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Making Minimally Invasive Thr Safe: Conclusions From Biomechanical Simulation and Analysis

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ORIGINAL PAPER

Making minimally invasive THR safe: conclusions from biomechanical simulation and analysis

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Abstract The use of smaller surgical incisions has become popularized for total hip arthroplasty (THR) because of the potential benefits of shorter recovery and improved cosmetic appearance. However, an increased incidence of serious complications has been reported. To minimize the risks of minimally invasive approaches to THR, we have developed an experimental approach which enables us to evaluate risk factors in these procedures through cadaveric simulations performed within the laboratory. During cadaveric hip replacement procedures performed via posterior and antero-lateral mini-incisions, pressures developed between the wound edges and the retractors were approximately double those recorded during conventional hip replacement using Charnley retractors ($p<0.01$). In MIS procedures performed via the dual-incision approach, lack of direct visualisation of the proximal femur led to misalignment of broaches and implants with increased risk of cortical fracture during canal preparation and implant insertion. Cadaveric simulation of surgical procedures allows surgeons to measure variables affecting the technical success of surgery and to master new procedures without placing patients at risk.

Places where work was performed: The Institute of Orthopedic Research and Education and The Methodist Hospital, Houston, TX.

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Introduction

In recent years, minimally invasive surgical techniques have been popularised for total hip arthroplasty as a means of causing less trauma to soft tissues. Despite the promise of these developments, hip surgeons universally recognise that these new techniques carry an increased risk of complications, including infection, fat and skin necrosis, neuro-vascular injuries, component malpositioning, femoral fractures, leg length discrepancies and prosthetic instability [1–8]. As many of these complications have a biomechanical component, we have developed an experimental approach to the systematic analysis of the variables affecting bone preparation and implant placement in THR through laboratory simulation of MIS procedures using human cadavers.

Simulation of the operating room environment

To avoid exposing patients to experimental procedures or operations in which there is a significant risk of technical complications, we perform surgery on fresh human cadavers in a controlled laboratory setting. In this environment many of the variables affecting operative procedures may be standardised. In addition, experimental techniques may be utilised to measure variables affecting the technical success of surgery. In the case of minimally invasive hip arthroplasty, we monitor the position and orientation of the instruments and implants during the operative procedure with surgical navigation and fluoroscopy. After the surgical procedure, we can recreate the insertion path of each instrument and the implants virtually, by combining a computer model of the pelvis and femora, generated from CT scans, with CAD models of the instruments and implants. Using this technique, we are able to replay the procedure on the computer screen, and monitor variations in component positioning or the placement of instruments. Based on this information, we can objectively assess whether under-sizing or malalignment of instruments occurred, potentially leading to cortical fractures. Additional techniques have been developed to allow real-time measurement of loads applied to skin and bone during operative procedures. The deformation of skin and adjacent tissues may be monitored during retraction of the incision and preparation of the femur and the acetabulum. We also monitor the forces applied to rasps and implants during insertion into the femur through attachment of strain gauges and acceleration transducers to each device, and by using a special mallet with an impact-sensitive head to drive the implants and instruments into the bone.

Applications

Tissue pressures developed during MIS THR

We have performed a series of experiments in which experienced hip surgeons performed 30 THR procedures in 14 fresh cadavers via posterior and antero-lateral incisions of 6–9 cm in length. We measured the deformation of the implantation site during each of these procedures by tattooing a grid of markers onto the skin overlying the hip which allowed us to record the displacement of the grid intraoperatively. The magnitude and direction of skin deformation was determined through computer analysis of digital photographs of the marker grid at key stages of each procedure (Fig. 1). The contact forces and interface pressures developed between the wound edges and the surgical retractors, and the femoral and acetabular reamers were measured with deformable contact transducers placed within the wound. For comparative purposes, the skin pressure measurements were also performed after placement of a standard Charnley self-retaining retractor within each incision. These measurements were repeated at the end of each experiment after extending the initial mini-incision from 6–9 cm to a conventional length of 20 cm.

