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INDEXING/ABSTRACTING

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EDITORS FOR THIS ISSUE

EDITORIAL

Conversion total hip arthroplasty: Primary or revision total hip arthroplasty

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Abstract

Total hip arthroplasty (THA) is an increasingly common procedure among elderly individuals. Although conversion THA is currently bundled in a diagnosis related group (DRG) with primary THA, there is a lack of literature supporting this classification and it has yet to be identified whether conversion THA better resembles primary or revision THA. This editorial analyzed the intraoperative and postoperative factors and functional outcomes following conversion THA, primary THA, and revision THA to understand whether the characteristics of conversion THA resemble one procedure or the other, or are possibly somewhere in between. The analysis revealed that conversion THA requires more resources both intraoperatively and postoperatively than primary THA. Furthermore, patients undergoing conversion THA present with poorer functional outcomes in the long run. Patients undergoing conversion THA better resemble revision THA patients than primary THA patients. As such, patients undergoing conversion THA should not be likened to patients undergoing primary THA when determining risk stratification and reimbursement rates. Conversion THA procedures should be planned accordingly with proper anticipation of the greater needs both in the operating room, and for in-patient and follow-up care. We suggest that conversion THA be reclassified in the same DRG with revision THA as opposed to primary THA as a step towards better allocation of healthcare resources for conversion hip arthroplasties.

Key words: Conversion total hip arthroplasty; Primary total hip arthroplasty; Revision total hip arthroplasty; Hip fracture; Post-operative complications

Core tip: Conversion total hip arthroplasty (THA) is a challenging procedure that requires more resources both intraoperatively and postoperatively than primary THA. As such, these procedures should be planned to anticipate the greater needs in the operating room, and for in-patient and follow-up care. Patients undergoing conversion THA should not be likened to

patients undergoing primary THA when determining risk stratification and reimbursement rates. We suggest that conversion THA be reclassified in the same group with revision THA as a step towards better allocation of hospital resources.

INTRODUCTION

Hip fracture is an increasingly common complaint encountered by orthopedic surgeons in the United States. With the elderly population steadily expanding, the number of hip fractures is expected to rise to over 580000 in 2040[1,2]. These fractures are typically treated with open reduction internal fixation, implantation of an intramedullary device or dynamic hip screw and plate, hemiarthroplasty, or total hip arthroplasty (THA)[3,4].

While operative treatments for hip fractures are generally successful, postoperative complications commonly occur. Complications that may occur following surgery include non-union and mal-union of the fracture, migration of hardware, osteonecrosis of the femoral head, infection, and post-traumatic osteoarthritis[5-11]. Failed surgical fixation of hip fractures for any of these reasons often necessitates conversion arthroplasty as a salvage treatment. Conversion THA is also performed due to a failed acetabular fracture fixation, a failed hemiarthroplasty, or after the development of osteoarthritis in patients with a history of previous hip surgery for developmental dysplasia of the hip.

The increasing incidence of fractures and osteoarthritis due to an aging population may contribute to rising numbers of conversion THA procedures performed today in the United States. Currently, the Center for Medicare and Medicaid Services classifies conversion THA in the same diagnosis related group (DRG) as primary THA. However, there is an absence of literature on whether patients receiving conversion THA and primary THA have similar clinical characteristics and success rates to support this classification. This report aims to fill that void by comparing the intraoperative and postoperative factors and success rates following conversion THA, primary THA, and revision THA.

INTRAOPERATIVE FEATURES OF CONVERSION THA

Conversion hip arthroplasties pose unique obstacles that make these procedures more challenging than primary THAs. Due to the additional time required for removal of internal fixation devices and previous implants, conversion THAs are longer cases on average[8,10]. Furthermore, there are often broken screws or other hardware defects that require even more time to remove and address successfully during conversion THAs[12]. Winemaker *et al*[9] reported that conversion THA cases last 95 min (± 32.8) compared to 76.7 min (± 26.1) for primary THA cases ($P = 0.015$). A study by Zhang *et al*[10] reported even longer surgical times, with conversion THA procedures lasting 176 min on average.

Previous studies also state that conversion THA procedures result in increased intraoperative blood loss[8-10,12]. This is because of the need to operate through old scar tissue during conversion THA that is not encountered in primary THA[8,10]. Srivastav *et al*[8] and Zhang *et al*[10] both reported mean blood loss of the conversion arthroplasties at about 1300 mL. Schnaser *et al*[12] compared the average blood loss during conversion THA to primary THA and demonstrated a significant difference between the groups, with 668 mL (SD 230 mL) lost in the conversion THA group and 270 mL (SD 230 mL) lost in the primary THA group ($P = 0.01$)[12]. Winemaker *et al*[9] reported results that trended towards a significant difference between the groups, with 521.7 mL (± 218.9) blood lost during conversion THA and 406.5 mL (± 190.9) during primary THA ($P = 0.06$).

POSTOPERATIVE FEATURES OF CONVERSION THA

Many surgical and medical complications have been reported to occur following conversion THA. Archibeck *et al*[5] reported that 12 of 102 patients (11.8%) who underwent conversion THA experienced early surgical complications. A study by D'Arrigo *et al*[6] reported similar complication rates at 9.5% following conversion THA. Some studies listed even higher complication rates, with Zhang *et al*[10] stating that complications occurred in 9 of the 19 conversion THA patients (47%). The most common surgical complications include fractures either intraoperatively or postoperatively, dislocations, and infections[13]. Other less common surgical complications include limb-length discrepancies, loosening of prosthesis components, heterotopic bone formation, muscle disruption and dysfunction, injury to the sciatic nerve, and hematomas[13]. Medical complications have included acute myocardial infarction, congestive heart failure, atrial fibrillation, pulmonary embolism, gastrointestinal bleeding, acute renal failure, paralytic ileus and urinary tract infections[13].

Studies have shown that the complication rates following conversion THA are higher than the rates following primary THA[12,14,15]. This is in accordance with previous literature that states infection rates increase in previously operated areas with additional hardware[16]. McKinley *et al*[15] identified a statistically higher rate of superficial infections and dislocations following conversion THA than primary THA. That study also

indicated that the patients who underwent conversion THA are more likely to require a revision procedure after one year than the patients who received primary THA.

FUNCTIONAL OUTCOMES OF CONVERSION THA

Researchers commonly use the Harris Hip Score (HHS) to determine a patient's level of function either before or after a hip arthroplasty. A review of seven papers by Schwarzkopf et al[13] demonstrated that the mean pre-conversion HHS was 36.9 (range, 13 to 74), and the mean post-conversion HHS was 80.7 (range, 30 to 100). Overall, the functional outcomes of these patients were significantly better after conversion THA, with a mean improvement in HHS of 43.7 (range, 37 to 47.6) ($P < 0.05$). However, two studies have compared the HHS of patients receiving conversion THA to those of patients receiving primary THA and they both reported significantly lower HHS in the conversion THA cohort, which indicates a worse level of function in this population[12,15]. Schnaser et al[12] listed an average HHS of 70 in the post-conversion THA group, compared to an average HHS of 90 in the post-primary THA group. According to these studies, conversion THA results in lower success rates than primary THA overall.

CONVERSION THA COMPARED TO PRIMARY THA AND REVISION THA

Despite the overall success of conversion THA as a procedure to improve pain and function in patients who have had previous surgery in their hips, studies have demonstrated worse intraoperative and postoperative courses for patients following conversion THA compared to primary THA. Conversion arthroplasties require more time in the OR, result in more intraoperative blood loss, lead to more postoperative complications, have a higher return rate to the OR, and result in poorer functional outcomes[8-10,12,14,15]. Nevertheless, conversion THAs are classified with primary THAs under the same DRG.

There are many studies in the literature that compare the course of conversion THA to primary THA. However, there is a lack of research comparing conversion THA and revision THA to understand if the intraoperative and postoperative courses of these two procedures are more similar. We recently accessed the American College of Surgeons National Surgical Quality Improvement Project database to compare preoperative, intraoperative, and postoperative factors between conversion, primary and revision THA procedures[17]. Our study revealed that that conversion and revision THAs are more similar than conversion and primary THAs; there were many fewer significant differences in the patients' preoperative, intraoperative, and postoperative factors between conversion and revision hip arthroplasties than between

conversion and primary hip arthroplasties[17]. Although conversion THA is currently associated with primary THA, these results may suggest that conversion and revision THA are more similar procedures in terms of complexity and outcomes. Therefore, the burden of conversion THA on the health system is more similar both in cost and resources to revision THA, and not to primary THA.

CONCLUSION

Conversion THA is a challenging procedure that requires more resources both intraoperatively and postoperatively than primary THA. Furthermore, patients undergoing conversion THA have poorer functional outcomes and success rates than patients undergoing primary THA. As such, these procedures should be planned to anticipate the greater needs in the OR, and for in-patient and follow-up care. Patients undergoing conversion THA should not be likened to patients undergoing primary THA when determining risk stratification and reimbursement rates. We suggest that conversion THA be reclassified in the same DRG with revision THA as a step towards better preparing for conversion hip arthroplasties, as well as for more accurate planning of institutional resource utilization.

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EDITORIAL

Orthopedic cellular therapy: An overview with focus on clinical trials

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Abstract

In this editorial, the authors tried to evaluate the present state of cellular therapy in orthopedic field. The topics the authors try to cover include not only the clinical trials but the various research areas as well. Both the target diseases for cellular therapy and the target cells were reviewed. New methods to activate the cells were interesting to review. Most advanced clinical trials were also included because several of them have advanced to phase III clinical trials. In the orthopedic field, there are many diseases with a definite treatment gap at this time. Because cellular therapies can regenerate damaged tissues, there is a possibility for cellular therapies to become disease modifying drugs. It is not clear whether cellular therapies will become the standard of care in any of the orthopedic disorders, however the amount of research being performed and the number of clinical trials that are on-going make the authors believe that cellular therapies will become important treatment modalities within several years.

Key words: Orthopedics; Cellular therapy; Treatment gap; Disease modifying drugs; Standard of care

Core tip: The use of cellular therapies for the treatment of orthopedic diseases is one of the pioneering developments in the history of medical research. Many papers have reported on basic research on cellular sources and methods to localize the cells. Although many review articles have been published, papers discussing clinical trial status were not always available. The authors attempted to review not only the research status of cellular therapy but the status of clinical trials which are on-going in the United States. We hope this editorial can help orthopedic surgeons in keeping up to date in their knowledge of clinical and research stage cellular therapy.

Noh MJ, Lee KH. Orthopedic cellular therapy: An overview with focus on clinical trials. *World J Orthop* 2015; 6(10): 754-761 Available from: URL: http://www.wjgnet.com/2218-5836/full/v6/i10/754.htm DOI: http://dx.doi.org/10.5312/wjo.v6.i10.754

INTRODUCTION

Orthopedic diseases are one of the earliest targets for cellular therapy. Cartilage repair was the first indication for cellular therapy and bone repair has been tried clinically with bone morphogenic protein (BMP). Mesenchymal stem cells (MSCs), embryonic stem cells, umbilical cord blood cells, primary cultured cells from specific sites and cell mediated gene therapies are the possible sources of cells for tissue repair. Quite naturally, cellular therapy became the one of the promising solutions in the regenerative medicine field. After reviewing papers, the authors came to believe that cellular therapy has great potential for becoming the standard of care in certain orthopedic disorders. We believe it is time for orthopedic surgeons to review the advancements of orthopedic cellular therapies within the scope of research and clinical trials.

HISTORY OF CELLULAR THERAPY AS TISSUE ENGINEERING

In 1994, one of the pioneering papers in orthopedic field was presented in the *New England Journal of Medicine*[1]. Lars Peterson's group tried to regenerate cartilage tissue with autologous cartilage cells and showed evidence of regeneration in both animals and humans. Until that point, most orthopedic surgeons believed that cartilage tissue cannot regenerate. This article was considered as a breakthrough but raised many questions about the mechanism of action. Nevertheless, they showed clearly that cartilage tissue can be regenerated by infusing cartilage cells into the lesion site. That means the cartilage cells can adhere to the site and produce type Ⅱ collagen and glycosaminoglycan at the damaged area.

As investigators' interests increase about tissue engineering with different sources of cells, many cells have been tried to show the regeneration potential for orthopedic disorders[2,3]. Cell adhesion studies, mechanical stimulation and cytokine stimulation of cells have been reported to elucidate the mechanism of action[4,5]. Stem cells have been most widely used[6], and cell mediated gene therapies have reached phase Ⅲ clinical trials[7]. It is quite amazing that this new era of cell based on orthopedic therapies has developed into a burgeoning new industry[8]. The relationship of United States spending to innovation of regeneration therapies has also been reported[9]. Even though autologous chondrocyte transplantation was not successful commercially, the potential revenue generation of regenerative medicine using cellular therapy is becoming a more important economic issue. Allogeneic cells with mass production potential may provide a possible answer for the commercial success of cellular therapy.

TENDON REGENERATION

This new technology garnered popular interest after the reporting of autologous platelet injection into the knee joint to help repair ligament damage after a sports injury in a professional football player. The fans witnessed the superstar playing in critical games within short period of time after the injury. This was very impressive debut of cellular therapy in the orthopedic arena. Autologous platelet injection is in phase Ⅰ clinical trials in United States. Tendon injuries can be considered as a serious and unsolved condition because the damaged tendon heals slowly and restoring structural integrity can be sometimes difficult even with a surgical procedure. Mechanical stimulation is another important factor that influences the healing process of the tendons[10].

Chronic injury of the tendon is also challenge for orthopedic surgeons because there are not many transplantable tissues available. To regenerate the tendon and ligaments, MSCs and gene therapy approaches have been reported[11]. Adipose derived stem cells have been tried for primary tendon repair[12] and biomechanical and immunological evaluations have also been performed after treatment. Autologous adipose derived stem cells are sufficient in number to heal or regenerate the damaged tendons. Dosage effects on cellular responses and cytokine profiles have been reported[13]. Interestingly, the lower dose of cells proved to be more effective in improving functional properties. We believe that different tissues will show different cell numbers are optimal for maximum efficacy. Skeletal muscle cells and bone marrow derived stromal cells were also used to compare the differentiation capabilities into the tendon[14].

BONE REGENERATION

In 2008, Lee *et al*[15] published a review paper about cell therapy for bone engineering. They covered the issues such as sources of stem cells, scaffolds, gene therapy and clinical applications in nonunion, tumors, osteonecrosis, revision arthroplasties, and spine fusion. They concluded that there exist opportunities to translate MSC technologies into clinical treatments even though challenges remain. To overcome the challenges, cell sources have been evaluated in terms of the ability to scale up manufacturing procedures under current good manufacturing practice (cGMP) guidelines[16]. The biological characteristics of peripheral blood cell derived MSCs were also evaluated to determine an adequate number of cells to regenerate bone[17]. For use of cells in human, identifying a sustainable source of cells that can be manufactured in sufficient quantities is important for commercial success.

Apoptotic resistance, proliferation kinetics, cellular senescence, and karyotype analysis were performed to compare the characteristics of peripheral blood and bone marrow derived MSCs. The influence of hormones on osteogenic differentiation of MSCs was also evaluated[18]. 17-β estradiol showed both osteogenic and adipogenic stimulatory effects *in vitro*. Estrogen

stimulated osteogenesis through both estrogen receptor (ER) α and β and stimulated adipogenesis through ER β[19]. Dexamethasone supplementation to expand the MSCs was also evaluated and it was shown that a low concentration rather than the physiological concentration facilitated osteogenic proliferation[20]. Other cell types besides bone marrow derived MSCs, such as umbilical cord-derived MSCs (UCB-MSCs), adipose-derived stem cells (ADSCs), muscle-derived stem cells and dental pulp derived stem cells were also evaluated[21]. A gene therapy approach also showed osteogenic potential with *BMP-2* gene[22] transfected chondrocytes. We believe that the chondrocytes can induce bone formation through the endochondral ossification process.

Methods for modulating endochondral ossification with multi-potent stromal cells were also reported by Gawlitta *et al*[23]. In this paper, potent modulators of endochondral bone formation including oxygen tension and mechanical stimuli were reviewed. We believe that autocrine stimulation of chondrocytes with BMP-2 protein production within the cell can also modulate the endochondral ossification. Cell adhesion is a very important issue to consider in determining the mechanism of action of how the cells can generate tissue. Cell adhesion to scaffolds with extracellular matrix proteins was reviewed[24]. Extracellular matrix proteins can be an anchor for the cells to adhere in bone and cartilage damaged sites. Alkaline phosphatase, osteonectin, BMP-2 and Runx2 expression were used to evaluate the efficacy of bone regeneration[25]. With these parameters, bone marrow MSCs showed a better capacity for osteogenic differentiation than unrestricted somatic stem cells and adipose MSCs.

Cellular interaction between two different cell types is very interesting topic for differentiation and proliferation. Zachos *et al*[26] cultivated MSCs together with programmable cells of monocytic origin (PCMO) to test whether co-cultures promote the osteogenic differentiation process. They showed that PCMO obviously promote osteogenic differentiation of MSCs *in vitro*. Mixed cell therapy can be another way to address the problem of providing treater cell numbers. A dynamic 3-D culture system was evaluated to assess the effect on proliferation and differentiation of MSCs[27]. The authors observed the increased ingrowth and osteogenic differentiation in 3-D dynamically cultured human MSCs. They explained this phenomenon by generation of fluid shear stress and enhanced mass transport to the interior of the scaffold mimicking the native microenvironment of bone cells. Red light emitted from a light-emitting diode was also evaluated for its effect on MSCs[28]. They concluded that noncoherent red light can promote proliferation but cannot induce osteogenic differentiation of MSCs. Low level laser irradiation was also tried for MSC proliferation[29], and the authors concluded that low-level laser irradiation might lead to reduction in healing times and potentially reduce risks of failure.

A preliminary trial of autologous adipose-derived stem cells trial from elderly patient with osteoporosis provided interesting observations that bear watching for future study[30]. The authors used a collagen I hydrogel scaffold with ADSCs and showed osteogenic potency. In rabbit model, Fu *et al*[31] showed enhanced bone formation and demonstrated successful posterolateral spine fusion by using a combination of MSCs with low dose rh-BMP-2 proteins. The BMP protein has already reached the clinic for dental use and ADSCs are in phase Ⅱ clinical trials now. One of the most interesting clinical trials in orthopedic field was reported in Japan[32]. The authors injected MSCs mixed with β-tricalcium phosphate (β-TCP) in 10 patients with idiopathic osteonecrosis of the femoral head. All procedures were successful and some young patients with extensive necrotic lesions demonstrated good bone regeneration with amelioration of pain. They performed this procedure with a vascularized iliac bone graft. It is not clear that the regeneration happens only with MSCs because the effect of β-TCP and the vascularized bone graft cannot be clearly ruled out. A multiplex rehabilitation program[33] also helped the patients to achieve significant improvements in physical function and pain. In addition to this non-life-threatening disorder, MSCs were used for treating malignant bone tumors[34]. The authors injected the MSCs to the host-to-allograft bone junction after bone tumor resection in 92 patients. They found no increase in the local cancer recurrence rate in patients after an average follow-up period of 15.4 years. MSCs were also used clinically to ameliorate the host *vs* graft rejection phenomenon.

CARTILAGE REGENERATION

Osteoarthritis (OA) is a disease of aging. The patient population is so large that it is not easy to calculate how many patients are there in the world. But in the United States alone, more than 500000 patients undergo total knee replacement arthroplasty every year. The course of OA is so long that each patient has to have customized treatment according to their stage of OA. Nevertheless, the currently available treatments until do not adequately cover each patient's need. There is a definite need for optional treatments in moderate and severe OA. In addition, there is no disease modifying treatment for OA currently available. This treatment gap opens a large avenue for cellular therapy. To achieve tissue regeneration with cells, the mechanism of action is to make the basic elements of cartilage within the damaged area. Cytokines produced by the cells can be useful to improve the healing by augmenting the body's own regenerative potential[35]. A lot of preclinical research and numerous clinical trials have been reported for cartilage repair[36].

As previously mentioned, autologous chondrocyte implantation was the first treatment to regenerate cartilage. A recent paper pointed out that the OA is a rising global burden among musculoskeletal diseases[37].

They explore the challenges associated with cartilage repair using cell-based therapies. The cell-based therapies also allow the versatility of using scaffolds and growth factors, or gene therapy[38]. They pointed out the challenges in identifying the optimal source of stem cells, along with the conditions that enhance expansion and chondrogenesis. Brady *et al*[39] studied Transforming growth factor-β3 (TGF-β3) and BMP-2 for their potential to generate type II collagen and proteoglycan. They concluded that these growth factors can initiate chondrogenesis. Warsat *et al*[40] also showed that TGF-β enhances the integrin α2β1-mediated attachment of MSCs to type I collagen. Interestingly, TGF-β1 and rhGDF-5 showed different responses to human MSCs[41]. We believe that TGF-β1 exhibits different responses depending on its concentration in accordance with its bimodal mode of action. Intra-articular injection of FGF-18 is currently in phase II clinical trials.

