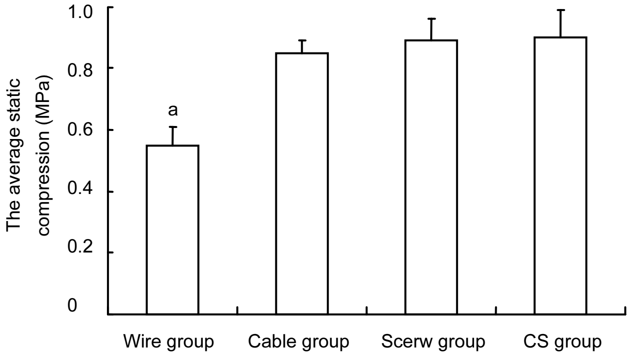

Figure 3 Multiple comparisons of static compression between four fixation groups

Note: There were significant differences in the means between the four groups (F=30.128, P=0.000). The average static compression between fragments in wire group was significantly less than in the other three groups ($^{a}P < 0.05$). There were no significant differences between in three other groups ($P > 0.05$). Data are expressed as mean ± SD in all samples for each group (n=6; one-way analysis of variance followed by the Bonferroni *post hoc* test). CS: Cannulated screw.

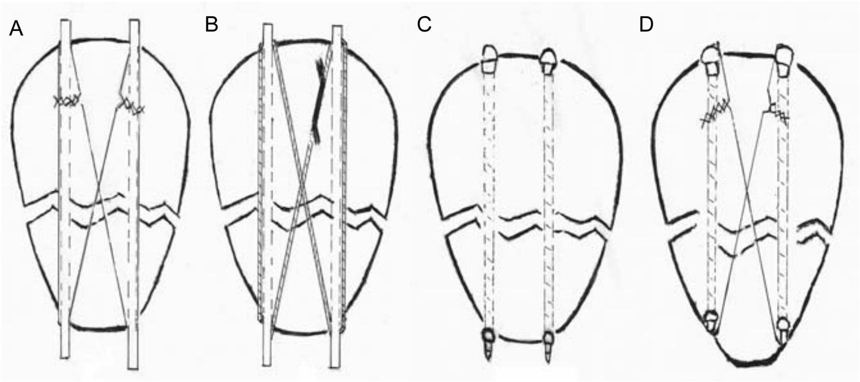

Figure 2 Fixation with four techniques for patellar fracture

Note: A: Modified tension band wiring (wire group); B: Modified tension band with braided cable (cable group); C: Interfragmentary screw fixation (screw group); D: Cannulated screw tension band with wire (cannulated screw group).

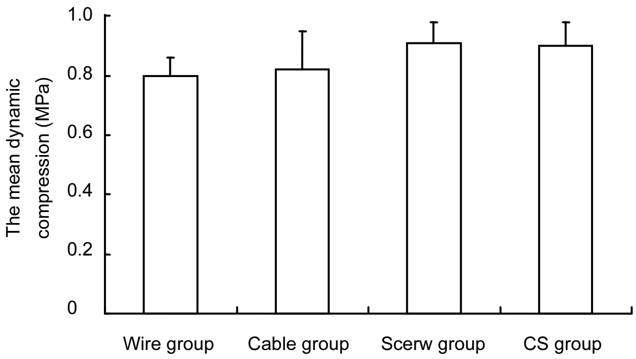

Figure 4 Multiple comparisons between the dynamic compression of four fixation groups

Note: Loaded with 5 000 N, there were no significant differences in the means between the four groups (F=2.381, P=0.100). Wire group had a similar dynamic compression to other three groups. Data are expressed as mean ± SD (n=6) in all samples for each group. One-way analysis of variance followed by the Bonferroni *post hoc* test was used. CS: Cannulated screw.

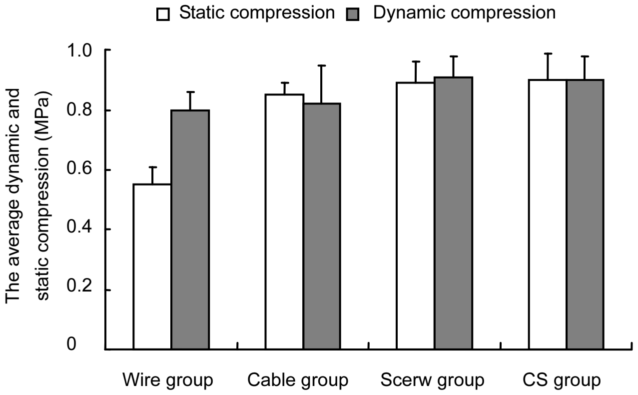

Figure 5 Unpaired sample t-test between the average static and dynamic compression pressures of four fixation techniques

Note: Loaded with 5 000 N, the average dynamic compression pressure was significantly increased relative to static compression only in wire group (P=0.000). Data are expressed as mean ± SD (n=6) in all samples for each group (unpaired sample t-test). CS: Cannulated screw.