During each procedures, the pressure developed between each retractor and the edges of the incision were relatively non-uniform, with average values of 1,500–2,200 mmHg during preparation of the femur and 1,400–1,800 mmHg during reaming of the acetabulum. Much higher values were observed in discrete areas over the surface of each retractor, with peak pressures ranging from 2,600–5,400 mmHg during access to the femur and 2,400–5,000 mmHg during access to the acetabulum. In comparison, average pressures between the Charnley self-retaining retractors and the wound edges decreased only slightly when the incision was extended from 6 cm to 20 cm (1,800 mmHg vs. 1,500 mmHg), whereas, peak values were almost halved (average reduction: 47%; 2,020 mmHg vs. 3,800 mmHg). The force applied to the wound edges averaged 40–45 N during procedures performed via 6-cm incisions, close to three times higher than observed using Charnley self-retaining retractors with the conventional (20 cm) incision.

During each procedure the incision was elongated by an average of 95–130%, which was greatest during acetabular reaming (115–150%). The only instances of skin maceration occurred in some cases at the ends of the incision, secondary to excessive stretching and abrasion through contact with the edges of retractors or instruments. The overall increase in incision length during these experimental procedures was typically 1.0–1.5 cm, primarily due to permanent stretching of the skin. Detailed analysis of the digital photographs demonstrated that there was a total increase in the exposed wound area of 195–255% during acetabular preparation, and 110–350% during femoral preparation.

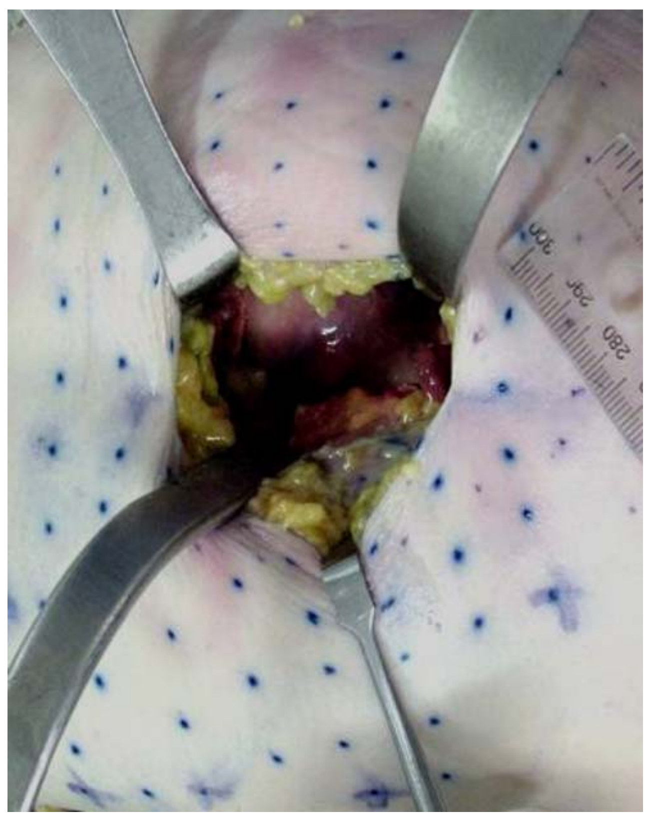

Fig. 1 Typical view of a posterior mini-incision showing the tattooed grid and the pattern of skin displacement

The biomechanics of intra-operative fractures during MIS procedures

Intra-operative femoral fractures are a disturbing complication of hip replacement procedures performed via the anterior and dual incision approaches [1, 3, 9]. To investigate the mechanics of this complication, we have performed THR on cadavers in which devices (strain gages) were attached to the femur prior to surgery to monitor strains developed within the bone during every stage of the procedure.

We performed a series of total hip replacement procedures in which femoral stems of the Zweymuller design were implanted in cadavers via the dual incision of Berger, consisting of a 50-mm anterior incision for exposure of the acetabulum and a 25-mm posterior incision for femoral preparation and stem insertion [10]. Prior to THR surgery, strain gauges were attached to the cortices of each femur at five key sites located proximally (medial, anterior and posterior), distally (lateral), and in the mid-stem (medial) region.