Small molecules that can modulate chondrogenesis were also reviewed[42]. ERK1/2 inhibitor promoted chondrogenesis of MSCs. The influence of ascorbic acid and collagen matrix was also evaluated[43]. An immunogenicity study of MSCs reported that chondrogenic differentiation may increase the immunogenicity of MSCs by leading to stimulation of dendritic cells. The up-regulated expression of B7 molecules on the chondrogenic-differentiated MSCs may be responsible for this event[44]. The longevity of cells was also evaluated[45] and showed that the chondrogenic potential of MSCs declines with age. Synovium-derived stem cells were also evaluated for chondrogenic potential[46]. The combination of hypoxia, FGF-2 and extracellular matrix contribute to the highest expansion rate. They indicated that the three-dimensional microenvironment for *ex vivo* expansion can be optimized to provide high-quality stem cells for cartilage repair.

Materials that can promote cartilage regeneration were also interesting topics of study[47]. Biomimetic composites such as biomaterial scaffolds, nano-fibrous scaffolds and hydrogels were reviewed. The interactions of these materials with embryonic stem cells, ADSCs, MSCs and progenitor stem cells were reported. The effects of chondroitin sulfate-coated nano-topographies on cell characteristics and chondrogenic differentiation on human MSCs were also investigated[48]. This study demonstrated the sensitivity of MSC differentiation to surface nano-topography and highlighted the importance of incorporating topographical design in scaffolds for cartilage tissue engineering. Mineralized collagen was also reviewed for its influence on MSC proliferation[49]. They concluded that the integration of transplanted cells and MSC associated matrix synthesis encourages the use of MSC loaded mineralized collagen for tissue engineering. A similar report was also published by Ragetly *et al*[50]. They reported that cell attachment and distribution were improved on chitosan coated with type II collagen. A study of the effect of growth factors on the proliferation of MSCs encapsulated in a hydrogel scaffold was also reviewed and TGF-β3 was

the most potent for maintaining the cell phenotype[51]. Interestingly, an induced pluripotent stem cell approach without a scaffold showed enhanced chondrogenesis[52]. The authors used electroporation-mediated transfer of *SOX* trio genes (*SOX-5, SOX-6, and SOX-9*) to enhance the chondrogenesis of MSCs.

Cellular therapy for the treatment of cartilage lesions is the most advanced in terms of clinical trials[53]. However, the authors emphasized the need for a randomized study to evaluate the advantages and disadvantages. They also emphasized the need for long-term follow up. Arthroscopic injection of MSCs was evaluated in an animal model[54]. Additionally single stage arthroscopic human cartilage repair procedures were evaluated in 30 patients[55]. The surgical procedure involved debridement of the lesion, micro-fracture and application of concentrated bone marrow aspirate concentric cells with hyaluronic acid and fibrin gel under CO_2 insufflation. Clinical outcome showed significant benefit but the effect of cells only should be evaluated. The efficacy of cellular therapy can be augmented by combining it with multiple injections, arthroscopic injection and with minor surgery. A cell mediated gene therapy with irradiated TGF-β1 transfected chondrocytes and normal chondrocytes (Invossa™) was evaluated in a placebo-controlled, randomized clinical trial in patients with Kellgren and Lawrence grade III OA of the knee with statistically significant improvement seen in pain (visual analog scale) and function (International Knee Documentation Committee subjective knee score)[56].

SCAFFOLD AS A CARRIER

Scaffolds have been used for orthopedic disorders for long time. Porous coating of implants for the ingrowth of osteoid tissue is one example. They serve not only as the 3D structural support but also as an artificial extracellular environment to regulate stem cell behavior[57]. Biomaterials with various physical, mechanical and chemical properties can be designed to control MSCs' development for regeneration. Murphy *et al*[58] compared several substances such as allografts, demineralized bone matrix, collagen and various forms of calcium phosphate for cellular proliferation. They concluded that biochemical and structural properties of biomaterials play in cellular function, potentially enhancing or diminishing the efficacy of the overall therapy. Autologous chondrocytes implanted into a scaffold (NeoCart™) is in phase III clinical trials. Small molecules have been impregnated to a poly (lactic-co-glycolic acid) scaffold to promote chondrogenesis[59].

The cell/matrix/ceramic constructs showed immediate *in vivo* bone formation[60]. For bone reconstruction surgeries, large defect area were filled with newly formed bone. In these cases, this technology may be a solution in consideration of the improved MSCs' proliferation and differentiation capacities. Magnetic nanoparticles (MNP) have been applied to aid the development and translation of orthopedic therapies

from research to the clinic[61]. Characterization of cell localization and associated tissue regeneration can be enhanced, particularly for *in vivo* applications. MNPs have been shown to have the potential to stimulate differentiation of stem cells for orthopedic applications. Hydroxyapatite (HA)-containing composite nanofibers with MSCs were evaluated for osteogenic potential[62]. They showed that the introduction of HA could induce MSCs to differentiate into osteoblasts. Moreover, 3D poly (3-hydroxybutyrate-co-3-hydroxyvalerated)/HA scaffolds made from aligned and random-oriented nanofibers were implanted into critical-sized rabbit radius defects and exhibited significant effects on the repair of cortical bone defects. A report on scaffold based management of osteochondral lesions of the human ankle was also reviewed[63]. They concluded the regenerative surgical approach with scaffold-based procedures is emerging as a potential therapeutic option for the treatment of chondral lesions of the ankle. However, they concluded that well-designed studies are lacking, and randomized long-term trials are necessary to confirm the potential of this approach.

UMBILICAL CORD BLOOD CELLS AS RESOURCES

Cord blood banking has become very popular in many countries including the US. Theoretically, everybody can reserve their potential future personalized medicine in a bank. Cord-blood-derived stem cells have been proven clinically useful for numerous diseases as have been MSCs[64]. MSCs in cord-blood heralds cord blood as an untapped resource for nonhematopoietic stem cell-based therapeutic strategies. Cord blood MSCs were compared with bone marrow-derived MSCs for the repair of segmental bone defects in a rabbit model[65]. This study showed that cord-blood MSCs have similar biological characteristics and osteogenic capacity as bone marrow-derived MSCs. They concluded cord blood-derived MSCs can be used as a new source of seeding cells for bone regeneration. An additional study of osteogenesis *in vivo* evaluated seed cells with human cord blood cells for bone tissue engineering[66]. They showed that cord blood MSCs loaded with the scaffold displayed the capacity for human osteogenic differentiation leading to osteogenesis *in vivo*. Human cord blood MSCs also exhibited an immature nucleus pulposus cell phenotype in a laminin-rich pseudo-three-dimensional culture system[67].

FUTURE OF CELLULAR THERAPY IN ORTHOPEDICS

Recently, one of the interesting topics in biology is CRISPR/Cas9 as a versatile tool for engineering biology[68]. By custom designed single gene modification, many genetic disorders can be treated. In addition, with iPS technology, reprogramming cells to switch their fate is

Table 1 Summary of cellular therapy for regenerative medicine

Target tissue	Source of cell	Ref.
Tendon	Autologous platelet	Sakabe *et al*[10], 2011
	Mesenchymal stem cell	Hoffmann *et al*[11], 2007
	Adipose-derived stem cell	Uysal *et al*[12], 2012
	Stromal cell	Sassoon *et al*[14], 2012
Bone	Peripheral blood-derived stem cell	Fu *et al*[17], 2012
	Multi-potent stromal cell	Gawlitta *et al*[23], 2010
	Adipose-derived stem cell	Jiang *et al*[30], 2014
	Cord blood-derived stem cell	Fan *et al*[65], 2012
Cartilage	Autologous cartilage cell	Brittberg *et al*[1], 1994
	Mesenchymal stem cell	Vilquin *et al*[36], 2006
	Synovium-derived stem cell	Li *et al*[46], 2011
	Allogeneic chondrocyte	Ha *et al*[56], 2012

possible[69]. This paper reviewed landmark developments in cell reprogramming and technical developments on the horizon with significant promise for biomedical applications. Pluripotent stem cells can be directly generated from fibroblasts of the patient by gene transfer technology[70]. The number of gene therapy clinical trials has increased dramatically worldwide since 2012[71]. The basic knowledge gained by cellular differentiation research is enormous right now. The authors believe that by combining several technologies, there is hope for the near future in treating many orthopedic single gene mutation diseases that were previously untreatable.

CONCLUSION

The first human clinical trial of a cellular therapy was performed for an orthopedic disorder. Two of the major indications of cellular therapy are bone and cartilage repair. Most advanced clinical trials of cellular therapies are being performed for orthopedic disorders. The results of several clinical trials have been reported and showed initial indication of efficacy. Even though it is not clear whether cellular therapy can become a standard of care, the data are being generated to evaluate the efficacy of this technology (Table 1). Because there exists a definite treatment gap in some orthopedic disorders, the authors believe that cellular therapy can attain the status as a standard of care within several years especially when supplemented with procedures that improve the efficacy of these treatments.

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EDITORIAL

Effects of exercise on physical limitations and fatigue in rheumatic diseases

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Abstract

Physical activity covers not just sports but also simple everyday movements such as housework, walking and playing. Regular exercise has a great importance in maintaining good health, indeed inactivity is a risk factor for different chronic diseases. Physical exercise can play a crucial role in the treatment of rheumatic diseases, optimizing both physical and mental health, enhancing energy, decreasing fatigue and improving sleep. An exercise program for patients with rheumatic diseases aims to preserve or restore a range of motion of the affected joints, to increase muscle strength and endurance, and to improve mood and decrease health risks associated with a sedentary lifestyle. In this editorial I describe the benefits of the exercise on physical limitations and fatigue in rheumatic diseases that seem to have a short and long-term effectiveness. A literature review was conducted on PubMed, Scopus and Google Scholar using appropriate keywords based on the present editorial.

Key words: Physical activity; Physiatric rehabilitation therapy; Rheumatic diseases; Flexibility training; Home exercise program; Knee osteoarthritis

Core tip: In this interesting editorial, I illustrated the beneficial effects of the physical activity in our life and in rheumatic diseases, including home and gym exercise programs, flexibility training and physiatric rehabilitation therapy. Physical exercise is able to improve balance, reduce pain, activate muscle and increase functional joint stability in patients with rheumatic diseases and osteoarthritis. The benefits of the exercise on physical limitations and fatigue in rheumatic diseases that seem to have a short and long-term effectiveness.

Musumeci G. Effects of exercise on physical limitations and fatigue in rheumatic diseases. *World J Orthop* 2015; 6(10): 762-769 Available from: URL: http://www.wjgnet.com/2218-5836/full/v6/i10/762.htm DOI: http://dx.doi.org/10.5312/wjo.v6.i10.762

INTRODUCTION

Physical activity covers not just sports but also simple everyday movements, no training exercise, such as housework, walking, biking and playing (Figure 1). Indeed, according to the World Health Organization, "any effort exerted by the muscle-skeletal system which results in a higher power consumption than that in the rest position" is classified as physical activity[1]. Regular exercise has a great importance in maintaining good health. Inactivity is a risk factor for chronic diseases and the benefits of a regular and moderate exercise include reduced risks of coronary artery disease, hypertension, diabetes, obesity, serum lipid abnormalities, osteoporosis and cancer[2]. Moreover, physical activity is a good way to socialize and an excellent anti-stress, decreasing the urge to smoke. Physical exercise can play a crucial role in the treatment of rheumatic diseases in optimizing both physical and mental health, enhancing energy, decreasing fatigue and improving sleep. In this way, the muscles around the affected joints become strong, the bone loss decreases and the control of joint swelling, stiffness and pain improves thanks to a better lubrication of the joint cartilage[3]. Moreover, immediately after exercising, anxiety decreases and the mood improves. An exercise program for patients with rheumatic diseases aims to preserve or restore a range of motion of the affected joints, to increase muscle strength and endurance, and to improve mood and decrease health risks associated with a sedentary lifestyle[3]. The management of these patients is multidisciplinary involving rheumatologists, radiologists, human movement scientists, rehabilitation physicians, physical therapists, sports instructors and research assistants.

The aim of this editorial is to illustrate the beneficial effects of the physical activity in our life and in rheumatic diseases, including home and gym exercise programs, flexibility training and physiatric rehabilitation therapy. Physical exercise is able to improve balance, reduce pain, activate muscle and increase functional joint stability, in patients with rheumatic diseases and osteoarthritis (OA).

THE EFFECTS OF PHYSICAL ACTIVITY IN RHEUMATIC DISEASES

Rheumatic diseases are disorders affecting the musculo-skeletal system and in general the connective tissues[4]. Such diseases are very different from each other, also for their severity. Some of them can affect not only joints, bones, tendons, but also other tissues and organs having thus a systemic expression[5]. Rheumatic diseases lead to pain, disability, loss of functional autonomy, reducing the quality of life, both for the side effects of drugs, and for the involvement of vital structures of the organism. Fatigue is common in patients affected by various chronic medical conditions with a low physical activity. For example, in patients with rheumatoid arthritis (RA) and fibromyalgia (FM), reduced levels of fatigue were reported in association with a higher daily physical activity[3,6]. In patients with RA, fatigue can be associated not only with the inflammation per se, but especially with pain, disability, anxiety, depressive thoughts, reduced self-efficacy, feelings of helplessness, sleep disturbances, and limitations in social functioning. Based on these findings, psychosocial factors may have an important role in the onset and persistence of fatigue[7-9]. Both cognitive-behavioral therapy and physical exercise are reported to be effective for treating fatigue in patients with RA[10]. Furthermore, exercise can enhance weight loss and promote long-term weight management in those rheumatic diseases patients who are overweight. Water is an excellent environment for the exercises and the water temperature (between 28 ℃ and 32 ℃) can give pain relief. It allows the patient to be in a situation of reduced weight, thus allowing some patients to perform exercises that they would otherwise not be able to perform. FM is a chronic pain disorder, commonly associated with a reduced quality of life, since it is accompanied by other symptoms such as fatigue, psychological distress, cognitive disorders, no restorative sleep, poor balance, and impaired physical function[11-13]. The current treatment for FM envisages a comprehensive assessment including pharmacological and non-pharmacological therapies. The latter provide for a multimodal approach including physical activity, sleep hygiene, behavioural therapy, regular education and monitoring of treatment response[14,15]. It has been shown that regular exercise, in particular aerobic, improves pain, fatigue and sleep disturbance in patients with FM. Physical exercise is one of the most widely recognized and beneficial forms of non-pharmacological therapy[16], effective in reducing pain and depression and producing positive effects on physical function, fitness, and global health[17], particularly in patients affected by rheumatic disease[18]. No one particular form of exercise is preferred and all types may be considered. The most consistent results have been demonstrated for aerobic and strengthening exercise that, when combined with stretching, had equivalent effects on limiting pain severity among patients with FM[19]. Patients who express concerns regarding the possible worsening of pain and fatigue need to be reassured. The initiation of any exercise program, indeed, must be slow and gradual[20]. A good way to start could be an exercise regimen with hydrotherapy pool, as the warmth of the water and relative weightlessness relieves symptoms while the resistance provides a gentle workout[19]. Moreover, it has been shown that the combination of aerobic exercise, strengthening, and flexibility improves psychological health status and quality of life, preventing depression[21]. There is evidence to support the use of *yoga*, *qi gong* and *tai chi* (disciplines including stretching exercises) in patients with fibromyalgia[22]. Studies in which the use of these therapies resulted in improvement in fibromyalgia
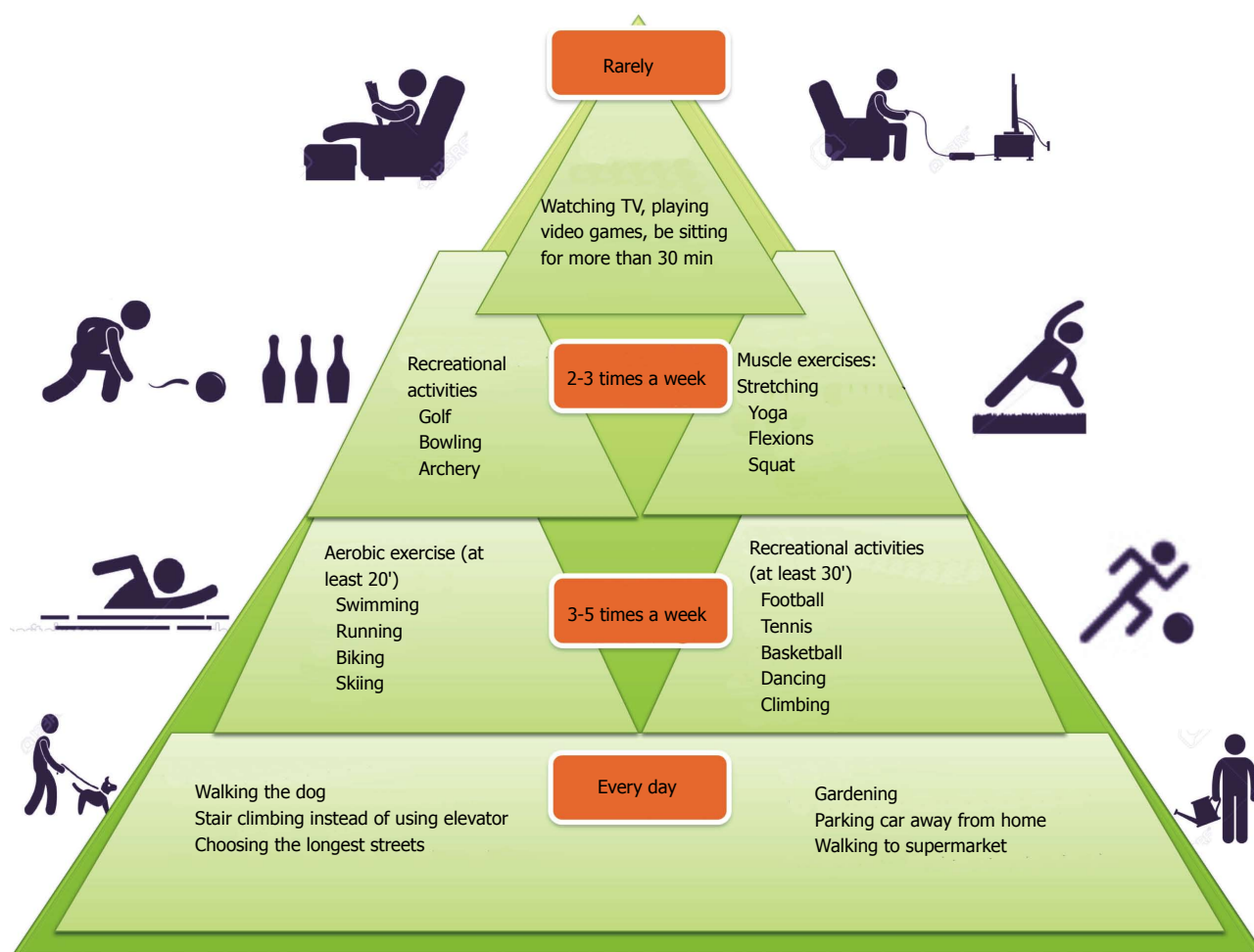
Figure 1 Graphic design of physical activity guidelines during our normal life in one week, suggested by the World Health Organization recommendations, to prevent the onset of some diseases related to sedentary lifestyle. This graphic represents the pyramid of the physical activity recommendation. At the base the suggestions for every day's activities and at the top the activities to perform rarely are shown.

symptoms and physical functioning were generally small and unblended, however, given the lack of serious adverse effects and the promotion of self-efficacy, these management modalities are generally useful options. Graded exercise training and cognitive-behavioural therapy are the two interventions considered to be effective in chronic fatigue syndrome (CFS)[23]. Myalgic encephalomyelitis, commonly known as chronic fatigue syndrome, is a debilitating and complex disorder characterized by profound medically unexplained fatigue that is not improved by bed rest and that may be worsened by physical or mental activity. Symptoms affect several body systems and may include weakness, musculoskeletal pain, sleep disturbance, impaired memory and/or mental concentration, which can result in reduced participation in daily activities. Compared to healthy controls equal in age, patients with CFS are significantly less physically active[24]. After exercise therapy, patients with CFS may generally feel less fatigued, and no evidence suggests that exercise therapy may worsen outcomes. Moreover, a positive effect with respect to sleep, physical function and self-perceived general health has also been observed[25].