thereby promoting bone healing. Dynamic mechanical loading can promote osteogenesis through the process of mechanotransduction[18], using appropriate mechanical tension-stress, does not break the callus but rather it stimulates and maintains osteogenesis[19]. The interfragmentary pressure should be higher under dynamic compression than under static compression. The classic modified tension band wiring can generate good dynamic compression but poor static compression (unstable fixation). This is because if the wire is tightened too much for interfragmentary compression, the wire may break, causing fixation failure. A flexible fixation of the fractured site can induce fracture callus formation, whereas an unstable fixation can lead to a nonunion[20]. If monofilament wire is replaced by braided cable, the static compression and the fixation stability would increase significantly, but the effect of dynamic compression and the process of mechanotransduction would also weaken. As opposed to secondary healing in cortical bone, healing in cancellous bone (patella) occurs without the formation of significant external callus. Under stable conditions, cancellous bone healed by direct formation of woven bone, instability resulted in an internal cartilaginous callus[21]. Less fixation rigidity and increased fracture gap induce a later response of bone formation and greater endochondral bone formation, leading to prolonged time for full ossification[22]. Thus, for patella (cancellous bone) healing, enhancing stability by increasing static compression should be prior to dynamic compression.

The more rigid fixation, the less dynamic compression was. This study performed the three-point bending test at 5 000 N, which is far more than a physiological loading force. The peak patellofemoral joint reaction force of humans during forward step-down is (51.1±2.7) N/kg[23] –about 3 500 N for 70 kg of weight. Hence, with fixation using the tension band technique *in vivo*, dynamic compression should be weaker than our test at 5 000 N *in vitro*. Nevertheless, in our experiments, there were still no significant increases in dynamic compression pressures when compared with static compression. Why? The use of Kirschner wires must resist the bending stress exerted on the concave side with joint flexion, and dynamic compression should be reduced. The larger the diameter of the Kirschner wires, the stronger the resistance to bending stress on the concave side is and with less dynamic compression. If Kirschner wires were replaced by more rigid fixation (*e.g.*, a lag or cannulated screw), which can generate better static compression, dynamic compression would be almost unmeasurable.

How should we think about the contradiction between static and dynamic compression? The principles of the tension band technique should include two components: (1) fixation on the side of tension stress (*e.g.*, the convex side or extra-articular anterior surface of the patella); (2) application of a tension band to neutralize or, ideally, convert tensile force (*e.g.*, between the quadriceps muscle and the tibial tuberosity) into compression force at the opposite cortex when the joint is flexed. The current patellar fracture fixation techniques seem to follow only the principle of fixation on the side of tension stress. This usage loses sight of the effect of dynamic compression, although it is highly praised for the more stable fixation with more static compression[3-4, 7-10, 14], but is that a bad thing?

The more rigid fixation, the better biomechanical performance is. Although the effect of fixation with braided cable or screws on dynamic compression is not better than with the traditional tension band fixation with Kirschner wires and monofilament wire, many studies have shown that the biomechanical performance of the screw fixation system is superior to that of the tension band wiring technique[3-9, 24-28]. Addition of screws to tension band techniques reduces fracture separation by providing compression throughout the range of motion and by resisting tensile loading during terminal extension[8]. Some studies with simulated knee extensions proved that fractures stabilized with a modified tension band are displaced more often than those fixed with screws alone or screws plus a tension band[3-4]. Fractures fixed with cannulated screws plus the tension band failed at higher loads than those stabilized with screws alone or those with a modified tension band[8-9]. Tested by applying a cyclic load, the screws plus tension band technique was performed significantly better than the screws alone or the modified tension band, with a smaller fracture gap[3-4, 8]. Regarding the modified tension band, the braided cable tension loop was superior to the monofilament wire tension loop during cyclic loading[4-5, 11-12].

The greater static compression, the more stable fixation is. Although dynamic compression must exist regardless of whether it can be measured, the fact is that greater static compression is associated with more stable patellar fixation and less dynamic compression. Therefore, the prime aim of current patellar fracture fixation techniques is more stable fixation with high static compression-giving little thought to dynamic compression, which does reduce the displacement of a fragment under a load[3-14] and ensures good healing of patellar fractures[3-14, 27-29]. Simple wiring techniques alone may provide better dynamic compression, but not provide sufficient fixation to allow immediate range of motion[26, 30]. In that sense, compared with dynamic compression, more stable fixation with greater static compression is more necessary, more advantageous, and more efficient, so this is not a bad thing.

For now, the stronger static compression, the better fixation technique is. The strength of static compression depends on the strength of the wire or braided cable or on the compression of screws. Although addition of the tension band wire to the screws did not significantly increase static compression in our test, it can effectively resist tensile stress on the convex side of the patella during cyclic loading[3-4, 8, 14]. Combining interfragmentary screw fixation with the tension band principle appears to provide better stability than the modified tension band or screws alone for transverse patellar fractures[3, 8, 14]. Thus, under physiological cyclic loading conditions, addition of the tension band wire or cable is still effective. In patella fractures, cannulated screws with tension band wiring technique provide stable fixation, allows early motion exercise[25-26] and maintains an anatomic reduction in oteoporotic bone[28]. Nevertheless, in Baran study, cyclic loading tests indicate that all tension band wiring applications lose their initial stability, excessive initial compression by the tension band resulted in bending of the Kirschner wire and thus reduction failure[29-30]. At present, if stability and dynamic compression cannot be balanced, although expensive, combining interfragmentary cannulated screw fixation with the tension band (cable) principle seems to be the best choice for achieving osteosynthesis of transverse patellar fractures, because it provides the most stable fixation and the best static compression. A new fixation technique for both stable fixation and dynamic static may be developed in the future.