The magnitude and distribution of strains in the femur varied extensively with the magnitude of the impact delivered, the alignment of the rasps and stems and the difference in shape between the canal and the prosthesis. In general, cortical strains increased with the progression of rasp sizes and were largest during stem insertion. Strains also varied with location on the cortical surface and were largest in the proximal medial region and also the distal lateral regions, especially in cases where the stem was placed in a varus alignment. In several instances, we measured strains approaching the fracture limit of cortical bone, and in one instance a cortical crack was observed (Fig. 2). The measurements of rasp impact and acceleration demonstrated that significant impact forces are generated in the medial and anterior/posterior directions during manual impaction of the rasp.

Statistical analysis of the cortical strain data from over 100 recordings showed that primary factors contributing to fracture risk were high impact forces and misalignment of the femoral rasp. A secondary factor was the direction of impact applied to the rasp or implant. Further investigation using computer reconstruction of the femur and implant demonstrated that implant misalignment was caused by mal-placement of the entry point into the proximal femur.

Discussion

All minimally invasive hip replacement procedures are designed to provide the surgeon with access to the femur and the acetabulum. These procedures may be made less traumatic than conventional THR if the femur and acetabulum can be exposed with minimal cutting of muscle, tendon and capsule [1, 11–15]. This requires that the surgeon is able to determine precisely, in advance, where the initial skin incision needs to be placed in order to provide the most direct access for instruments and implants to the femur and acetabulum [16]. To a large extent, the most efficient use of the access provided by the incision requires that the surgeon anticipate the necessary path of instruments and components rather than depending on the mobility of the incision and the femur to provide the necessary exposure.

This study demonstrates that, during THR performed via mini-incisions, large pressures are developed between the retractors and the wound edges, potentially leading to skin complications, including delayed wound healing and fat necrosis. The risk of these outcomes may be reduced through using the longest necessary incision to reduce tissue pressures to customary levels, through careful anatomic placement of the incision with respect to the skeleton and by minimising the duration of tissue compression beneath each retractor.

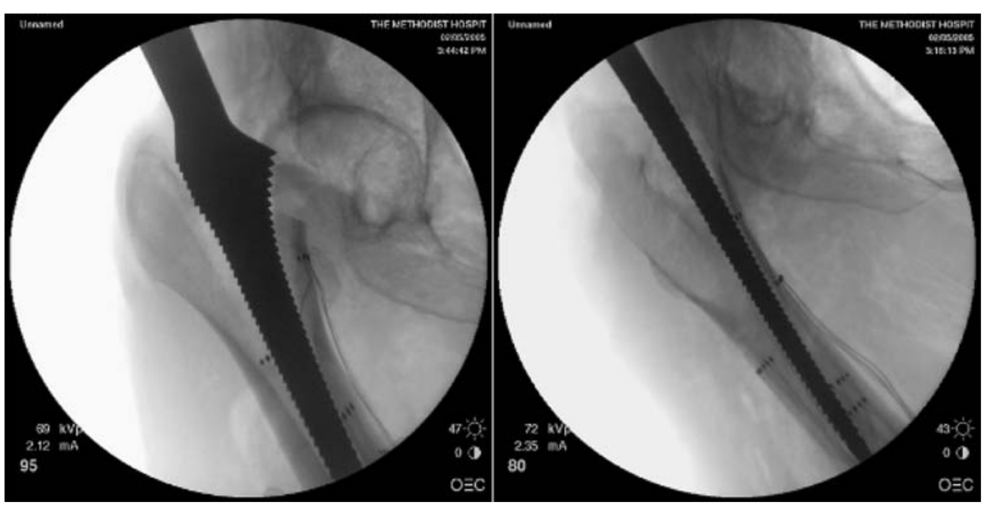

Fig. 2 Fluoroscopic images of broach malalignment during dual-incision MIS procedures

Our cadaveric simulations of minimally invasive procedures also confirmed that the dual incision of Berger increases the risk of femoral fractures [3]. This occurs because of several factors, including the direction and magnitude of forces delivered to the broach and implant and the alignment of components within the femur. In our experiments, the loss of visual and tactile feedback associated with the dual incision approach increased the tendency for malalignment to occur. These experiences suggest that careful preoperative preparation may be even more important if hip replacement is performed via minimally invasive approaches. It is clear that precise templating, proper rasp alignment and careful technique must be achieved with cementless THR to avoid malalignment and thus large femoral strains leading to fractures of the femur. This is particularly important in elderly and osteoporotic patients where bone stock is often compromised.

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