The most frequent degenerative rheumatic disorder in the population is OA[26]. Unfortunately, in contrast to systemic inflammatory rheumatic diseases, such as RA, the therapeutic options in OA are still limited[27]. OA is a chronic disease characterized by degenerative and productive changes of the joints (Figure 2)[28]. It is essentially linked to an imbalance between excessive cartilage damage and the ability of cartilage to "heal", but involves and compromises the whole joint, in all its aspects, both macroscopic and microscopic changes (Figure 2)[29-31]. Risk factors include age[32,33], mechanical factors[33], obesity[34], and inflammation[35,36]. The key intervention in the management of OA is exercise therapy[37,38]. It is well known that exercise training affects the articular cartilage metabolism and modifies the cartilaginous structure by a mechanotransduction response[37-39]. Biomechanical stimulus generated by dynamic compression, during a moderate exercise, can reduce the synthesis of proteolytic enzymes, regulating the metabolic balance and preventing the progression of the disease[40,41]. Moreover, reduction in inflammation seems to be a crucial mechanism, since exercise is a potential anti-inflammatory treatment for patients with
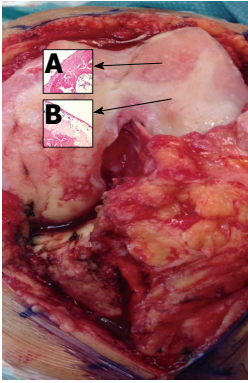
Figure 2 Macroscopic and microscopic signs of osteoarthritis knee hyaline cartilage. A: The microscopic observations of osteoarthritis knee hyaline cartilage showed structural alterations, reduction of cartilage thickness of the cartilage zones and subchondral bone fibrillations; B: The microscopic observations of healthy knee hyaline cartilage showed a preserved morphological structure with no sign of cartilage degradation.

Figure 3 Graphic design of the three basic categories of physical activity. Aerobic (aerobic physical exercise such as walking or jogging), resistance (anaerobic endurance exercise such as marathon or cross country skiing), and flexibility training (stretching exercises to increase functional range of motion and to reduce the risk of injury).

rheumatic diseases and OA[41,42]. The exercise regime could range from mild to moderate in OA patients, and also, more importantly, must be "adapted" or "tailor-made", since the level of exercises will be dependent on the tolerability of the patients, as recommended by the American College of Rheumatology, the EULAR and OARSI guidelines[41-43]. Authors recently showed that a higher increase in muscle strength is associated to a higher increase in physical functioning[44], tolerability was assessed at every training session, for the patients who were not able to tolerate high intensity training, training intensity was adapted to a lower level[3-5].

Moreover, in order to preserve the articular cartilage, physicians should promote a healthy lifestyle. Physical activity (mild exercise) must be associated to a balanced diet, such as Mediterranean Diet (olive oil and red orange), in order to prevent and reduce the progression of rheumatic and OA disease[35,44-47].

Exercise programs

Exercise and physical activity are usually classified in three basic categories (Figure 3): (1) aerobic, such as walking and jogging, which are repetitive, rigorous, rhythmic, and involve the large muscles; (2) resistance, which utilizes resistance to muscular contraction to build the strength, anaerobic endurance and size of skeletal muscles; and (3) flexibility training, which keeps the body flexible, relaxes muscles and protects from physical injury[48]. Sometimes initially patients complain of the increase of pain and fatigue usually decrease with the continuation of the physical activity and can be avoided by introducing breaks in the exercise sessions.

Flexibility training

Flexibility programs can increase functional range of motion and reduce the risk of injury. Joint flexibility may decrease with age, affecting normal daily function, older adults could maintain the ability improving

flexibility through stretching exercises (Figure 4)[49,50]. The 2009 American College of Sports Medicine position statement "exercise and physical activity for older adults" highlighted the lack of studies on the effects of a range of motion exercises on flexibility outcomes in older populations and also the absence of consensus about the prescription of stretching exercises[51]. Despite the lack of scientific support for the recommendation of a flexibility component in older adult exercise programs, many activity programs place a considerable emphasis on flexibility. When injuries or diseases result in a restricted range of motion of the joints, stretching exercises are used in the rehabilitation context in order to regain "normal" range of motion in the major muscle tendon groups in accordance with individualized goals[52]. For the majority of the aging population, the goals are not related to athletic performance, but rather to daily living activities. Despite the lack of research confirming the health benefits[53], it is common to find in the literature flexibility training as a presumed "component of fitness" and a beneficial adjunct to other forms of exercise. Other physical therapies can be helpful in the management of rheumatic diseases, particularly those that can be self-administered.

Physiatric rehabilitation therapy

Patients with rheumatic diseases have a high risk of progressive deterioration of articular function over the years. The main limitations are due to the pain, a reduced range of motion, the muscle wasting and the reduction in strength. Psychological motivations of anxiety and depression are often associated and could further compromise the ability to address common daily activities. Physiotherapy and kinesiology is an essential component in the overall treatment of the disease. It provides for interventions predominantly educational and preventive but also with specific measures targeted to the condition of each patient. The levels of intervention include: Training on the prevention of damage (joint protection), training in

Head, neck and upper limb stretching exercises

Spine and upper limb stretching exercises

Spine and lower limb stretching exercises

Lower limb stretching exercises
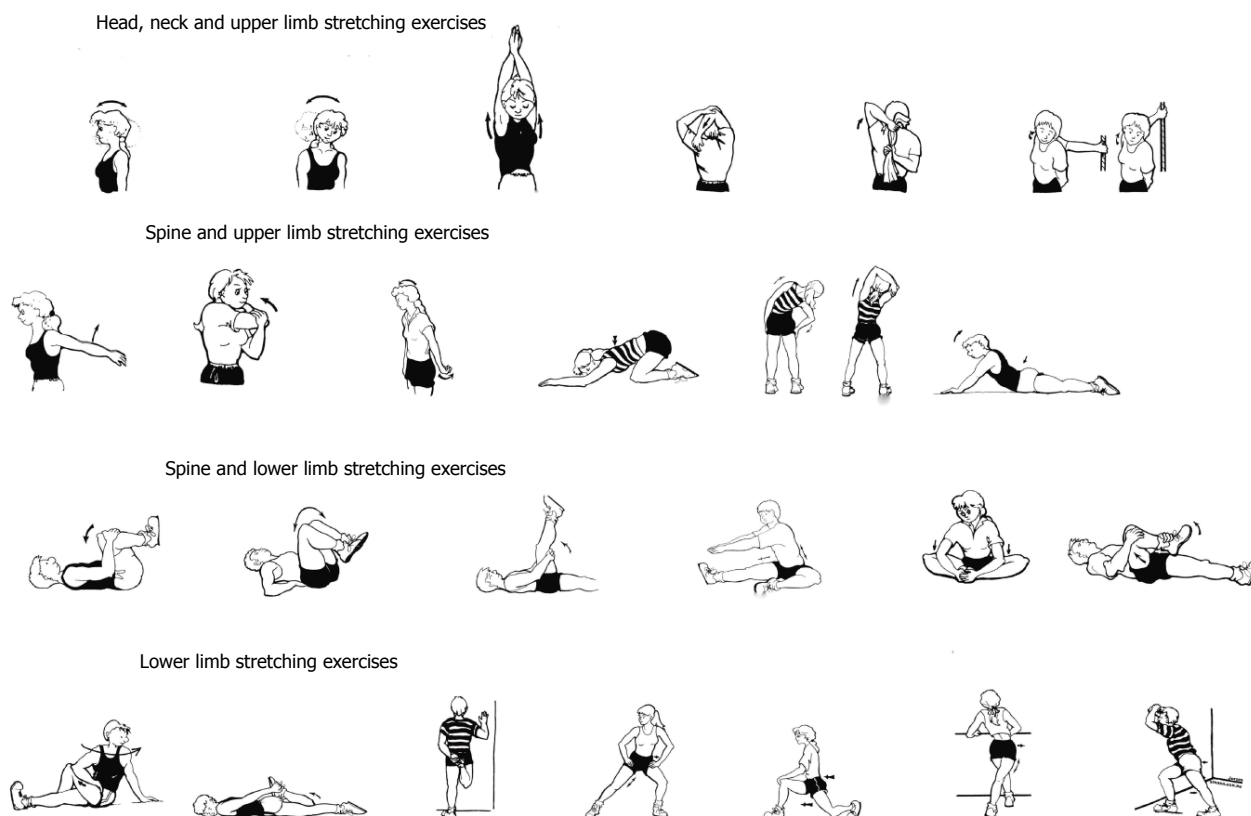
Figure 4 Graphic design of different stretching exercises (head, neck, spine, upper and lower limb stretching exercises). This graphic includes the stretching movement for all joints and muscles of the body such as flexion, extension, adduction, abduction, pronation, supination, intra and extra rotation, circumduction.

autonomy (use of aids), and specific rehabilitation treatment in relation to surgery[54]. The first step is to inform and educate the patient about the nature and consequences of the disease. The conviction of the importance of taking care of their joints is an important element in the treatment. The articular overexertion during repetitive daily activities, contributes to the deterioration of appearance and aggravation of the deformations[55]. The joint protection is based on gesture education, avoidance of incorrect movements and use of the most appropriate ones. This technique reduces the risk of joint deterioration, minimizing the efforts that exert on the joint structures in order to facilitate the movements and make them more comfortable when they are painful and tiring[56]. The program is carried out by qualified personnel in phy-siatric facilities. It consists of passive motion exercises, assisted active and stretching exercises to increase the extensibility. Mobilization exercises are usually associated with those of muscle strengthening. It is shown that a static or dynamic exercise program can improve strength, aerobic capacity and physical performance without increasing disease activity or aggravating joint damage[48]. In cases where surgical orthopedic treatment is indicated, physiatric preparation and follow up to the intervention is necessary - rehab-ilitation adapted to the type of operation, the situation of the patient[49].

Home exercise program

After the completion of the rehabilitation programme in hospital, the patient is then discharged with a home exercise program and followed up at regular intervals[57]. Home exercise program (Figure 5) should be adapted to the patient's capacity. It is a crucial aspect of the rehabilitation program, allowing the patients to return home. The training program should be made in the patient's home environment in order to ensure the patient's independence. Patients improvements and general condition should be evaluated at regular intervals[58]. Moreover, the training should be gradually changed, according to the improvement of the patients to facilitate the more complex activities of daily living, and also in the late stages when the patients return to work[58]. In addition to the exercises performed during the subacute and chronic stages, shoulder, wrist, hand, hip and knee joint exercises (flexion and extension), full abduction, extension and flexion exercises for abdominal, sacrospinal, iliopsoas, gluteus maximus, gluteus minimus, hamstring, and quadriceps muscles, and resistive exercises for oblique abdominal muscles are recommended to be performed at home[59]. Exercises to increase respiratory capacity are continued. Cardiovascular moderate exercises (spinning, running) are also advised/prescribed. At the end of the rehabilitation program patients experienced less pain, improve their range of motion and were able
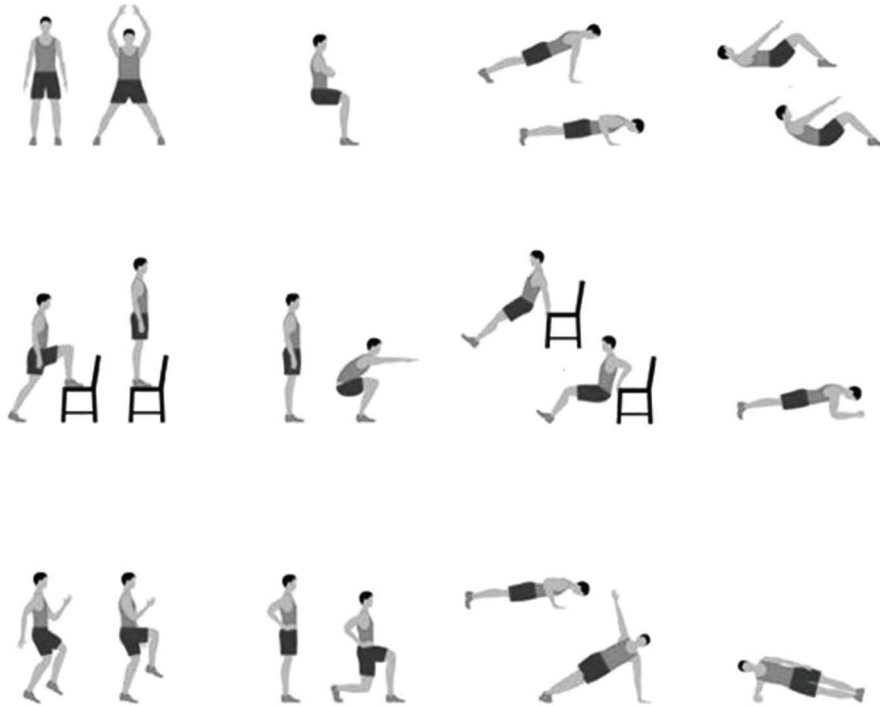
Figure 5 Graphic design of some home exercise. This graphic includes different types of exercises that can be performed safely at home, using the common home furniture.

to perform their daily work with fewer complications. Help in home exercise can come from listening to music during activity, helping in maintaining a good rhythm, body coordination, and motivation in the rehabilitation program and distracting the mind from the pain[60-62].

CONCLUSION

Exercise can be beneficial both physically and psychologically. It works by improving muscle trophism and capillarisation, and reducing muscle hypoxia. It also promotes the secretion of endorphins and growth hormone; increases the production of serotonin in the brain and activates adrenergic mechanisms of pain inhibition. Inactivity in patients with rheumatic diseases is very harmful both physically (reduced muscle strength, deconditioning, greater rigidity), and psychologically (fear of movement, depression, loss of self-confidence). The exercise suggested is aerobic with moderate intensity, adapted to the patient and then slowly increased according to the improvement of the conditions.

In conclusion I can assert that regular moderate physical activity (housework, slow running, walking, biking and swimming) combined with a useful stretching has a great importance in maintaining good health. Moreover, physical activity can play a crucial role in the treatment of rheumatic diseases in optimizing both physical and mental health. In fact, in patients with rheumatic diseases, physical activity is a great method to improve: pain, sleep, a range of motion, body coordination, balance, motivation, functional joint stability; also it is able to reduce the tender points, enhance energy, decrease fatigue and it is an excellent anti-stress strategy. Moreover, physical activity is a good way to socialize, an excellent anti-stress agent and the best aesthetic method for our body "mens sana in corpore sano". We all should follow the example of some north European countries such as Germany, the Netherlands, Switzerland, Finland and others, more sensitive to disease prevention through the use of physical activity, where moderate exercise is a lifestyle. I hope with this editorial to help readers and the scientific community to better understand the importance of physical activity in our lifestyle.

It's never too late to begin to move, there is no minimum level to have benefits: A bit of activity is better than none. The benefits begin as soon as you start to be more active.

ACKNOWLEDGEMENTS

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EDITORIAL

Treatment options for irreparable postero-superior cuff tears in young patients

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Abstract

Rotator cuff tears (RCTs) occur more commonly with advanced age, with most rotator cuff abnormalities in patients less than 30 years old being painful tendinoses or partial-thickness RCTs. Irreparable postero-superior cuff tears has been reported as frequent as 7% to 10% in the general population, and the incidence of irreparable RCTs in young patients is still unknown. Several surgical procedures have been proposed for young patients with irreparable postero-superior RCTs, such as rotator cuff debridement, partial rotator cuff repair, biceps tenotomy/tenodesis, rotator cuff grafting, latissimus dorsi tendon transfer, and reverse shoulder arthroplasty. After being thoroughly investigated in open surgery, arthroscopic techniques for latissimus dorsi tendon transfer have been recently described. They have been shown to be an adequate option to open surgery for managing irreparable postero-superior RCTs refractory to conservative management.

Key words: Postero-superior rotator cuff tears; Young patients; Irreparable; Latissimus dorsi; Tendon transfer

Core tip: Irreparable postero-superior cuff tears have been reported as frequent as 7% to 10% in the general population, and they are challenging, especially in young and active patients. In this patient population, the number of therapeutic options dramatically decreases. Several surgical procedures have been proposed for young patients with irreparable postero-superior rotator cuff tears, such as rotator cuff debridement, partial rotator cuff repair, biceps tenotomy/tenodesis, rotator cuff grafting, latissimus dorsi tendon transfer, and reverse total shoulder arthroplasty. Latissimus dorsi tendon transfer seems to be a viable option to restore function and decrease pain in young and active patients.

INTRODUCTION

Rotator cuff tears (RCTs) occur more frequently in elderlies, with asymptomatic tears reported in up to 54% of patients aged > 60 years[1,2]. Degenerative tears are more common in the older patient population, whereas more variability can be found in a younger population[3]. In patients 30 years old or younger, rotator cuff tendons are generally healthy, robust, and less likely to be the source of symptoms[4]. Nevertheless, this patient population can be affected by degenerative tears, partial tears of the articular ("PASTA" lesions) side, partial tears of the bursal side, full-thickness tears and lesions secondary to calcium deposits. Eventhough the occurrence of an irreparable RCT is an infrequent condition in young individuals, it represents a significant challenge to the orthopedic and rehabilitation comunity.

For shoulder arthroplasty patients, young has been arbitrarily defined as younger than 55 years[5,6], and no clear definition has been made for rotator cuff patients. After open rotator cuff repair, younger patients (< 55 years of age) have been found 3.5 times less satisfied than older patients (≥ 55 years of age)[7]. Returning to a premorbid state may be more difficult in the younger population because of their increased demands and expectation. Consequently, a clear distinction between younger and older patients undergoing rotator cuff surgery would seem warranted.

The term irreparable RCT is commonly and often inaccurately used interchangeably with the term massive RCT. Indeed, not all massive RCTs are irreparable. Massive RCTs are defined as lesions with a diameter of > 5 cm[8,9] or with the involvement of 2 or more tendons[10,11]. Irreparable tears can be defined in terms of retraction, fatty infiltration, and atrophy of the muscle belly[12]. Diagnostic criteria, usually confirmed by computed tomography (CT) or magnetic resonance imaging (MRI) findings, include stage-3 tendon retraction[13], stage-3 or 4 fatty infiltration[14,15], and stage-3 muscle atrophy[16]. Another important radiographic parameter that may be used to determine whether an RCT is repairable or not is represented by acromiohumeral distance, with an acromiohumeral distance of < 7 mm (*i.e.*, superior migration of the humerus) being associated with decreased likelihood of reparability[17]. Once an irreparable RCT is diagnosed, it can be further classified as follows: Complete tears of the supraspinatus, infraspinatus, and teres minor tendons are postero-superior tears; complete tears of the supraspinatus and subscapularis tendons, sometimes with long head of the biceps tendon involvement, are antero-superior tears[18]. Massive postero-superior RCTs may account up to approximately 40% of the repaired rotator cuff[19] and irreparable postero-superior cuff tears have been reported as frequent as 7% to 10% in the general population[20].

Irreparable RCTs can occur in two physiologically distinct patient groups: (1) patients older than 70 years of age (usually females and less active); and (2) patients in the fifth/sixth decade of life (usually men and higher-demand), with a history of previous rotator cuff repair, chronic rotator cuff injury, or with symptoms of pain and disability after an acute event[18]. Many older patients with irreparable RCTs respond favorably to nonsurgical treatment. Physical therapy is the keystone of treatment in this patient population, with a special focus on deltoid reconditioning[21], strengthening of any remaining cuff tissue, and periscapular strengthening[22]. Nonsteroidal anti-inflammatory drugs (NSAIDs) and subacromial corticosteroid injections may be also used. When patients fail to respond to nonsurgical measures, surgical treatment should be considered and several techniques have been proposed such as rotator cuff debridement[23-25], partial rotator cuff repair[26-28], biceps tenotomy/tenodesis[29,30], rotator cuff grafting[31-36], latissimus dorsi tendon transfer (LDTT)[12,37-45], and reverse total shoulder arthroplasty (RTSA)[46,47] (Table 1). However, it should be considered that most of these techniques are less than optimal for the treatment of young patients with irreparable RCTs.

RTSA

Currently, the RTSA is advocated for patients with[48-50] and without[47,51] glenohumeral arthritis in the presence of an irreparable postero-superior RCT. Irreparable RCTs with pseudoparalysis of anterior elevation are the most favorable indication for RTSA[48]. However, there are concerns regarding the longevity of RTSA and limited possibilities for salvage after implant failure. As a result, RTSA is not used in young and active patients and it is usually reserved for patients above 65 years of age.

Rotator cuff debridement

Debridement of rotator cuff tendon stumps with sub-acromial decompression has been shown to produce good results in patients with low demands (*i.e.*, older, less active patients). However, it has previously been shown that subacromial debridement is much more effective in small tears than in massive tears. Furthermore, debridement has been shown to correlate with progressive joint degeneration, so it has limited role in the treatment of irreparable RCTs, especially in the youngest individuals[48].