The numerical values in this study are thus not the same as would be found in humans, although the conclusions should be the same. The cow model of a patella used in this test has much higher bone density and is also much more likely to allow higher wire or cable tension or interfragmentary screw compression than in human bone. Therefore, the load is increased for the three-point bending test accordingly, although is far higher than the physiological loading force on the human patella. However, it was much easier to find similar cow models than cadaveric patellas. With this in mind, we were able to focus our study on the interesting biomechanical characteristics of fixation techniques, without the wide variations that may caused by differences in properties of cadaveric patellas[9, 14-15], such as shape and bone density.

Comparing current patellar fracture fixation techniques, the use of braided cable or screws provided significantly greater static compression, but had less effect on dynamic compression than the classic modified tension band wiring technique consisting of two Kirschner wires and monofilament wire. The increased static compression may weaken the effect of dynamic compression. At present, more stable patellar fracture fixation with high static compression can be achieved by combining interfragmentary cannulated screw fixation with the tension band (cable) principle.

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髌骨骨折植入物内固定评价：动力和静力加压的生物力学特点

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文章亮点：

1 经典的改良张力带内固定技术可以产生良好的动力加压作用，但静力加压强度则较差。目前髌骨折固定技术的主要目的是提供更大静力加压强度的更稳定的固定，即使同时消弱了动力加压作用。

2 文章首次测量并对比了目前常用髌骨骨折内固定方法导致的动力和静力加压强度变化，发现髌骨骨折应用螺钉结合张力带固定原则，比改良张力带或单独螺钉固定提供更好的稳定性。

关键词：

植入物；骨植入物；髌骨骨折；骨关节生物力学；动力加压；静力加压；张力带内固定；生物力学；骨内荷载传递；张应力；压应力

主题词：

生物力学；髌骨；骨折；固定

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摘要

背景：骨折块间的静力加压作用由内固定本身(如张力带钢丝和螺钉)产生，而动力加压作用在关节屈曲时产生。髌骨横行骨折张力带固定方法的力学强度和稳定性方面优势明显，但尚缺乏对这些内固定方法的静力和动力加压作用的量化对比研究。

目的：观察目前4种髌骨骨折内固定方法的动力和静力加压作用的强度变化及其临床意义。

方法：选择新鲜牛髌骨制作相同横行骨折模型，随机分成4组，钢丝组用改良张力带钢丝固定技术固定，钢缆组用改良张力带钢缆固定技术固定，螺钉组用单纯加压螺钉内固定技术固定，空心螺钉组采用空心螺钉+张力带钢丝联合固定。进行骨折固定前，于骨折块间放置富士压力敏感膜，用以测量内固定后骨折块间的压力，即静力和动力加压强度。每组骨折固定模型再分别进行以下两种力学测试：①固定完成后即拆除内固定，取出压力敏感膜。②完成内固定后，使用材料试验机，对样本进行3点弯曲试验(5 000 N载荷)，模拟膝关节弯曲时产生的骨折块间动力加压作用，而后取出压力敏感膜。使用prescale FPD-8010E压力分布图系统软件对每个取出的压力敏感膜进行测量，获得骨断端间的平均压力，并进行统计学分析，比较各组骨断端间的静力和动力加压强度。

结果与结论：钢丝组骨折块间的平均静力加压强度显著低于钢缆组、螺钉组和空心螺钉组(P < 0.05)。5 000 N载荷下动力加压后，钢丝组与钢缆组、螺钉组和空心螺钉组相比较具有相似的骨断端间压力强度(P > 0.05)。钢丝组的动力加压强度高于其静力加压强度(P < 0.05)。结果证实，比起改良张力带钢丝固定技术，使用钢缆或螺钉可以更显著的增加骨断端的静力加压强度，但同时也削弱了骨断端的动力加压作用。

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作者贡献：徐峰博士参与本项目立项、实验测试、数据整理分析和论文写作等全过程；刘克敏博士负责本项目的立项、实验测试和统计分析及写作的全面审查和指导；王安庆教授、殷晓峰博士和闵红巍博士共同参与立项、实验测试、统计分析和论文修改等方面的工作。

利益冲突：文章及内容不涉及相关利益冲突。

学术术语：动力加压-由于附着肌肉的牵拉，将骨折处的张应力转化为压应力，这种应力转化即是所谓的动力加压。动力加压在关节屈曲活动时产生，如髌骨骨折内固定术后，膝关节屈曲时在骨断端产生的应力转化。静力加压-骨折块间的由内固定本身(如张力带钢丝和螺钉)直接对骨断端加压产生。

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