Partial rotator cuff repair

Partial repair has been considered a reasonable option in patients with irreparable postero-superior RCTs by providing pain relief and restoring function[23,26]. However, it has been noted that over 50% of patients treated with partial rotator cuff repair had significantly inferior functional outcomes and they had structurally failed using ultrasound[52]. In this light, such option of treatment does not appear suitable in a young pop-

Table 1 Demographic characteristics and clinical outcomes for different surgical options for patients with irreparable postero-superior cuff tears

		Age (yr)	FU (mo)	Constant	DASH	UCLA	ASES	JOA	WORC
RCB	Berth *et al*[23]	64.3 (60-72)	24.7 (21-28)	50.4 ± 15.3	35.3 ± 18.6	nr	nr	nr	nr
	Gartsman *et al*[24]	62.0 (42-77)	63.2 (48-117)	52.4 (nr)	nr	20.8 (nr)	55.3 (nr)	nr	nr
	Melillo *et al*[25]	60.0 (36-79)	nr	nr	nr	19 (nr)	nr	nr	nr
PRCR	Berth *et al*[23]	62.5 (60-67)	23.8 (21-28)	72.8 ± 16	23.8 ± 16.8	nr	nr	nr	nr
	Kim *et al*[27]	62.3 (54-72)	41.3 (36-52)	74.1 ± 10.6	nr	25.9 ± 5.0	nr	nr	nr
	Wellman *et al*[28]	65.0 (48-79)	47.0 (13-103)	71.0 (nr)	nr	nr	nr	nr	nr
BT/T	Boileau *et al*[29]	68.0 (52-85)	71 ± 6	66.5 ± 16.3	nr	nr	nr	nr	nr
	Walch *et al*[30]	64.3 (39-81)	57.0 (24-168)	67.6 ± 14.7	nr	nr	nr	nr	nr
RCG	Audenaert *et al*[31]	67.0 (51–80)	43.0 (24–86)	72.1 (34–89)	nr	nr	nr	nr	nr
	Bond *et al*[32]	54.4 (39-74)	26.7 (12-38)	84.0 (68–100)	nr	30.4 (22–35)	nr	nr	nr
	Mihata *et al*[33]	65.1 (52-77)	34.1 (24-51)	nr	nr	32.4 ± 4.3	92.9 ± 11.3	92.6 ± 9.0	nr
	Sclamberg *et al*[34]	67.5 (52-79)	nr (6 to 10)	nr	nr	nr	58.4 (30-95)	nr	nr
	Wong *et al*[35]	53.6 (39-67)	nr (24-68)	nr	nr	27.5 (nr)	84.1 (nr)	nr	75.2 (nr)
LDTT	Aoki *et al*[37]	64.0 (48-82)	35.6 (26-42)	nr	nr	28.0 (11-35)	nr	nr	nr
	Castricini *et al*[38]	60.0 (46-67)	27.0 (24-36)	74.0 (40-84)	nr	nr	nr	nr	nr
	Habermeyer *et al*[41]	61.0 (47-76)	32.0 (19-42)	74.6 (64.5-81.5)	nr	nr	nr	nr	nr
	Lehmann *et al*[42]	64.0 (41-78)	24.0 (12-41)	70.0 (27.0–98.0)	nr	nr	nr	nr	nr
	Zafra *et al*[44]	54.0 (37–72)	28.0 (12-58)	70.25 (55–85)	nr	nr	nr	nr	nr
	Grimberg *et al*[45]	62.0 (31-75)	29.4 (24-42)	65.4 ± 12.1	nr	nr	nr	nr	nr
	Paribelli *et al*[57]	62.5 (45–77)	32.0 (12-60)	nr	nr	30.3 ± 4.2 (29-34)	nr	nr	nr
RTSA	Ek *et al*[46]	60.0 (46-64)	93.0 (60-171)	74.0 (31-100)	nr	nr	nr	nr	nr
	Mulieri *et al*[47]	71.0 (52-88)	52.0 (24-101)	nr	nr	nr	75.4 (25-100)	nr	nr

Range in parenthesis. FU: Follow-up; ±: Standard deviation; nr: Not reported; RCB: Rotator cuff debridement; PRCR: Partial rotator cuff repair; BT/T: Biceps tenotomy/tenodesis; RCG: Rotator cuff grafting; LDTT: Latissimus dorsi tendon transfer; RTSA: Reverse total shoulder arthroplasty; Constant: Constant-Murley Shoulder Outcome score; DASH: Disabilities of the Arm, Shoulder and Hand score; UCLA: University of California-Los Angeles Shoulder scale; ASES: American Shoulder and Elbow Surgeons score; JOA: Japanese Orthopedic Association score; WORC: Western Ontario Rotator Cuff Index.

ulation with irreparable RCTs.

Biceps tenotomy

Severe pain or dysfunction caused by an irreparable RCTs associated with a biceps lesion can be effectively treated with arthroscopic biceps tenotomy or tenodesis. Relief of pain has been reported in 85% of patients who had undergone an arthroscopic tenotomy of the long head of the biceps tendon for the treatment of an irreparable RCT, with no effect on strength or range of motion[30]. However, the tenotomy of the biceps tendon may not represent the solution to menage irreparable RCTs of young and active patients that have much higher expectations of functional outcomes from their shoulder surgery. In addition, severe rotator cuff arthropathy and pseudoparalysis represent contraindications to this procedure[29].

Rotator cuff grafting

Issues to be considered when contemplating using rotator tendon grafting materials should be the cost, the extra operative time required to place the material, and the potential morbidity of the grafting material[53]. Whereas promising early results have been reported[32,35], there is definitive evidence that some materials (*e.g.*, porcine small intestine submucosa) are detrimental[36].

Latissimus dorsi tendon transfer

In this light, irreparable postero-superior RCTs ass-ociated with functional impairment of the shoulder are challenging, especially in young and active patients. In this patient population, the number of therapeutic options dramatically decreases and tendon transfers seem to be a reasonable solution to restore function and decrease pain[18,48,54]. Tendon transfers are not indicated for older, more debilitated patients since the amount of muscle reeducation has been shown to determine, at least in part, the amount of success[18].

Several authors have investigated techniques to perform the LDTT in open surgery, reporting overall good results[12,37,39,41,42,44]. LDTT was first described in patients with brachial plexopathies causing loss of external rotation. Gerber *et al*[55] first used LDTT to improve shoulder external rotation in younger patients with irreparable postero-superior RCTs. The authors reported good to excellent results after this procedure. Since then, similar results have been reported by several other studies[12,37,39,41,42,44]. However, proper patient selection is crucial with this procedure. Factors associated with poor outcome include subscapularis and/or deltoid dysfunction, osteoarthritis of the glenohumeral or acromioclavicular joint, and loss of teres minor function[12,56].

Recently, to preserve the deltoid muscle arthroscopic techniques for LDTT have been described[40,43]. To the best of our knowledge, there are only three reports published on arthroscopic-assisted LDTT for irreparable RCTs[38,45,57].

Castricini *et al*[38] reported on 27 patients with a mean age of 60 years (range 46 to 67 years) with irreparable postero-superior RCTs associated with shoulder fun-
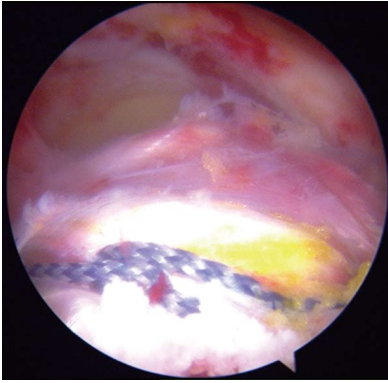
Figure 1 Intra-articular view from the lateral portal showing the fixation of the latissimus dorsi tendon to the greater tuberosity.

ctional impairment treated with arthroscopic-assisted LDTT (Figure 1). The authors showed a significant improvement in the mean Constant and Murley score, pain score, muscle strength in forward elevation, and range of motion in external rotation ($P < 0.05$) at a mean follow-up of 27 mo. The authors used a true anteroposterior radiograph to evaluate the grade of osteoarthritis in the shoulder pre- and postoperatively according to the Samilson and Prieto three-stage classification system[58]. They also assessed the proximal migration of the humeral head on true anteroposterior radiographs in neutral rotation, using a three-stage classification (stage 1, no proximal migration; stage 2, mild proximal migration; stage 3, severe proximal migration). MRI was performed preoperatively to evaluate the rotator cuff tendon tear and muscle quality. MRI was not performed postoperatively at any follow-up visit. The authors did not report significant osteoarthritis progression and proximal migration of the humeral head after surgery.

Grimberg *et al*[45] evaluated the clinical (Constant score and Subjective Shoulder Value), radiologic (acromiohumeral distance), and MRI (transferred tendon aspect) results of arthroscopic-assisted LDTT performed in 55 patients with a mean age at the time of surgery of 62 years (range 31 to 75 years) with irreparable postero-superior RCTs. The patients were evaluated at a mean follow-up of 29 mo. The authors reported statistically significant improvement in Constant score, Subjective Shoulder Value, and range of motion ($P < 0.001$) from preoperatively to postoperatively. All patients underwent a preoperative radiologic evaluation of the shoulder with assessment of the subacromial space and the grade of glenohumeral arthrosis according to the Hamada classification[59], as well as a CT arthrogram or MRI with assessment of atrophy and/or fatty infiltration of the subscapularis, supraspinatus, infraspinatus, and teres minor according to Fuchs *et al*[14], Goutallier *et al*[15] and Thomazeau *et al*[16]. The postoperative radiologic evaluation comprised: (1) an immediate postoperative MRI; (2) an MRI at a minimum of 1 year postoperatively to assess the integrity of

the transferred tendon; and (3) standard radiographs at maximum follow-up. The authors did not report any statistical difference in acromiohumeral distance and osteoarthritic stage between preoperative and final follow-up. However, four patients had a ruptured latissimus dorsi tendon on MRI at 1 year follow-up.

Paribelli *et al*[57] compared clinical results [University of California Los Angeles (UCLA) shoulder rating scale, ROM, measurement of the strength and the rotator cuff quality of life (RC-QOL) questionnaire] in two groups of patients with irreparable RCTs treated surgically: one group (20 patients) received an arthroscopic-assisted LDTT, and the other (20 patients) an arthroscopic partial rotator cuff repair. The patients were evaluated at a mean follow-up of 2.8 years (1-5, SD 3). The authors reported statistically significant improvement ($P < 0.05$) in UCLA score results, strength and RC-QOL questionnaire for patients treated with arthroscopic-assisted LDTT compared to patients treated with arthroscopic partial rotator cuff repair, with no differences found between groups for pain relief. One case of latissimus dorsi tendon rupture was reported (13 mo after surgery) and the patient underwent a reverse total shoulder arthroplasty surgery.

Procedures other than arthroscopic-assisted LDTT have been proposed and are currently accepted as viable symptomatic options. In light of recent publications[38,45,57], there is growing interest in arthroscopic-assisted LDTT techniques for the treatment of young patients with irreparable postero-superior RCTs. There is a need for more long-term, well-conducted studies to confirm the efficiency of this technique for relieving pain and improving function in young patients with postero-superior cuff deficiency and to determine whether arthroscopic-assisted LDTT can be the treatment of choice in this patient population.

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Surgical management of osteonecrosis of the femoral head in patients with sickle cell disease

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Abstract

Sickle cell disease is a known risk factor for osteonecrosis of the hip. Necrosis within the femoral head may cause severe pain, functional limitations, and compromise quality of life in this patient population. Early stages of avascular necrosis of the hip may be managed surgically with core decompression with or without autologous bone grafting. Total hip arthroplasty is the mainstay of treatment of advanced stages of the disease in patients who have intractable pain and are medically fit to undergo the procedure. The management of hip pathology in sickle cell disease presents numerous medical and surgical challenges, and the careful perioperative management of patients is mandatory. Although there is an increased risk of medical and surgical complications in patients with sickle cell disease, total hip arthroplasty can provide substantial relief of pain and improvement of function in the appropriately selected patient.

Key words: Sickle cell disease; Total hip arthroplasty; Core decompression; Orthopedic; Osteonecrosis; Avascular necrosis; Hip

Core tip: The management of hip pathology in sickle cell disease presents numerous medical and surgical challenges, and the careful perioperative management of patients is mandatory. Key aspects of medical optimization and surgical care are presented in this brief review.

INTRODUCTION

Sickle-cell anemia results from a point mutation in the β-globin chain of hemoglobin, replacing the amino acid glutamate with the amino acid valine at the

Figure 1 Anterior-posterior radiograph of the pelvis in a 24-year-old female with sickle cell anemia and long-standing, disabling bilateral hip pain.

sixth position. The association of two normal α-globin subunits with two mutant β-globin subunits forms hemoglobin S. Under low-oxygen tension, the abnormal erythrocytes are susceptible to sickling. Clinically, this presents as anemia secondary to intravascular hemolysis and decreased hematopoiesis, and this pathology produces recurrent pain episodes, as well as chronic end organ damage and infarction.

Sickle cell disease (SCD) has a number of orthopedic manifestations, including osteonecrosis of the femoral head (ONFH). To address this pathology and to improve quality of life, a number of surgical options may be entertained. For patients with avascular necrosis (AVN) due to SCD, the hip pathology can be a major limiting factor in terms of level of activity and function. This article serves to outline the evaluation of the painful hip in patients with sickle cell hemoglobinopathy, to review the surgical options available to treat these patients, and to discuss the perioperative complications associated with this patient population.

The sickle cell hemoglobinopathies have a multitude of clinical presentations. Orthopedic insult occurs after chronic end-organ damage. Historically, patients with SCD patients have had a decreased lifespan, and these patients died before boney changes were clinically apparent. With modern day therapeutics and diagnosis, orthopedic manifestations are increasingly evaluated and treated. The specific orthopedic manifestations of SCD and its sequelae include osteonecrosis, infection, and bone marrow hyperplasia. ONFH has been reported to occur in up to 50% of patients with SCD based on the type of hemoglobinopathy[1-4]. It is important to note that, although some demographic groups have mild forms of SCD, such as certain Arab populations, these groups still demonstrate a high frequency of AVN development[5].

Sickling of red blood cells causes vascular congestion, venostasis, and thrombosis in the microvasculature of the bone. Resulting ischemia is compounded by an increase in intraosseous pressure secondary to medullary hyperplasia. This produces bone infarction and necrosis[4]. Patients with symptomatic ONFH typically report groin pain and pain with ambulation. Physical examination reveals painful restrictions in the hip range of motion. Multiple other joints may be affected, including the knees, feet, and back, so a comprehensive examination is important. The hips may be involved bilaterally (Figure 1), and it is not uncommon for necrosis to be asymptomatic, especially in early stages[6]. One study reported radiographic evidence of AVN in the contralateral, asymptomatic hip in 39% of patients with unilateral hip pain[7].

NON-SURGICAL MANAGEMENT

Red blood cell transfusion therapy is used to prevent the primary manifestations of SCD. Transfusion therapy may be warranted for the primary prevention of stroke, chronic pain crises, pulmonary hypertension, chronic renal failure, acute chest syndrome (ACS), and end-organ damage[8].

Hydroxyurea is a widely prescribed drug for management of SCD. It induces HbF synthesis, resulting in decreased sickling and improved red-cell survival. Hydroxyurea is also metabolized into the vasodilator nitric oxide with positive effects on vascular inflammation. Patients with SCD treated with hydroxyurea have significantly fewer acute painful episodes and episodes of ACS, decreased transfusion requirements, and enhanced survival[9,10].

Stem cell transplantation is a novel treatment modality and can be curative in individuals with SCD. Due to inherent risks of the procedure, stem cell transplantation is reserved for patients with significant complications, such as a history of stroke, and those who have a matched sibling stem cell donor[11]. There is more than a 90% survival rate after this procedure and approximately 85% survive free from SCD[12,13].

Many patients with SCD develop AVN of the hip, as well as other synovial joints (knee, foot, and back) despite the advances in medical management. Unfortunately, the natural history of symptomatic AVN of the femoral head secondary to SCD is progressive degenerative changes. Non-surgical management of AVN of the femoral head should be used initially and consists of pain management, activity modification, and ambulatory assistive devices. In addition to plain X-rays, magnetic resonance imaging may be used to assess the severity of femoral head involvement (Figure 2). Non-operative treatments may provide maximal benefit in early stages of disease, prior to collapse of the femoral head articular surface[14].

SURGICAL OPTIONS

Core decompression

The use of core decompression for the treatment of ONFH is controversial because well-controlled prospective trials are lacking. This procedure is reserved for the early stages of AVN (Figure 3). A prospective case-
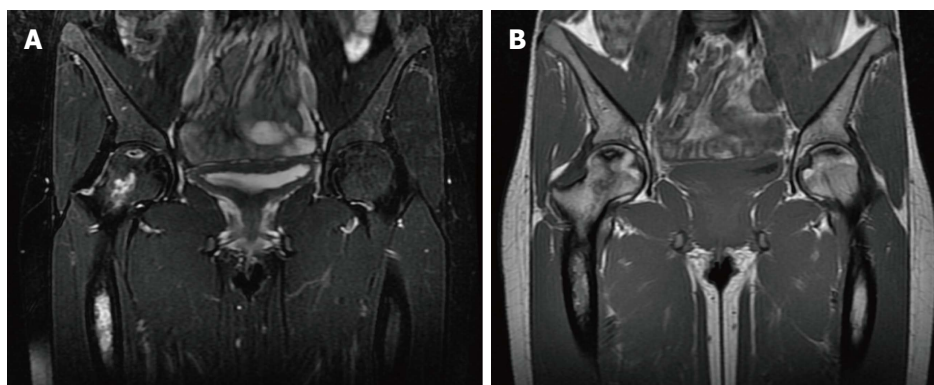
Figure 2 T2-weighted (A) and T1-weighted (B) coronal magnetic resonance imaging sequences demonstrating evidence of bilateral hip avascular necrosis and marrow changes consistent with sickle cell anemia.
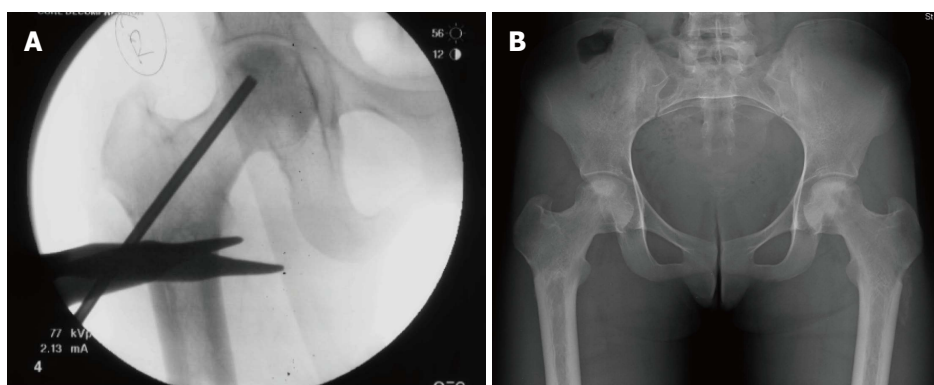
Figure 3 Intra-operative anterior-posterior fluoroscopic view (A) during a core decompression of the right hip, post-operative anterior-posterior radiograph of the pelvis (B) after bilateral core decompression.

Table 1 University of Pennsylvania System for staging avascular necrosis[38]

Stage	Criteria
0	Normal or non-diagnostic radiograph, bone scan, MRI
I	Normal radiographs, abnormal bone scan and/or MRI
	A: Mild (< 15% of femoral head affected)
	B: Moderate (15%-30%)
	C: Severe (> 30%)
II	Cystic and sclerotic changes in femoral head
	A: Mild (< 15% of femoral head affected)
	B: Moderate (15%-30%)
	C: Severe (> 30%)
III	Subchondral collapse (crescent sign) without flattening
	A: Mild (< 15% of articular surface)
	B: Moderate (15%-30%)
	C: Severe (> 30%)
IV	Flattening of femoral head
	A: Mild (< 15% of surface and < 2 mm depression)
	B: Moderate (15%-30% of surface and 2-4 mm depression)
	C: Severe (> 30% of surface and 4 mm depression)
V	Joint narrowing or acetabular changes
	A: Mild[1]
	B: Moderate[1]
	C: Severe[1]
VI	Advanced degenerative changes

[1]Average of femoral head involvement; as determined in stage IV and estimated acetabular involvement. MRI: Magnetic resonance imaging.

control study showed that core decompression was most efficacious in the early stages of ONFH[15]. Radiographic and clinical outcomes in this study were best in Steinberg Classification (Table 1) stages I and II. Another study reported symptomatic improvement in eleven of thirteen patients who underwent core decompression in pre-collapse stages[16]. Core decompression combined with autologous bone grafting may provide superior clinical outcomes than core decompression alone: a significant difference in Harris Hip Scores and visual analog scores, at a year post-operatively, were seen in patients who underwent core decompression with bone grafting when compared with core decompression alone[17]. Traditionally, there has been debate regarding whether core decompression should be performed in asymptomatic patients. Hsu *et al*[18] examined thirty-one patients with ONFH who underwent simultaneous bilateral core decompression and grafting. Ten patients with asymptomatic hips at the time of surgical decompression went on to require total hip arthroplasty (THA); thirteen patients required THA in the symptomatic side. The authors found that the proportion of hips ultimately requiring THA were similar between the two groups. When compared to AVN secondary to other etiologies, ONFH secondary to SCD has a poor clinical and radiographic response after core decompression. It has been posited that these inferior results after core decompression are because the decompression may decrease intraosseous pressure but not successfully relieve vascular congestion to prevent future vaso-occlusive events. Furthermore, there are diffuse changes in the femoral head in SCD patients, which may make complete decompression difficult[19]. In a study by Hernigou *et al*[7], more than 40% of the femoral head in SCD was involved, regardless of the stage of ONFH.
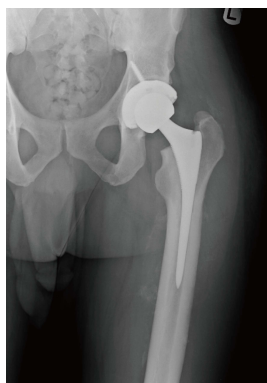
Figure 4 Anterior-posterior radiograph of the left hip in a 36-year-old male status post total hip arthroplasty for end-stage degenerative arthritis secondary to avascular necrosis.

THA

The use of THA for the treatment of ONFH in SCD has increased in popularity and is now the mainstay of the treatment for advanced disease. The primary indication for THA in SCD is persistent, intractable pain of the hip in a patient who has failed non-operative management. The patient must be medically fit to undergo elective surgery[20], and they must understand the post-operative rehabilitation needs, activity restrictions, and complication risks. A well-positioned (Figure 4) and well-functioning THA affords pain relief and functional mobility. Several preoperative considerations are warranted in patients with SCD. It is imperative to prevent crises through appropriate fluid maintenance and adequate oxygenation. Congestive heart failure may be present in some patients with chronic anemia, which requires meticulous attention to fluid balance and co-management with a hematologist familiar with sickle cell patients. Plasmapheresis and preoperative transfusion should be considered to improve oxygen carrying capability. Certain pre-operative hemoglobin levels may decrease the risk of sickle cell related complications[20]. However, aggressive transfusion thresholds may not be necessary: in a series of seventy-four patients, the rate of sickle cell complications did not significantly differ between a conservative (hemoglobin greater than 10 mg/dL) and aggressive (hemoglobin greater than 10 mg/dL; hemoglobin S level less than 30%) transfusion regimen[21]. Transfusion related complications can also be avoided with a more conservative pre-operative transfusion approach. Post-operatively, the SCD patient population is predisposed to infection due to functional asplenia. Periprosthetic and wound infection rates in sickle cell patients after THA have been reported between 16%-20%[22-24]. Remote site infections can seed the prosthesis, and chronic stasis ulcers in patients with SCD are just one of many potential sources of infection[25]. There exists heterogeneity in the series reporting the results of THA in patients with SCD. Multiple studies have demonstrated the effectiveness of THA as a treatment option for disabling pain secondary to ONFH caused by sickle cell hemoglobinopathies. However, complication rates have been reported to be as high as 80% at 6 years[26]. Studies have shown revision rates as high as 63% at 6.5 years post-operatively[23]. On the other hand, several series have shown that THA provides SCD patients pain relief and increased function[22,26-30]. One study reported a significant improvement in Harris Hip Scores, from a mean of 35 points preoperatively to a postoperative mean of 86 points (mean follow-up, 9.5 years)[31]. Another study reported that 73% of patients were without pain and activity restriction at a mean of 8.9 years follow-up[15]. Another series of 244 patients showed that 64% of patients were free of pain: the score for function averaged three points (range, 1-4 points on the Merle D'Aubigne scale) preoperatively and 5.4 points (range, 4-6 points) postoperatively. Furthermore, the score for the cumulative range of motion of the hip averaged 3.1 points (range, 1-6 points on the Postel scale) preoperatively and 5.2 points (range, 4-6 points) postoperatively[30]. Hanker *et al*[23] reported a mean improvement in pain relief at 6.5 years follow-up.

There are few prospective studies comparing cemented *vs* cementless fixation for THA in SCD, and the selection of prosthesis fixation in patients with SCD is controversial. Good results have been demonstrated using cementless THA[24,26,29]. Cementless fixation has potential advantages in patients with SCD. Multiple studies have reported a lower rate of aseptic loosening when using cementless components, which is important in this young patient population[24,26]. At a mean follow-up of 5.7 years, Ilyas reported only one case of acetabular cup loosening in a series of eighteen consecutive patients who underwent bilateral cementless THA[29]. Polymethylmethacrylate cement has also been implicated as a source of high infection rates and septic loosening[27]: The use of cement may cause thermal necrosis, further predisposing the bone to infection and loosening[29]. Several small series have reported a rate of aseptic loosening of 10%-38% in cementless THA[27]. A recent study using cemented components reported an 8% incidence of aseptic loosening[30]. One study reported a 33% aseptic loosening rate in primary THA with cemented cups[27]. A more recent retrospective study reported better results with cemented components[30]. There are some advantages that cemented fixation may provide, including additional hemostasis, decreased risk of femoral perforation and avoidance of biologic fixation in avascular/necrotic bone[20]. Furthermore, the use of cementless components relies on bony ingrowth for fixation in bone that may be largely necrotic. Hip dislocation has also been reported in patients with sickle cell hemoglobinopathy. The rate of hip dislocation has been reported in as many as 26% of hips in one study[26], and may be due to underlying abnormal anatomy seen in patients with SCD.

Alternative surgical options

Other surgical options for the management of AVN in this population include femoral osteotomy, hemiarthroplasty, arthrodesis, and resection arthroplasty. These are

largely historical techniques when compared to core decompression or THA. By redirecting weight-bearing forces, osteotomy can alleviate pressure in discrete areas of the femoral head, but it does not address the underlying pathology and progression of diffuse hip disease. Long-term failure is related to the amount of femoral head involvement[32]. Likewise, hemiarthroplasty only addresses changes in the proximal femur, and the quality of the bone in the SCD acetabulum is often poor. Reciprocal acetabular changes or subsequent migration of the prosthesis into the pelvis have been reported[27,28,33]. Due to the frequency of bilateral hip involvement in ONFH due to SCD, arthrodesis is rarely indicated and leads to significant shortening of the limb after debridement of non-viable bone required for successful fusion. Primary resection arthroplasty is rarely performed because THA provides greater potential benefits, but acceptable results have been reported when used as a salvage procedure after failed primary THA[22].

COMPLICATIONS

Medical and surgical complications are increased in patients with SCD undergoing THA. These complications can be described according to procedural-related complications and those complications specifically related to SCD.

Immediate

An immediate post-operative complication of THA is blood loss requiring transfusion and resulting transfusion reactions. Blood loss during THA in this population is often greater than blood loss seen in patients without the disease. The procedure in patients with SCD may be technically more difficult due to acetabular protrusion, or with difficulties preparing the femoral canal. These challenges may cause an increase in operative time and blood loss. There are also reports in the literature demonstrating that blood loss increases when patients have many preoperative transfusions, alloantibodies, or red blood cell exchange[30,34]. Vichinsky et al[21], in a series of 52 patients, reported excessive intra-operative blood loss in the majority of patients who underwent primary THA. The aggressive replacement of blood products is warranted and may decrease cardiopulmonary and neurological complications. It is currently recommended to keep the post-operative hemoglobin in patients with SCD > 10 mg/dL. Likewise, any signs and symptoms of anemia such as tachycardia, syncope, angina, ACS, and hypoxia should be addressed with transfusion[35]. Multiple transfusions throughout the lifetime of these patients lead to alloimmunization. Alloimunization is seen in more than 20% of patients[27]. This accounts for the increased frequency of major transfusion reactions in this population. Hernigou reported an incidence of major transfusion reactions of 12% in his series of primary THA in patients with

SCD[30]. Other studies have reported an incidence as high as 4%[24,27].

Other immediate postoperative complications include SCD related events such as vaso-occlusive crises and ACS (17% incidence)[34]. Episodes of vaso-occlusive crisis can present as pain anywhere in the body. Sickle cell crises can be managed with administration of parenteral fluids and analgesics[10,36]. Optimal analgesia is generally achieved with opiates given at pre-determined time intervals or by patient-controlled analgesia. Non-steroidal anti-inflammatories, such as ketorolac or ibuprofen, are also effective but are typically avoided in the immediate post-operative setting secondary to the increased risk of hematoma formation. Other infectious etiologies (e.g., postoperative pneumonia) should be ruled out with appropriate testing.

Acute chest syndrome is a form of acute lung injury in sickle cell patients and presents a major cause of morbidity and mortality[36]. The diagnosis of ACS is clinical and involves the presence of a new pulmonary infiltrate on chest X-ray, along with respiratory tract symptoms, hypoxemia, and/or fever. Intubation and mechanical support may be necessary if the symptoms progress. Acute chest syndrome is associated with a high mortality; therefore, an aggressive treatment strategy should be initiated early. This treatment includes aggressive oxygenation, analgesics, antibiotics as needed, and/or simple or exchange transfusions[37]. Incentive spirometry should also be encouraged through out the peri-operative period.

Short term

Patients with SCD are predisposed to infection. Studies have reported postoperative wound infections in 16%-25% of THAs[23,35]. A first generation cephalosporin should be used for antibiotic prophylaxis in these patients. No empiric coverage of *Salmonella* is generally necessary. However, authors have recommended the frequent use of intraoperative bone cultures to rule out infection before implanting the prosthesis[29]. Patients with SCD also have increased development of wound complications including increased wound drainage and hematoma formation, and complication rates have been reported in the literature[27].

Late

Late peri-prosthetic infection is a particular concern for patients with SCD because recurrent bacteremia is commonly seen and may result in hematogenous seeding of the prosthesis[30]. The risk of late infection has been reported and may ultimately require resection arthroplasty for treatment. Hernigou et al[30] reported that late infection, at a rate of 3%, was the main complication in his series. Late infection was the reason for resection arthroplasty in 100% of patients in another study[22]. Small series have reported rates of non-infectious (aseptic) prosthetic loosening of 10%-38%[27]. The reliance on bony ingrowth for fixation in necrotic

bone with cementless implants may be the cause of this phenomenon. A recent study using cemented components reported a lower incidence of aseptic loosening (8%) and posited that a properly placed cemented component may decrease the risk of aseptic loosening[30]. Hip dislocation is also a late complication, and has been reported in patients with sickle cell hemoglobinopathy. The rate of dislocation has been reported in as many as 26% of hips, and may be due to the changes in the bony anatomy seen in patients with SCD[26].

CONCLUSION

Avascular necrosis of the femoral head due to SCD can be quite debilitating. The surgical management of hip pathology in patients with SCD can be challenging, as there is an increase in medical and surgical complications in this patient population. To ensure a successful outcome, it is imperative that the surgeon consider all perioperative management strategies, including a multi-disciplinary approach to care with medical, anesthesia, and hematology colleagues. In early stages of ONFH, core decompression with or without bone grafting is a viable option to attempt to prevent progression of the disease. In patients with intractable pain and advanced disease, primary THA is the most reliable option for pain relief and functional improvement. The evaluation of the hemodynamic and oxygenation status of the patient minimizes sickle cell related complications in those undergoing operative interventions. Modern day cementless THA components have demonstrated encouraging outcomes in SCD patients. Total hip arthroplasty in the appropriately selected patient with SCD can provide improved hip function and enhanced quality of life.

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REVIEW

Collecting shoulder kinematics with electromagnetic tracking systems and digital inclinometers: A review

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Abstract

The shoulder complex presents unique challenges for measuring motion as the scapula, unlike any other bony segment in the body, glides and rotates underneath layers of soft tissue and skin. The ability for clinicians and researchers to collect meaningful kinematic data is dependent on the reliability and validity of the instrumentation utilized. The aim of this study was to review the relevant literature pertaining to the reliability and validity of electromagnetic tracking systems (ETS) and digital inclinometers for assessing shoulder complex motion. Advances in technology have led to the development of biomechanical instrumentation, like ETS, that allow for the collection of three-dimensional kinematic data. The existing evidence has demonstrated that ETS are reliable and valid instruments for collecting static and dynamic kinematic data of the shoulder complex. Similarly, digital inclinometers have become increasingly popular among clinicians due to their cost effectiveness and practical use in the clinical setting. The existing evidence supports the use of digital inclinometers for the collection of shoulder complex kinematics as these instruments have been demonstrated to yield acceptable reliability and validity. While digital inclinometers pose a disadvantage to ETS regarding accuracy, precision, and are limited to two-dimensional and static measurements, this instrument provides clinically meaningful data that allow clinicians and researchers the ability to measure, monitor, and compare shoulder complex kinematics.

Key words: Biomechanics; Glenohumeral; Kinematics; Reliability; Scapulothoracic; Validity

Core tip: This review compiles the available evidence regarding the accuracy and precision of measuring glenohumeral and scapulothoracic motion with electromagnetic tracking systems and digital inclinometers. These instruments have been found to be adequately reliable and valid with the majority of measurement error originating from operator inaccuracies associated

with palpation.

INTRODUCTION

The ability to objectively measure shoulder complex kinematics is key to gaining a thorough understanding of normal and abnormal movement, and may assist clinicians in the diagnosis and management of shoulder dysfunction[1]. Earlier studies[2,3] exposed participants to potentially harmful radiography in order to assess static two-dimensional motions of the shoulder complex that may inaccurately describe what is actually occurring three-dimensionally[4,5]. Subsequently, technological advances have allowed for noninvasive three-dimensional analysis of glenohumeral and scapulothoracic kinematics utilizing electromagnetic tracking systems (ETS)[6-11]. The main obstacle to analyzing three-dimensional shoulder movements is the difficulty of tracking the movements of the scapula. Unlike the upper and lower extremity segments, the scapula glides and rotates underneath layers of soft tissue and skin requiring investigations into the ability to accurately and repeatedly measure scapular kinematics using noninvasive measures[7-9,11-20]. Furthermore, other real limitations exist in that these systems are neither cost effective nor practical for the clinical setting[21,22]. Due to these difficulties, other methods of measuring shoulder complex kinematics that are easily accessible in the clinical setting have been investigated[21-23].

The availability of reliable and valid clinical instrumentation enables clinicians to make sound clinical decisions that are effective, efficient, and safe. Clinically accessible methods have been established that qualitatively and quantitatively assess scapular resting position and scapular orientation during humeral elevation[24-28]. Of the two, quantitative methods improve objectivity that may lead to decreased clinician error. Several studies have utilized the digital inclinometer to investigate various kinematic measures of the shoulder complex. While a three-dimensional analysis provides a thorough investigation of glenohumeral and scapulothoracic kinematics, the digital inclinometer provides clinicians with a more simplistic mean of analyzing kinematic data.

Instances in the literature exist where inclinometers were validated against three-dimensional scapular kinematic data collected by ETS[21,23]. Other studies have established criterion-related validity and reliability of other clinical instruments against data collected with a digital inclinometer[22]. To our knowledge no articles have been published that review the reliability and validity of ETS and digital inclinometers as measurement tools for collecting shoulder complex kinematics. The purpose of this paper is to provide such a review, with emphasis placed on the various factors, methods and motions that affect reliability and validity, and selected clinical applications utilizing these instruments.

ETS

ETS permit investigators the ability to track the position and orientation of sensors in space. These systems utilize an electromagnetic transmitter that generates an electromagnetic field and a series of sensors tethered to a computer system. Combined, the transmitter and computer system are able to detect the location and orientation of the sensors allowing for the six degrees of freedom required for three-dimensional analysis. In the field of biomechanics, these sensors can be mounted to the surface of the skin overlying various anatomical landmarks that enables the measurement of body segment kinematics. Currently, there are two ETS (Polhemus, Colchester, VT and Ascension Technology Corporation, Burlington, VT) that are commonly used in the study of biomechanics. In order to acquire and analyze data collected by the hardware, users must either write their own code using a commercially available product such as MATLAB (The MathWorks, Inc., Natick, MA) or purchase a commercially available software interface system, such as MotionMonitor® (Innovative Sports Training, Inc., Chicago, IL) that is a comprehensive turnkey data acquisition and analysis system. As it relates to data acquisition and analysis, post-treatment analysis of the data is performed to quantify shoulder kinematics. Presently, in order to facilitate the reporting of shoulder kinematics among researchers and clinicians, the International Society of Biomechanics has published standards for joint coordinate systems and rotation sequences for the thorax, clavicle, scapula, and humerus[29].

Calibration

Accuracy and precision are necessary in order to effectively utilize any data that is collected by laboratory/clinical instruments. Ascension has published information regarding accuracy for the Flock of Birds (FOB) system with root mean square (RMS) errors of 7.62 mm for linear position and 0.5° for orientation. However, the environment in which these data were attained is unclear. It is well understood that metallic objects within the vicinity of the electromagnetic transmitter will alter the magnetic field, thus affecting accuracy of the ETS[30,31]. Milne *et al*[30] demonstrated significant alterations in measurement accuracy (positional difference of 5.26 cm and angular difference of 9.75°, $P < 0.001$) when mild steel was introduced into the electromagnetic field of the ETS. They collected the kinematic data utilizing the default settings with a sampling frequency of 103 Hz. LaScalza *et al*[31] investigated different sampling frequencies and their effects on accuracy when aluminum

and steel were introduced into the electromagnetic field. While both materials had significant effects ($P < 0.0001$) on measurement error, a significant interaction of sampling frequency and metal type ($P < 0.0001$-0.0016) indicated errors in all three coordinates. The FOB system was found to be more accurate at lower frequencies (*i.e.*, 20 Hz) when aluminum was placed within the electromagnetic field, whereas the system was more accurate at higher frequencies (*i.e.*, 120 Hz) when steel was present[31]. Therefore, users of ETS should be cognizant of their testing environment and utilize calibration procedures to adjust for interferences created in the electromagnetic field.

Earlier studies[6,7,9,10,13] investigating scapular kinematics utilizing ETS were limited to static measurements through a given range of motion. Meskers *et al*[32] investigated the accuracy of the FOB system before and after a static calibration procedure. Positional measurements were collected in a 1 m^3 space located 1 m above the floor utilizing a stylus. The error calculated prior to calibration was unacceptably high with RMS errors of 20.8 mm (x-coordinate), 22.2 mm (y-coordinate), and 20.4 mm (z-coordinate). The authors attributed these errors due to a large disturbance of the electromagnetic field caused by metal in the testing environment, particularly the steel reinforced concrete floors. After calibration, the RMS errors were reduced to acceptable levels of 3.24 mm (x-coordinate), 5.64 mm (y-coordinate), and 2.73 mm (z-coordinate). Further, when removing measurements taken closest (1 m) to the steel reinforced concrete floor, RMS error measurements improved to 2.07 mm (x-coordinate), 2.38 mm (y-coordinate), and 2.35 mm (z-coordinate)[32]. Others have reported static RMS errors of 5.3 mm in position, 3.1 mm in linear displacement, and 0.23° in orientation and have suggested that system accuracy be established for each testing environment[14].

As methodologies[4,8,33] have evolved, the collection of dynamic scapular kinematics has become the norm; therefore, an understanding of the dynamic accuracy of the FOB is necessary. McQuade *et al*[34] investigated the dynamic accuracy and repeatability of the FOB utilizing a dynamic pendulum calibration technique. RMS errors were reported for position (3.7-10 mm), angular displacement (0.3°-0.5°), and angular velocity (1.1°- 2.2°/s). In addition, the authors suggested that studies examining motions with speeds greater than 250°/s would incur large errors in accuracy[34]. Therefore, studies investigating high velocity uncontrolled athletic movements should use caution in the reporting of results.

Scapula tracking methods
The ability to accurately and precisely track dynamic movements of the scapula in a noninvasive manner has been a limiting factor in analyzing detailed kinematics of the shoulder complex. The current gold standard for tracking scapular kinematics involves use of invasive, transcutaneous, cortical pins being placed in the scapular spine[4,8]. While this method allows for dynamic assessment of scapular motion, it is obviously undesirable in large-scale clinical studies. Nonetheless, cortical pins provide a means of directly collecting bony kinematic data that may be less comfortable for the patient. The usefulness of this methodology can be seen in the study by Karduna *et al*[8] in validating the scapular tracker and acromion method, both being noninvasive methods. Three noninvasive methods have been described for use with an ETS to track scapula orientation: Scapula locator, scapula tracker, and acromion method. Each of these noninvasive methods have been described and validated based on the associated measurement error when comparing novel approaches.

Scapula locator: Johnson *et al*[13] first described the scapula locator as a means to record three-dimensional scapular orientations in space. The measurement jig consisted of a housing that supports three rods that could be positioned over the posterolateral acromial angle, the root of the scapular spine, and the inferior angle of the scapula. An electromagnetic sensor affixed to the jig allowed orientation of the locator, relative to the thorax, to be recorded by an ETS during quasi-static trials. Quasi-static trials involved the participant moving to selected positions and holding those positions while the scapula locator was used to collect orientation data. This apparatus eliminated the need to individually digitize the three anatomical landmarks as described by van der Helm[10], which decreased error and increased speed of analyses[7,13].

Three studies evaluated the reliability of the scapula locator and found it to be applicable in three-dimensional kinematic studies of the scapula[7,9,21]. Johnson *et al*[13] reported 95% confidence interval ranges for intra-observer and inter-observer errors. They reported intra-observer errors ranging from 0.89° to 2.34° for anterior-posterior tilt, 0.91° to 1.87° for medial-lateral tilt, and 1.05° to 2.69° for upward-downward rotation, while inter-observer errors ranged from 4.98° to 7.88°, 4.5° to 6.04°, and 5.64° to 11.02°, respectively. Following designed modifications and improvements, Barnett *et al*[9] reported 95% confidence intervals for inter-observer errors that ranged from 2.55° to 2.72° for anterior-posterior tilt, 3.57° to 3.63° for medial-lateral tilt, and 3.47° to 3.85° for upward-downward rotation. Similarly, Meskers *et al*[7] reported standard deviations for inter-observer errors, which were 2.73° to 2.87° for anterior-posterior tilt, 2.98° to 3.21° for medial-lateral tilt, and 3.80° to 3.91° for upward-downward rotation. In addition to inter-observer errors, they reported inter-trial (1.93°-1.96°; 2.26°-2.46°; 2.37°-2.53°; respectively), inter-day (2.83°-3.03°; 4.01°-4.17°; 3.43°-3.73°; respectively), and inter-subject (7.81°-8.02°; 7.86°-9.02°; 6.05°-7.04°; respectively) variability[7].

The reported error measures for the scapula locator indicate sufficient reliability for its use in clinical research[7,9,13]. The fairly low inter-day error measures reported by Meskers *et al*[7] demonstrates

the ability to reliably align the scapula locator with adequate precision, especially considering the amount of error that may be associated with identifying anatomical landmarks. In a more recent modeling study, Langenderfer et al[20] indicated that variability in scapular kinematic descriptions could range as high as 11.7° in anterior-posterior tilt, 16.6° in medial-lateral tilt, and 12.3° in upward-downward rotation when allowing for 4 mm in anatomical landmark variability. Nonetheless, Meskers et al[7] reported considerably smaller errors caused by palpation when digitizing the anatomical landmarks with the scapula locator (0.53°-1.52°). Although the scapula locator has been demonstrated to be a reliable method for measuring quasi-static scapula kinematics, its relevancy falls short given the inherent dynamics of normal human movement. Furthermore, the locator has not been compared against the gold standard method to establish accuracy.

Scapula tracker: Karduna et al[8] first described the scapula tracker as a valid method for noninvasive tracking of three-dimensional scapula motions. The scapula tracker was a custom made plastic jig made of three parts: A base, an arm, and a footpad. The base was affixed to the skin overlying the spine of the scapula. The attached arm was adjustable to reach the acromion, which was affixed to the flat part of the acromion *via* the footpad. An ETS sensor was connected to the base of the scapula tracker that allowed dynamic tracking of three-dimensional scapula kinematics. The scapula tracker was compared to simultaneous measurements captured by a sensor attached to transcutaneous cortical pins that were drilled into the spine of the scapula. In an effort to validate the scapula tracker, the authors reported RMS errors of 3.2° to 10° for all scapular orientation angles (anterior-posterior tilt, medial-lateral tilt, and upward-downward rotation) during four active motions of the shoulder complex (scapular plane elevation, sagittal plane elevation, horizontal abduction, and external rotation). Interestingly, while most efforts to validate an instrument involve an assessment of concurrent validity through correlation analyses, an evaluation of RMS error was utilized instead. In these instances, while no acceptable level of error was defined, investigators sought to define methods that resulted in as little error as possible. Given the nonlinear nature of the data, the use of RMS appears to have served as an appropriate alternative for establishing validity. No articles were found that specifically addressed reliability for the scapula tracker.

Acromion method: The acromion method is a skin-fixed method by which an ETS sensor is adhered to the flat surface of the acromion that allows noninvasive tracking of three-dimensional scapula motions[8,33,35]. This method allows for dynamic tracking of the scapula that does not restrict the motions of subjects, is more comfortable, reduces the data collection time and

motor noise associated with other palpation methods (*i.e.*, scapula locator), and does not require a custom designed piece of equipment (*i.e.*, scapula locator and scapula tracker)[11]. Karduna et al[8] established concurrent validity of the acromion method against an invasive method whereby an ETS sensor was attached to transcutaneous cortical pins that were drilled into the spine of the scapula. They reported RMS errors of 3.7° to 11.4° for all scapular orientation angles (anterior-posterior tilt, medial-lateral tilt, and upward-downward rotation) during four active motions of the shoulder complex (scapular plane elevation, sagittal plane elevation, horizontal abduction, and external rotation). Generally, the acromion method underestimated the bone fixed measurements; however, upward rotation was overestimated[8]. In contrast, Meskers et al[11] found the acromion method underestimated all scapular orientation angles by an average of 6.5° (maximally 13°) when compared to measurements obtained with a scapula locator.

Karduna et al[8] found that RMS errors increased for all scapular orientation angles as humeral elevation increased indicating the presence of skin motion artifacts. Due to the relationship of error and elevation, they indicated that the acromial method was acceptable for tracking scapular motions below 120° of elevation. A systematic error pattern was identified for upward rotation; therefore, the authors presented a correction model that reduced the overall RMS error of upward rotation from 6.3° to 2°. In likeness, Meskers et al[11] was able to reduce RMS errors for scapular orientation angles to approximately 2° when applying a linear regression model to correct skin motion artifact to improve the RMS error calculated between the acromion method and scapula locator. It was confirmed that measurement error increased as elevation increased indicating the sensor was sensitive to skin motion artifact[11]. In contrast, Lin et al[16] found no significant differences or significant correlations in scapular orientation angles that would have suggested skin motion artifact. They concluded that skin motion artifact had little impact on the scapular kinematics when evaluating four functional tasks.

Alternate methods to improve accuracy of tracking scapular motions, which have been described as less complex than skin motion artifact correction models, have been proposed in studies utilizing optoelectronics tracking systems[36,37]. Brochard et al[36] developed a double calibration technique of the local scapula coordinate system that resulted in lowered RMS errors ranging from 2.96° to 4.48° as compared to the larger RMS errors of a single calibration (6°-9.19°). Shaheen et al[37] reported that optimal positioning of the acromial marker (the meeting point of the spine of the scapula and acromion) and angle of abduction (90° of shoulder elevation) during the initial calibration of the local scapular coordinate system resulted in improved RMS errors (3° to 5°). While the reduction in RMS errors reported by Brochard et al[36] and Shaheen

Table 1 Electromagnetic tracking system reliability of scapular measures during isolated planar motion of the humerus

Ref.	Motion studied			Reliability coefficient			Measurement error		
Thigpen *et al*[15]	Dynamic		CMC			RMS			
		Ascending		Inter-trial	0.88-0.97		1.35°–1.74°		
			Sagittal	Within-day,	0.74-0.94		3.43°–5.18°		
			Scapular	Inter-session					
			Frontal	Inter-day	0.68-0.94		4.27°–6.65°		
Ludewig and Cook[33]	Dynamic		ICC			SEM			
		Ascending		Inter-trial	0.93-0.98		< 3.3°		
			Scapular						
Scibek and Carcia[14]	Quasi-static		ICC						
		Ascending		Inter-trial	0.95-0.99				
			Sagittal	Inter-day	0.36-0.98				
			Scapular						
			Frontal						
Roren *et al*[18]	Dynamic		ICC			SEM		SRD	
		Ascending		Inter-trial	0.83-0.98				
			Sagittal	Inter-day,	0.76-0.95		0.56°-1.61°		1.54°–4.47°
			Frontal	Intra-observer					
				Inter-day,	0.49-0.92		0.89°–3.57°		2.46°–9.89°
				Inter-observer					
Haik *et al*[19]	Dynamic		ICC			SEM		MDC	
		Ascending and descending		Inter-trial	0.92-0.99		0.86°–3.17°		
			Sagittal	Inter-day	0.54-0.88		2.77°–7.44°		6.43°–17.27°

CMC: Coefficient of multiple correlation; ICC: Intraclass correlation coefficient; RMS: Root mean square; SEM: Standard errors of measurement; SRD: Small real difference; MDC: Minimal detectable change.

et al[37] were not as substantial as Karduna *et al*[8] and Meskers *et al*[11], the simplicity of the techniques are appealing. Therefore, investigation into the utilization of these calibration techniques[36,37] with ETS is warranted.

The reliability of tracking scapular motion during isolated humeral planar motions with ETS utilizing the acromion method has been relatively strong over time (Table 1). Inter-trial and within-day, inter-session reliability in both healthy and impaired subjects has been demonstrated to yield good to excellent. In addition, inter-day, intra-observer reliability demonstrated moderate to excellent results in healthy subjects with the exception of Scibek and Carcia[14] where inter-day reliability was found to yield fair to excellent results. Instances of lower inter-session or inter-day reliability may be due to anatomical landmark digitization error[14,20] and sensor placement error[11,14,37]. Thigpen *et al*[15] suggested that scapular orientation angles should be collected in the sagittal plane in order to best detect changes in kinematics due to the larger CMCs (0.82-0.94) and smaller RMS errors (3.43°-5.76°) compared to the scapular and frontal planes. With the exception of Scibek and Carcia[14], similar results were reported by Roren *et al*[18] (ICC = 0.77-0.93) and Haik *et al*[19] (ICC = 0.70- 0.82) regarding inter-day, intra-observer reliability measures during sagittal plane elevation. However, less favorable results (ICC = 0.58-0.88) have been found for the descending phase of motion in the sagittal plane[19]. Regarding error in the sagittal plane, Roren *et al*[18] found small SEM (0.69°-1.61°) and small real difference (SRD) (1.90°-4.47°) values, whereas Haik *et al*[19] found relatively large SEM (2.77°-6.79°) and minimal detectable change (MDC) (6.43°-15.76°) values. These differences are likely due to the lower range of motion (0°-90°)[18] studied as compared to the other two studies (30°-120°[15] and 0°-120°[19]) considering the known associated errors with higher levels of elevation[8]. While these studies have demonstrated acceptable reliability for assessing scapular kinematics in isolated planar motion, the large SRD and MDC question the ability of ETS to detect meaningful changes in scapular kinematics. SRD and MDC measurements have substantial value to clinicians, especially when determining outcomes of an intervention.

Only two studies in the literature were found that investigated the reliability of tracking dynamic scapular orientation angles during functional movement patterns with ETS utilizing the acromion method[16,18]. Lin *et al*[16] investigated the reliability of tracking shoulder complex motions during four functional activities (overhead height task, shoulder height task, sliding a box task, and reaching for a salt shaker task). They reported inter-trial ICC values based on peak scapular orientation angles that ranged from 0.78 to 0.99 for kinematic descriptions of the shoulder complex (scapular orientation angles and humeral orientation angles). Measurement error

was reported with SEM values that were less than 2° for all kinematic variables. In addition, the authors reported Pearson bivariate correlation values that ranged from 0.81 to 0.97, which served as an index of similarity across the trials of the recorded movement patterns during each respective functional task. Roren *et al*[18] assessed the reliability of tracking two functional movement patterns (simulated back washing and hair combing) based on scapular orientation angles at rest, 30°, and 90° of humeral elevation (only rest and 30° for back washing). They reported ICC values that ranged from 0.83-0.98 for inter-trial reliability; 0.64 to 0.92 for inter-day, intra-observer reliability; and 0.35 to 0.89 for inter-day, inter-observer reliability. SEM values ranged from 0.77° (MDC = 2.12°) to 1.67° (MDC = 4.64°) for inter-day, intra-observer, and 1.05° (MDC = 2.91°) to 3.23° (MDC = 8.96°) for inter-day, inter-observer.

The repeatability of functional movement patterns has been demonstrated to yield good to excellent inter-trial reliability[16,18]. While Lin *et al*[16] did not report inter-session or inter-day measures of reliability, Roren *et al*[18] demonstrated fair to excellent inter-day reliability. Of the two movement patterns, the hair combing movement pattern consistently demonstrated larger ICCs and smaller SEMs and MDCs. The authors speculated the less favorable measures of the back washing movement may be due to the subjects not being able to see the arm motion while looking ahead, thus not receiving visual feedback of the movement. Another note of importance that may have impacted the results of Roren *et al*[18] was that the authors utilized the original standardization protocol[38] instead of the most current[29]. Other studies have suggested higher measures of reliability were enhanced to restricting humeral elevation to one plane of motion for the collection of scapular kinematics[14,15]. The results of these two studies have demonstrated the ability to repeatedly measure functional tasks of the upper extremity that involved multi-planar motions[16,18]. However, some caution should be taken when comparing inter-day, inter-observer scapular kinematic data.

Humeral tracking method
As stated earlier regarding the tracking of scapular motions, the ability to accurately and precisely track dynamic movements of the humerus in a noninvasive manner is necessary to garner relevant data about shoulder complex kinematics. However, these types of studies are not applicable to large-scale clinical studies due to the invasive nature of the method. The most commonly used noninvasive method for tracking humeral kinematics with an ETS utilizes a hook-and-loop strap that secures a sensor to the surface of the upper arm (humeral cuff), and avoids the use of cortical pins making it more desirable for large-scale clinical studies.

Ludewig *et al*[39] simultaneously compared the tracking of humeral kinematics with a humeral cuff to a sensor affixed to an external humeral fixator in a single subject. Dynamic three-dimensional kinematic data were collected for humeral elevation in the scapular and sagittal planes and internal and external rotation with the upper arm maintained at the side. Different Euler angle rotation sequences were used to describe humeral rotation angles with respect to the trunk (z, y', z'') and scapula (y, x', z''). The humeral cuff was found to closely match humeral rotation angles with maximal underrepresentation of external rotation of 5.7° during elevation in the scapular plane and 15.6° of external rotation with the arm at the side. RMS errors for humeral rotation angles ranged from 1.3° to 7.5° for all respective motions.

In an effort to establish a noninvasive method, LaScalza *et al*[40] compared humeral kinematic data collected with a humeral cuff against a bone-fixed sensor in five cadaver specimens. The scapula of each specimen was prevented from moving by being rigidly fixed to a testing apparatus. The arms were directed through several motions including abduction, flexion, external rotation, three simulated reaching tasks, and a simulated overhand throw. Measurement errors calculated for all humeral rotation angles between the humeral cuff and bone-fixed sensor were reported as SEMs that ranged from 0.0° to 1.5°.

Hamming *et al*[41] established concurrent validity of a humeral cuff against an invasive method whereby ETS sensors were attached to transcutaneous cortical pins that were placed into the clavicle, acromion, and humerus. They reported average errors for all humeral orientation angles (angle of elevation, plane of elevation, and axial rotation) during five dynamic motions of the shoulder complex (frontal plane elevation, scapular plane elevation, sagittal plane elevation, axial rotation with the arm at the side, and axial rotation with the arm at 90° abduction). For all five motions, the mean errors for the humeral orientation angles for angle of elevation and plane of elevation ranged from 1.0° to 2.3°. However, mean errors for the humeral orientation angles for axial rotation were much larger for all five motions. Mean errors during the five dynamic motions ranged from 4.8° to 5.5° for the three motions of elevation, whereas the mean errors for the two rotation motions ranged from 14.3° to 11.5° with maximal differences approaching 30°. Furthermore, the authors found that differences in body mass index impacted measurement error with significant increases when subjects had index measures greater than 25.

These studies validate the use of the humeral cuff for tracking humeral kinematics[14,39-41]. In contrast to Ludewig *et al*[39], LaScalza *et al*[40] and Hamming *et al*[41] reported fairly large measurement errors for tracking humeral axial rotation during any type of shoulder complex motion. Furthermore, all three studies observed fairly slow movements (approximately ⩽ 40°/s) limiting the effects of skin artifacts caused by inertial movements of the sensor during faster motions. The measurement error reported for all elevation movements may support the use of the humeral cuff based on the significant

effects that anatomical landmark digitization can have on humeral kinematic descriptions. Langenderfer *et al*[20] indicated that variability in humeral orientation angle descriptions could range as high as 7.3° for elevation angle, 15.8° for plane of elevation, and 11.3° for axial rotation when allowing for 4 mm in anatomical landmark variability. Nonetheless, caution should be used when interpreting measures of humeral orientation angles of axial rotation as the validity and reliability of this measure is questionable.

Although the aforementioned studies bring forth skepticism in utilizing the humeral cuff, other research has demonstrated its effectiveness in collecting kinematic data. Scibek and Carcia[14] established criterion-related validity and reliability for their methodology of collecting shoulder complex kinematics. Quasi-static measurements of shoulder complex kinematics were collected during shoulder elevation in the sagittal, scapular, and frontal planes. Validity of the ETS was established against measurements collected with a digital inclinometer. Significant correlations ($P \leqslant 0.01$) determined validity of the ETS utilizing Pearson product-moment correlations that ranged from 0.85 to 0.99. The authors noted that angular measurements collected with the ETS for humeral elevation were consistently less than the inclinometer measurements ranging from -11.06° to 32.23°. Inter-trial reliability was reported with ICC values that ranged from 0.49 to 0.99, and inter-day reliability ICC values ranged from 0.05 to 0.99. While the inter-day reliability values appear to be less than favorable, the large majority of ICC values were found to be moderate to excellent.

DIGITAL INCLINOMETER

Many clinicians have limited or no access to state of the art three-dimensional biomechanical instrumentation for collecting kinematic data. Furthermore, clinicians do not have the time that is needed to set-up subjects, collect, and process the data collected with ETS. Clinicians need access to simple instrumentation that is both cost effective and practical to the clinical setting. The ability to quantitatively *vs* qualitatively measure shoulder movement is much more meaningful in the clinical setting. In addition, valid and reliable instruments provide clinicians with the ability to accurately measure, monitor, and compare changes in shoulder movement that may lead to better patient outcomes. The digital inclinometer has neither the ability to record three-dimensional nor dynamic shoulder movements. However, this tool provides clinically meaningful measures of two-dimensional shoulder kinematic data[42,43].

Scapular measurements

The digital inclinometer has been demonstrated to be a valid instrument in measuring two of the three axes of scapular motion: upward rotation[21] and anterior-posterior tilt[23]. Johnson *et al*[21] and Scibek and Carcia[23] established criterion-related validity of a modified digital

inclinometer against data collected with an ETS. Both studies utilized Pearson product moment correlations demonstrating strong relationships that ranged from 0.74 to 0.92 (mean differences 7°to 14°) for upward rotation[21] and 0.63 to 0.86 (mean differences 3.66° to 4.75°) for anterior-posterior tilt[23]. The smaller mean differences found with anterior-posterior tilt are most likely attributed to the smaller range of motion that occurs during humeral elevation as compared to the larger range of motion associated with upward rotation. Additionally, Johnson *et al*[21] compared static inclinometer measures to dynamic ETS measures with Pearson product moment correlations that ranged from 0.59 to 0.73. While the relationships were strong, the less favorable correlations reflected the expected inherent differences when comparing static to dynamic kinematics[17]. Regression analyses indicated positive relationships between the digital inclinometer and ETS. Johnson *et al*[21] reported the inclinometer detected 0.92° to 1.20° of change for every 1° detected by the ETS for upward rotation while Scibek and Carcia[23] reported slightly less favorable results with the inclinometer detected 1° of change in tilt for every 0.5° detected by the ETS for anterior-posterior tilt. It should be noted that Johnson *et al*[21] utilized participants with healthy and impaired shoulders while Scibek and Carcia[23] utilized only healthy participants highlighting the need for further investigation into the clinical usefulness of measuring anterior-posterior tilt in unhealthy shoulders.

Regarding reliability, Johnson *et al*[21] reported intra-rater, inter-trial reliability with ICC values that ranged from 0.89 to 0.96, and SEM values that ranged from 2.0° to 2.8°. Similarly, Scibek and Carcia[23] reported excellent inter-trial reliability with ICC values that ranged from 0.97 to 0.99. It appears that upward rotation can be repeatedly measured with acceptable consistency; however, no articles were found that have specifically assessed the reliability of assessing anterior-posterior tilt with a digital inclinometer.

Humeral measurements

Similar to scapular measurements, few investigations have reported on the validity of the utilization of digital inclinometers for humeral measurements. Two studies by Kolber *et al*[44,45] determined concurrent validity between measures collected with the inclinometer and a standard goniometer with ICC values for scaption (0.94), flexion (0.86), abduction (0.85), external rotation (0.97), and internal rotation (0.95) indicating good to excellent measures. Laudner *et al*[43] determined concurrent validity by measuring the relationship between horizontal adduction motion and internal rotation motion. Significant ($P < 0.01$) Pearson product moment correlations ranged from 0.52 to 0.72 between methods signifying an association of a loss of motion with contracture of the posterior capsular structures of the glenohumeral joint. While differences in methodology make comparisons difficult, these studies have demonstrated the digital inclinometer to be a valid instrument.

Two-dimensional measurements of shoulder motion utilizing a digital inclinometer has been demonstrated to exhibit moderate to excellent measures of reliability and validity. Similar to ETS, inter-observer measurements resulted in less than favorable reliability as compared to intra-observer measurements when utilizing digital inclinometers (Table 2). Therefore, caution must be taken when comparing angular measures of the shoulder complex that have been obtained by two different observers, and when measures are being compared that have been recorded from different instrumentation.

CLINICAL APPLICATIONS

Electromagnetic tracking systems and inclinometers have both shown to be both valid and reliable means of collecting shoulder complex kinematic data specific to movement of both humerus and scapula. When attempting to monitor clinical outcomes the ability to accurately quantify motions of these bony segments can provide useful data that could be used to drive clinical decision making. A variety of studies have demonstrated the usefulness of ETS in addressing clinically related questions, specifically those whose aim is to quantify shoulder kinematics associated with various shoulder patient populations.

Electromagnetic tracking systems have been useful in describing shoulder kinematics exhibited by the scapula and humerus in patients with rotator cuff pathology[46-52]. Lukasiewicz *et al*[46] noted altered scapular kinematic patterns in patients presenting with shoulder impingement when compared to participants with healthy shoulders. Similarly, in a study designed to compare three-dimensional shoulder kinematics in subjects with and without shoulder impingement, McClure *et al*[52] noted differences in scapular kinematics between groups, which were attributed to compensation strategies utilized for glenohumeral weakness and shoulder motion loss. In a treatment based study McClure *et al*[48] assessed scapular kinematics in patients with shoulder impingements before and after a six week intervention. While patients noted improvements in pain and shoulder function, no changes were noted in scapular kinematics following the intervention program[48]. Mell *et al*[47] utilized an ETS to identify variations in scapulohumeral rhythm between rotator cuff tear, tendinopathy, and healthy control subjects. Using the same equipment, others have investigated the role that pain and rotator cuff tear size has on scapulohumeral rhythm[49,50] and shoulder movement velocity[51]. Similarly, ETS have been utilized to capture three-dimensional scapular kinematics in patients with multidirectional instability[53], in a patient that had undergone shoulder arthroplasty[54], and in patients with frozen shoulders[55,56]. In all but one case[54], a noninvasive approach was utilized in conjunction with the ETS. In each case, data were obtained that enabled the clinicians to quantify the three-dimensional motion associated with the shoulder complex.

Electromagnetic tracking systems have also been useful in some clinically based studies designed to monitor three-dimensional scapular kinematics following an intervention. Wang *et al*[57] utilized an ETS to monitor alterations in scapular orientation following a stretching and strengthening protocol in a small sample of subjects presenting with forward shoulder posture. Similarly, Ebaugh *et al*[58,59], in two separate studies, evaluated the impact of shoulder muscle fatigue on the glenohumeral and scapular kinematics in samples of twenty healthy subjects. Others have also utilized ETS to monitor changes in scapular kinematics and scapulohumeral rhythm following fatigue protocols[60-62]. When evaluating the impact of glenohumeral internal rotation deficit (GIRD) in the shoulders of 23 subjects, Borich *et al*[63] noted that a significant relationship exists between GIRD and scapular orientation.

Although, ETS have been utilized in a variety of clinically based studies, the number of participants in these studies is relatively small. Often, access to these testing systems is limited due to the financial and physical resources necessary to own and operate this sophisticated equipment. Furthermore, although there are a variety of software packages and platforms that allow for data capture and analysis, the amount of time that must be invested in learning how to utilize these systems along with the time associated with setting up subjects is considerable and likely exceeds the available time for most clinicians. Still, investigators continue to utilize this equipment for their research; however, the number and size of these clinically based shoulder studies is limited. Interestingly, many of the studies involving the shoulder and ETS are validation studies designed to verify the clinical usefulness of a new, clinically available method of kinematic assessment. Johnson *et al*[21] took this approach when validating the digital inclinometer for use with assessing scapular upward rotation, which was replicated by Scibek and Carcia[23] for the monitoring of scapular anterior-posterior tilt. Still others have utilized ETS to establish the validity of a visual and clinically based scapular dyskinesis screening[26,27]. Ultimately, while ETS allow for accurate quantification of three-dimensional shoulder kinematics, accessibility limitations, along with physical and financial limitations make other tools and systems, such as inclinometers, an attractive option for clinical use and for addressing clinical questions.

In addition to the work of Johnson *et al*[21] and Scibek and Carcia[23], other investigators have suggested that inclinometers offer a cost effective and clinically useful means by which to quantify shoulder and scapular kinematics[64,65]. A number of studies involving assessment of the shoulder have relied on the use of inclinometers to quantify both scapular motion and glenohumeral motion. Borsa *et al*[66] utilized a digital inclinometer to quantify scapular upward rotation during humeral elevation in subjects with healthy shoulders. Scibek and Carcia[42] utilized a digital inclinometer to evaluate scapulohumeral rhythm in unimpaired subjects. A variety of clinically based studies have

Table 2 Digital inclinometer reliability of humeral range of motion measurements

Ref.	Motion	Reliability	ICC	SEM	MDC
Kolber *et al*[74]	Flexion	Intra-day, inter-observer	0.58	3.24°	8°
		Inter-day, intra-observer	0.83	1.64°	
	Abduction	Intra-day, inter-observer	0.95	1.63°	4°
		Inter-day, intra-observer	0.91	2.26°	
	Internal rotation	Intra-day, inter-observer	0.93	3.39°	8°
		Inter-day, intra-observer	0.87	4.27°	
	External rotation	Intra-day, inter-observer	0.88	3.98°	9°
		Inter-day, intra-observer	0.94	2.63°	
Kolber *et al*[44]	Scaption	Intra-day, inter-observer	0.89	3.4°	9°
		Inter-day, intra-observer	0.88	3.4°	9°
Laudner *et al*[43]	Horizontal adduction	Intra-observer	0.93	1.64	
		Inter-observer	0.91	1.71	
de Winter[65]	Abduction	Inter-observer	0.28–0.83		
	External rotation	Inter-observer	0.56–0.90		

ICC: Intraclass correlation coefficient; RMS: Root mean square; SEM: Standard errors of measurement; MDC: Minimal detectable change.

incorporated inclinometers when quantifying scapular motion and glenohumeral motion in overhead athletes and in patients with shoulder pathologies[43,67-72]. Dover *et al*[67] utilized inclinometers to measure glenohumeral range of motion and to evaluate proprioception in female softball athletes. Witwer and Sauers[68] evaluated scapular upward rotation in a group of collegiate water polo players. Similarly, Laudner *et al*[72] incorporated a digital inclinometer when comparing scapular upward rotation between baseball pitchers and positions players. Another inclinometer-based study examined scapular kinematics in 72 overhead athletes, with healthy and injured shoulders[69]. Interestingly, these studies where clinical data were obtained using an inclinometer routinely presented with larger sample sizes as compared to those clinically based studies that utilized ETS. Certainly, the statistical designs of these studies that utilized inclinometers may have required larger sample sizes; however, the ease of use associated with the inclinometer made it feasible to test large pools of subjects.

While there are few studies where ETS were used to measure changes in shoulder kinematics following an injury intervention program[48], inclinometers have been shown to be plausible options. Following the establishment of the digital inclinometer as a valid and reliable tool for assessing posterior shoulder tightness[43], Laudner *et al*[71] evaluated the acute effects of a sleeper stretch designed to increase posterior shoulder flexibility. Using the inclinometer, the investigators were able to observe significant increases in shoulder internal rotation and posterior shoulder motion following the stretching intervention[71]. Similarly, utilizing an inclinometer, McClure *et al*[73] compared the effectiveness of two stretching protocols, a sleeper stretch and cross body stretch, to increase shoulder range of motion. Although the randomized controlled trial utilized smaller sample sizes, they were able to detect significant and clinically meaningful increases in shoulder motion using an inclinometer[73]. Although not an intervention based study, Thomas *et al*[70] utilized a digital inclinometer to monitor changes in shoulder range of motion and scapular upward rotation in overhead athletes over the course of their competitive seasons. Based upon the observed changes in glenohumeral and scapular motion across their sport seasons, it was suggested that changes in motion should be monitored during their competitive seasons so as to address any changes that might contribute to the occurrence of shoulder injuries[70]. While both ETS and inclinometers can be utilized to monitor changes in shoulder complex kinematics over time or following intervention strategies, inclinometers provide an accessible, affordable, and clinically useful strategy for monitoring various aspects of shoulder motion.

CONCLUSION

The ability to gain valuable insight into the kinematics of the shoulder complex is heavily reliant on the accuracy and precision of the instrumentation utilized. The evidence presented in this review demonstrates that ETS and digital inclinometers are reliable and valid instruments. Similarly, it is apparent that ETS have an advantage regarding accuracy, precision, and the ability to capture three-dimensional and dynamic analyses, while digital inclinometers are much more cost effective and practical in clinical settings. Reliability of both of these instruments is highly dependent on the user as inter-rater measures were found to be less desirable when compared to intra-rater measures, with palpation error likely contributing to the increased variability. Although some evidence has been presented regarding the minimal detectable changes captured with ETS for scapular kinematics, further study is warranted to expand our understanding of the clinical usefulness of ETS. Conversely, inclinometers provide a clinically useful means to monitor kinematic changes during outcomes-based studies.

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MINIREVIEWS

Anterior knee pain following primary total knee arthroplasty

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Abstract

Despite improvements in technique and technology for total knee arthroplasty (TKA), anterior knee pain impacts patient outcomes and satisfaction. Addressing the prosthetic and surgical technique related causes of pain after TKA, specifically as it relates to anterior knee pain, can aid surgeons in addressing these issues with their patients. Design features of the femoral and patellar components which have been reported as pain generators include: Improper femoral as well as patellar component sizing or designs that result in patellofemoral stuffing; a shortened trochlear groove distance from the flange to the intercondylar box; and then surgical technique related issues resulting in: Lateral patellar facet syndrome; overstuffed patella/flange combination; asymmetric patellar resurfacing, improper transverse plane component rotation resulting in patellar subluxation/tilt. Any design consideration that allows impingement of extensor mechanism anatomical elements has the possibility of impacting outcome by becoming a pain generator. As the number of TKA procedures continues to increase, it is increasingly critical to develop improved, evidence based prostheses that maximize function and patient satisfaction while minimizing pain and other complications.

Core tip: Anterior knee pain continues to be problematic following primary total knee arthroplasty (TKA) procedures, oftentimes leading to revision surgery. While certain non-modifiable patient factors may lead to persistent post-operative pain, there are many modifiable elements including those related to the prosthesis and to surgical technique that also contribute. Addressing the prosthetic causes of TKA failure will allow improvements in implant design which may result in a decreased incidence of revision surgery. This paper aims to address several aspects of prosthetic design including femoral and patellar component features which may contribute to the development of anterior knee pain following TKA.

INTRODUCTION

Many improvements have been made to total knee arthroplasty (TKA) since its development in the early 1970s[1]. However, despite the implementation of such innovations, as few as 43% of patients report being completely pain free following a primary TKA procedure[2]. While pain alone is seldom utilized as a criterion for revision surgery, it is estimated that 2% of all TKAs ultimately fail due to pain. When associated with other factors leading to revision, such as component wear or loosening, pain contributes to a growing number of revision procedures, increasing the monetary burden on the healthcare system, with an additional projected cost of $5.8 billion by 2015[3,4]. The reported incidence of anterior knee pain following primary TKA is 8%[5]. Several studies have been conducted to determine the cause of anterior knee pain following TKA with variable results.

Patient related factors that may contribute to increased pain following TKA include younger age, female gender, and ethnicity while modifiable non-patient related factors include prosthesis design as well as surgical error[2,6-8]. In fact, up to 41.1% of patients have been found to experience patellofemoral complications related to these modifiable elements[9,10]. Causes of patellofemoral complications include rotational errors of the femoral or tibial component, implant maltracking, patellar fracture, aseptic loosening, and polyethylene wear[5,10,11]. Addressing the prosthetic causes of TKA failure will allow improvements to be made in implant design which may result in a decreased incidence of revision surgery and a lessened economic burden for both the patient and the healthcare system. This paper aims to address several aspects of prosthetic design including femoral and patellar component features which may contribute to the development of anterior knee pain following TKA.

BIOMECHANICS AND KINEMATICS OF THE NATIVE KNEE

Identifying the biomechanical and kinematic parameters of the native knee, particularly that of the patellofemoral joint, is essential when attempting to identify prosthetic design features implicated in anterior knee pain following primary TKA. In both native and prosthetic knees, anterior knee pain has been attributed to patellar mal-alignment and mal-tracking within the femoral trochlear groove[12,13]. The primary contribution of the patella to knee biomechanics resides in its facilitation of knee extension. Through its function as a fulcrum, the patella is able to increase the moment arm of the quadriceps force increasing the muscle's effectiveness in extending the knee[12]. The patella also plays important roles in the distribution of patellofemoral compressive forces during knee flexion as well as centralizing the multi-directional pull of the four quadriceps muscles in extension[12]. The contact area of the patella within the femoral trochlear groove is dynamic, with no contact in full extension, and contact beginning in the inferior pole of the patella with progressive increase in knee with continued knee flexion, this contact area continues to move peripherally on the patella as it goes into extreme flexion at the base of the trochlear groove[12].

The Q-angle is a measurement that aims to determine the lateral force vector acting on the patella, which is created by the combination of both the vector of the patellar tendon and the rectus[14]. It is defined as the angle between a line connecting the anterior superior iliac spine to the center of the patella and another line from the center of the patella to the tibial tubercle. This measurement describes the tendency of the quadriceps muscle to pull the patella laterally[12,15]. Higher Q-angles can increase the lateral pull by the quadriceps muscles, predisposing the knee to patellofemoral disorders such as patellar subluxation, dislocation, and increases in lateral patellofemoral contact pressure[14,15]. The Q-angle has also been demonstrated to influence active tibio-femoral kinematics through the positioning of the tibial tubercle. The extent of component rotation affects the position of the tibial tubercle and therefore the overall Q-angle[16].

ALTERATION OF KINEMATICS AFTER TKA

Anterior knee pain after TKA results primarily from excessive patello-femoral loads and abnormal patellar

tracking[13,17]. Such complications can be related to the alteration of the biomechanical and kinematic parameters of the native knee, primarily factors leading to an increase in the Q-angle of the prosthetic knee. It is important to realize that the positioning of all the components of the total knee can affect the overall Q-angle and the kinematics of the patella in the trochlear groove[13]. More specifically, external rotation of the femoral component or internal rotation of the tibial component (leading to lateralization of the tibial tubercle) can result in an increase in the overall Q-angle[13]. Thus lateralizing a narrower femoral component as well as preventing excessive medial placement of the tibial component lead to reduction in the Q-angle, providing a better patellar tracking[13]. Patellofemoral loads can also be decreased by a medial pivot placement, which allows contact stress to be homogenously distributed across the patella[17]. Additionally, avoidance of overstuffing with an increased patellar height and medialization of the patellar component also prevent increases in the Q-angle[13]. Alterations in patellar kinematics can also be attributed to change in the tibiofemoral joint line with elevations leading to patellar complications including inferior edge loading and patellar impingement[18]. Therefore it is important to attempt to restore normal tibiofemoral as well as patellofemoral kinematics in order to decrease the risk of anterior knee pain following TKA[13,17].

SURGICAL TECHNIQUES WHICH REDUCE PATELLOFEMORALCOMPLICATIONS/ ANTERIOR KNEE PAIN

Component mal-alignment following primary TKA
Component mal-alignment following primary TKA has a prevalence ranging between 9.4% and 11.8%[19,20]. Isolated internal rotation of the femoral component has been described as a potential source of prosthetic dysfunction, anterior knee pain, and potential early failure[21-23]. The degree of malrotation required to cause complications following TKA is not well delineated; however, surgical revisions have been successful in patients experiencing anterior knee pain and/or functional disability with ≥ 4 degrees of femoral component internal rotation[21,22].

Malrotation of the tibial prosthetic component constitutes another potential cause of a suboptimal clinical outcome following primary TKA[19,21,22]. While isolated tibial malrotation is not heavily explored in the literature, several techniques are described for quantifying the degree of component mal-rotation. One study defined the tibial component as internally mal-aligned when the rotation is of more than 18 degrees[22]. Subsequently, a strong correlation is reported between anterior or medial knee pain and isolated excessive tibial rotation[22]. When combined with femoral component internal rotation, as little as 3 degrees of mal-alignment can lead to pain and malfunction[22].

Femoral component rotation
Femoral component rotation also plays a key factor in patellar tracking and can contribute to patellofemoral complications following TKA. External rotation of the femoral component relative to the posterior femoral condyles facilitates central patellar tracking by reducing patellofemoral lateral shear forces[24-26]. External rotation of the femoral component leads to lateral positioning of the sulcus and preserves sulcus height which facilitates a more anatomic orientation of the trochlear groove[27]. This rotation also achieves a balanced flexion gap[2,5]. Therefore it is crucial for TKA systems to have instrumentation that allows for perfect external rotation of the femoral component in order to reproduce a more natural patellofemoral joint[25,27].

Patellofemoral overstuffing
Trochlear groove: Abnormal patellar tracking has been identified as a well-known cause of patellofemoral complications and anterior knee pain following TKA[24,28]. Several design features pertaining to the trochlear groove of the femoral component that directly influence the patellofemoral joint has been identified. The trochlear groove depth plays a major role in directing patellar tracking. A deepened trochlear groove better facilitates central tracking of the patella and can thus better secure the patellofemoral joint and minimize patellar instability, including lateral patellar subluxation, with increased degrees of knee flexion[25,28,29]. In addition to depth, the length of the trochlear groove can also improve overall patellar tracking by enabling a smooth transition from flexion to extension. Femoral components with a longer trochlear groove extend further proximally through the use of a longer anterior flange and allow for earlier capture of the patella in flexion, leading to a smoother articulation at earlier degrees of flexion[28,30]. Lateral tracking of the trochlear groove, facilitated by specific positioning of the femoral component, is also known to influence patellofemoral kinematics. Lateral placement of the femoral component enables earlier capture of the patella in addition to reducing patellar lateral sheer forces in early degrees of knee flexion[24,26,28]. Therefore a deeper and longer trochlear groove that tracks more laterally promotes stable and secure tracking of the patella thus producing a more natural and anatomic patellofemoral articulation[25,28,31]. In addition to improved patellar tracking, some of these design features may also facilitate a decrease in the rate of patellofemoral crepitance and patellar clunk syndrome[30]. Historically, femoral prosthesis designs did not adequately replicate the trochlear groove due in part to the lack of appropriate congruent angle. Native congruent angle is averaged to be 6 degrees with a standard deviation of 11 degrees. Data suggests that a congruent angle greater than 16 degrees was abnormal in 95% patients leading to a potential risk for malaligned result following TKA[32].
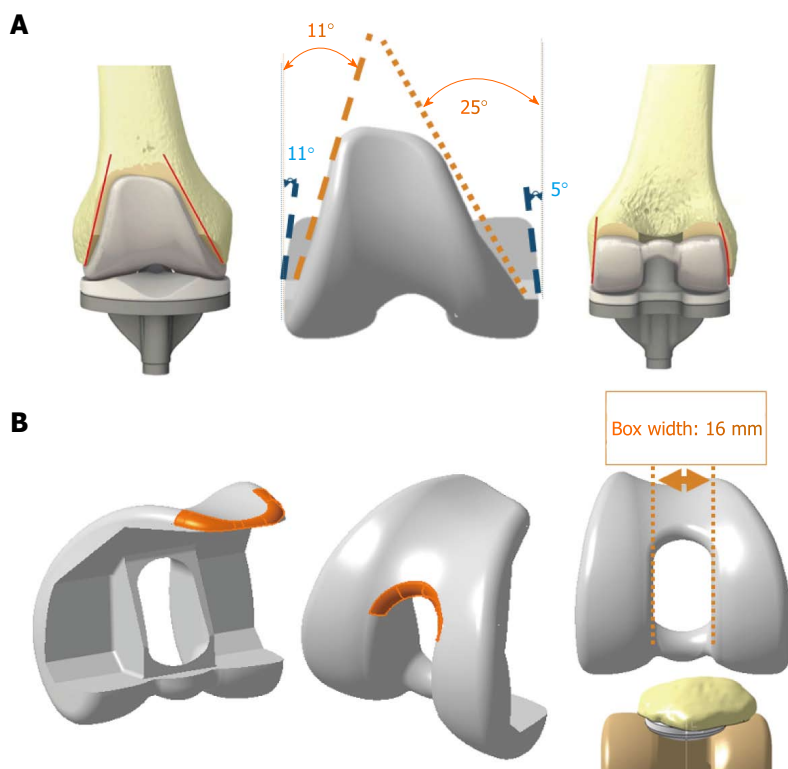
Figure 1 Femoral component design showing. A: Anterior and posterior narrowing to minimize disruption of soft tissue; B: Smoother transition radius.

DESIGN FEATURES OF THE FEMORAL COMPONENT WHICH REDUCE PATELLOFEMORAL COMPLICATIONS/ ANTERIOR KNEE PAIN

Anterior impingement (Figure 1)

Anterior impingement pain is an important potential consequence of TKA because it can cause further wear or even fracture of the post component[33,34]. It is determined by implant design, position of components in the sagittal plane, as well as the patient's activities[33,34]. Previous studies have considered various modifications of the anterior flange of the femoral component in order to reduce anterior impingement and pain following TKA. A femoral component with a wider and thicker anterior flange can lead to stuffing of the patello-femoral joint leading to increased patellar ligament tension and thus increased patellofemoral contact forces[35]. This will eventually cause accelerated polyethylene wear and an overall higher risk of patellar complications[35]. It has been shown that a femoral component that incorporates a smoother anterior edge can decrease patellar impingement[36]. Therefore modification to the anterior flange may potentially reduce complications following TKA; however, a definitive conclusion remains unattainable, with the lack of clinical experimentation.

Gender prosthetic variations and considerations

Researchers have recently studied the morphologic variation of the native femur both within and between genders in order to identify an association between complications following primary TKA, including anterior knee pain, with mal-fitting femoral and tibial components. It has been demonstrated that women, on average, have smaller distal femurs as well as clinically significant variation in distal femur morphology compared to their male counterparts. One morphological variation in particular is a much larger aspect ratio (anterior/posterior to medial/lateral measurement) which places this patient population at a higher risk for medial/lateral femoral component overhang[35,37-41].

Different body morphologic types have a significant correlation with distal femoral morphology. Patients with short and wide morphotypes have a wider medial-to-lateral dimensions irrespective of gender, whereas patients with long and narrow morphotypes (ectomorph) have a narrower knee[39]. Therefore patients fitted with standard femoral components who possess a more ectomorph morphology may also experience, as in women, femoral component overhang, leading to potential pain and further complications following primary TKA. As a result, in an attempt to reduce complications following TKA, the prostheses-design is continuously undergoing modifications, including gender specific implants (Figure 2). Overhang of ≥ 3 mm in at least one of the predetermined zones of the femoral implant is associated with a 90% increase in the risk of patient-reported knee pain 2 years following TKA[42]. Gender specific femoral components have been demonstrated to minimize femoral overhang and thus post-surgical complications by providing a component that better matches the morphological differences of the female knee[37]. Therefore to minimize complications following TKA, surgeons must be aware of the various morphological differences in the native anatomy of the

Figure 2 Femoral component design showing various sizing.

knee joint both between and within genders. By having prosthetics designed to better address this concern, medial to lateral overhang of the femoral component may be decreased leading to reduction in joint dysfunction and pain following primary TKA.

Ethnic prosthetic variations and considerations
In addition to gender, ethnicity also affects the morphologic type of both the femur and the tibia. Both male and female African Americans had increased anteroposterior height as compared to Caucasians and East Asians, while Caucasians had greater anteroposterior height as compared to East Asians[43]. There is a greater degree of curvature of the femoral condyles in Asian males and females[43]. With regards to the tibia, African American males had larger lateral anteroposterior height and smaller medial plateau anteroposterior height compared to Caucasian males, and larger mediolateral width and anteroposterior height as compared to Asian males[43]. Caucasian males and females had larger mediolateral width and anteroposterior height dimensions when compared to Asian males and females[43]. Despite known differences in the morphology of the femur and tibia among different ethnicities, prostheses are primarily made based on Caucasian morphology, which may contribute to an increase in patellofemoral complications, including anterior knee pain, following TKA in patients of different ethnicities[43].

Patellar clunk as related to the design of the femoral component
Patellar clunk syndrome is a complication that results in anterior knee pain and crepitus three to nine months following a TKA[44,45]. It is due to the formation of a fibrous nodule between the superior pole of the patellar

and femoral component and the quadriceps tendon, which causes pain and displaces (clunks) with extension of the knee from approximately 30 to 45 degrees of flexion[46-48].

The etiology is multifactorial with the femoral component considered to be one of the contributors leading to the development of this syndrome[45,47]. Several design flaws of the femoral prosthesis have been proposed including: a sharp anterior edge at the superior aspect of the intercondylar box, a high intercondylar box ratio, an increased posterior condyle offset, and the use of smaller femoral components[45,47,48]. In addition, specific total knee systems, most notable posteriorly-stabilized TKA, have been associated with a higher incidence of patellar clunk[44,46,48].

While treatment for this syndrome is accomplished by either open or arthroscopic correction, prevention is always preferred[45]. Attempts of reducing this postoperative complication have included the following modifications to the femoral components: smoothing the transition from the notch to the anterior flange, raising the lateral flange, deepening the trochlear groove, and incorporating a more posterior intercondylar box[45-48]. To minimize the occurrence of patellar clunk syndrome, both manufactures and surgeons must continue to assess the advantages of altering the current designs of femoral components.

DESIGN FEATURES OF THE PATELLAR COMPONENT WHICH REDUCE PATELLOFEMORAL COMPLICATIONS/ ANTERIOR KNEE PAIN

Since the inauguration of the dome patella, the incidence of anterior knee pain has dropped from 50% to 12%[48]. However, because patellar resurfacing has brought on its own complications, including component loosening, necrosis, and fracture, many studies have since been completed to determine the risks and benefits of employing patellar resurfacing in TKA[49,50]. One study demonstrated that while the overall rate of revision was similar, at 3.1% in resurfaced patellae and 4% in unresurfaced patellae, isolating anterior knee pain as the cause of revision garners different results: only 1% of resurfaced knees underwent revision due to anterior knee pain compared to 17% of unresurfaced knees[51]. Other studies reported similar numbers, with only 1%-5% of patients with a resurfaced patella experiencing chronic anterior knee pain compared to 10%-14% of patients with an unresurfaced patella[50,52]. However, other studies showed that there is no difference in anterior knee pain between resurfaced and unresurfaced patellae[53]. While many of the unresurfaced knees underwent secondary resurfacing due to anterior knee pain, revision surgery did not always resolve the pain[2]. Despite differing findings regarding the association of patellar resurfacing and decreased knee

pain, many researchers suggest that surgeons employ at least selective resurfacing, based on factors such as patellar height and patient age[54].

Utilizing a patellar component that does not adequately match the preoperative anatomy of the knee is another mechanism potentially leading to a "stuffed" patellofemoral joint. Patellofemoral overstuffing is the result of an increase in the anteroposterior size of the patella, femur, or both, and may lead to anterior knee pain following TKA[55]. The anteroposterior size of the femur can be increased by the use of an oversized femoral component or underresection of the anterior femur[56]. The femoral component's position in the anteroposterior plane has a crucial effect on patellofemoral biomechanics. If the size is incorrect or the component is improperly placed, the consequences could include increased patellar retinacular strain, patellar mal-tracking, or early polyethylene wear leading to premature joint failure, anterior knee pain, and decreased knee flexion[35,39,41,56-61]. The commonality of patellofemoral overstuffing is related to the design of the femoral component as well as the relatively limited availability of various component sizes[41,57,62]. An anterior buildup on the femur of 4-mm could result in as much as a 4-degree loss of passive knee flexion[41]. Therefore, it is critical that a large number of femoral component sizes be available at the time of surgery in order to prevent overstuffing of the patellofemoral joint. In addition, asymmetric patellar resurfacing can result in overstuffing. Patellar resection is performed free-hand and there are no standard guidelines or anatomic landmarks which should be used to guide the cuts, leading to an increased incidence of asymmetric resurfacing[55]. Asymmetric patellar resection can lead to bony impingement and patellar maltracking, both of which contribute to anterior knee pain post-operatively. A difference of 2 mm or greater in the thickness of the patella, as measured 15 mm from the medial and lateral edges, is considered asymmetric resection[55]. This occurs in up to 10% of procedures, and is more common in females, likely due to their smaller patellae, which makes resection technically more difficult[55]. A 15% increase in the combined anterior patellar displacement and anteroposterior femoral size is demonstrated to be associated with a significant increase in Knee Society Pain Score[57].

DESIGN CONSIDERATIONS AIMED AT RESTORING NORMAL TIBIOFEMORAL KINEMATICS IN POSTERIOR SUBSITUTING/STABAZLING TKA

The post-cam mechanism is often seen in posterior stabilized knee prostheses in order to mimic the posterior cruciate ligament (PCL), minimize tibial posterior displacement, and increase posterior femoral translation[63-65]. Distal placement of the femoral cam as well as a larger femoral posterior radius can increase the amount of posterior femoral movement; however, excessive anterior or posterior cam placement can cause femoral rollback impingement or excessive rollback, respectively[64]. Femoral condyle rollback is seen in normal knee kinematics during knee flexion but may be decreased in TKA[26] (Figure 3). It was found that up to 30% of different TKA designs rotate the opposite direction in axial rotation, which effect patellar kinematics and place a larger lateral vector on the patella in flexion[66]. Axial rotation patterns in knees after TKA are similar to those in normal knees, but the amount of rotation is less than in normal knees and is more variable due to prosthesis design and ligament abilities[66]. Constrained post–cam mechanisms are more susceptible to post wear or fracture, which can ultimately cause instability, impingement, pain and locking[63]. Constrained designs can be affected by local geometry, high contact loads, small contact areas, and abnormal extensor mechanism tracking[26]. These factors can influence whether patients develop patellofemoral complications such as anterior knee pain, patellar subluxation, abnormal polyethylene damage, and loosening[26]. Surface geometry may in fact be a stronger factor than the actual post–cam design when determining kinematic improvement[67]. Patellar tendon angle abnormalities can cause abnormal muscle loads and joint contact forces, whereas patellofemoral joint abnormalities can increase the patellar tendon angle[67].

FUTURE DIRECTIONS OF TKA DESIGN TO REDUCE PATTELOFEMORAL COMPLICATIONS/ANTERIOR KNEE PAIN FOLLOWING TKA

Design features of the polyethylene insert as it pertains to post-operative complications following primary TKA is an area that has not been well studied. However it is as important to identify and furthermore include the design of the polyethylene insert in an attempt to minimize anterior knee pain following TKA. The anterior edge of the polyethylene (PE) insert is a potential source of patellar tendon pain and tendonitis as the tendon is forced to glide against the sharp PE edge. Thus designing the PE insert to include a smooth anterior edge might decrease patellar tendon irritation (Figure 4). Furthermore, in PCL-substituting designs, anterior impingement has been related to tibial damage[33]. It has been demonstrated that a tibial post polyethylene insert can also cause anterior impingement through knee hyperextension when the post has been worn out[37]. Impingement of the patellar button from the polyethylene post is another potential source of complication in PCL-substituting TKA systems. Inserts which incorporate a posterior angulation to the polyethylene post can improve overall TKA kinematics by minimizing patellar button impingement.

Figure 3 Femoral rollback and medial pivot.

Figure 4 Polyethylene component showing an inclination of 55° and anterior cut-out to avoid conflicts with extensor mechanism.

CONCLUSION

Anterior knee pain continues to be problematic following primary TKA procedures, oftentimes leading to prosthesis failure and revision surgery. While certain non-modifiable patient factors may lead to persistent post-operative pain, there are many modifiable elements including those related to the prosthesis and to surgical technique that also contribute. In particular, rotation and sizing of the tibial and femoral components, trochlear groove size and rotation, and patellar resurfacing have been associated with anterior knee pain post-TKA. These elements alternate knee biomechanics, either directly or through their effects on the Q-angle, which may result in excessive patello-femoral loads and abnormal patellar tracking. With specific contributors to post-surgical anterior knee pain being identified, further research should investigate improvements in both prostheses and surgical technique which would allow more accurate mimicking of native knee biomechanics, potentially leading to a decrease in anterior knee pain following primary TKA and a resultant decrease in revision procedures.

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MINIREVIEWS
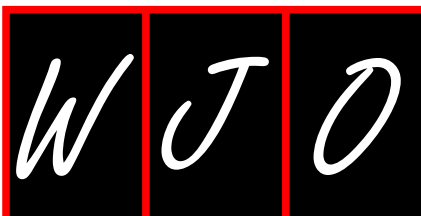
Minimally invasive knee arthroplasty: An overview

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Abstract

Minimally invasive surgery (MIS) for arthroplasty of the knee began with surgery for unicondylar knee arthroplasty (UKA). Partial knee replacements were designed in the 1970s and were amenable to a more limited exposure. In the 1990s Repicci popularized the MIS for UKA. Surgeons began to apply his concepts to total knee arthroplasty. Four MIS surgical techniques were developed: quadriceps sparing, mini-mid vastus, mini-subvastus, and mini-medial parapatellar. The quadriceps sparing technique is the most limited one and is also the most difficult. However, it is the least invasive and allows rapid recovery. The mini-midvastus is the most common technique because it affords slightly better exposure and can be extended. The mini-subvastus technique entirely avoids incising the quadriceps extensor mechanism but is time consuming and difficult in the obese and in the muscular male patient. The mini-parapatellar technique is most familiar to surgeons and represents a good starting point for surgeons who are learning the techniques. The surgeries are easier with smaller instruments but can be performed with standard ones. The techniques are accurate and do lead to a more rapid recovery, with less pain, less blood loss, and greater motion if they are appropriately performed.

Key words: Knee; Arthroplasty; Minimally invasive surgery; Replacement; Surgery

Core tip: Minimally invasive surgery for knee arthroplasty began in the 1990s and flourished in the year 2000 to 2005. Four primary techniques were developed along with some instrument changes and modifications in the postoperative treatment protocols. The surgery

is demanding and it is more difficult to develop the exposure. However, there is less pain, less blood loss, greater range of motion, with a faster, shorter recovery time.

INTRODUCTION

Minimally invasive surgery (MIS) for knee arthroplasty was initially introduced to the orthopaedic community in the early 1990s and was designed for unicondylar knee arthroplasty (UKA)[1,2]. The surgical approach was novel at that time and was met with a great deal of skepticism. Since the UKA prostheses only replaced one compartment of the knee joint, they were less bulky than the total knee prostheses and were potentially easier to implant. During that period of time, there was some skepticism about UKAs so the procedure and approach did not gain very much support. Just after 2000, orthopaedic surgeons began to look at the UKA results more critically and investigated using the approach for total knee arthroplasty (TKA)[3,4]. Several different surgical approaches were attempted that required varying levels of skill[5-8]. The MIS results included a faster recovery with less blood loss, greater range of knee motion, and less perioperative pain. However, there were multiple reports of complications and revisions[9,10]. The initial enthusiasm quieted and the approaches were all revisited with greater care and more attention to patient selection.

Many surgeons felt that the accelerated recovery and associated benefits of the MIS procedures were not entirely attributable to the surgical technique alone. They felt that improvements in the physical therapy, pain management, and anesthetic techniques were also significant contributors to the change in the result. While the surgical approaches were being refined, there many associated changes that were incorporated into the surgery that would be termed "MIS". The anesthetic techniques were modified to include spinal, epidural, peripheral nerve blocks, and intraarticular injections[11]. The pain medications were modified to avoid agents that inhibited a rapid recovery and had unacceptable associated side effects, such as nausea and vomiting[12-14]. This led to the introduction of a perioperative multimodal approach to pain management. The length of stay in the hospital was shortened in attempt to encourage a more rapid recovery with less complications[15].

The ultimate aim of all of these changes in the surgical experience was to improve patient satisfaction with the operation. This led to a more thorough investigation of the ultimate result with more consideration of the patient's view. New evaluation scores were designed leading to a more thorough evaluation of the final result from several different aspects[16-19].

Thus, the surgery, pain management, hospitalization, and rehabilitation were all modified with the introduction of the MIS procedures. The patient's perception of the result became much more important and the postoperative evaluation changed[20-22].

SURGICAL PROCEDURES

UKA and TKA were both developed in the early 1970s[23,24]. Exposure for the surgery was critical and the designers emphasized visualization. The early results of UKA were similar to the results of TKA but there was a good deal of controversy between the two designing camps. Marmor and Galante continued to develop the UKA and modify the prostheses to improve the results. Insall *et al*[25] reported high failure rates with UKA and discouraged many surgeons from pursuing the replacement. Murray introduced the mobile bearing design and supported it with good mid and long term results[26,27]. Despite this increased interest in UKA, TKA continued to be the most popular approach through the 1980s and 1990s.

In 1992 Repicci *et al*[1] implanted UKAs through a modified surgical approach that incorporated an abbreviated skin incision and arthrotomy. He encouraged the patients to ambulate immediately after the surgery and discharged most of the patients within 24 h of the operation. The incision was 10 cm in length and the median parapatellar arthrotomy extended from the superior pole of the patella just down to the tibial joint surface (Figure 1). The prosthesis was a fixed bearing design with cement fixation. He used smaller modified instruments from his dental experience that facilitated the operation. The results were exciting and raised the interest of many orthopaedic surgeons around the world. The early reports were quite encouraging but longer term follow up did show some prosthetic loosenings, perhaps related to the tibial inlay surgical technique[2].

Popularity of this approach for UKA continued and more reports came out in the literature supporting the technique[28]. The mobile bearing design was becoming more popular in Europe and a limited incision did lend itself to the technique. The overall number of UKAs in the United States during the 1990s was not very high so the technique did not get overwhelming support; however, the knee arthroplasty community was aware of the development and Repicci was invited to present his work to the Knee Society annual meeting in 2001. Total knee arthroplasty surgeons became more interested in the limited surgical approach and began to look into the possibility of implanting the total knee prosthesis.

There are four techniques that utilize a limited approach to total knee arthroplasty: Quadriceps sparing, mini-midvastus, mini-subvastus, and the mini-para-patellar.
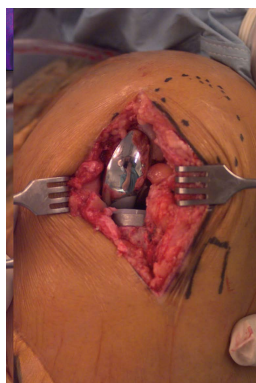
Figure 1 The incisions for minimally invasive surgery of the knee.
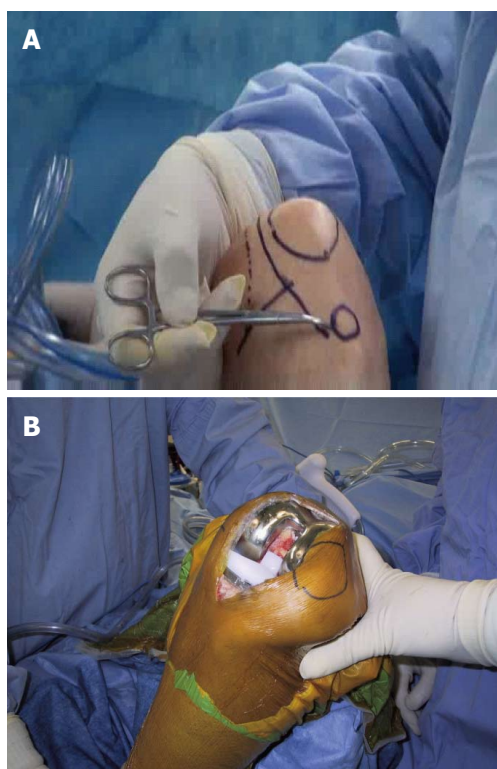
Figure 2 Anatomic location of the incision. A: The skin outline of the minimally invasive surgery incision and its relationship to the patella, the medial femoral condyle, and the tibial joint line; B: Total knee arthroplasty with the quadriceps sparing approach.

QUADRICEPS SPARING TECHNIQUE

In 2002, a technique was developed that implanted a total knee prosthesis through a limited median parapatellar incision that became known as the "quadriceps sparing approach"[3]. The skin incision was 10 cm in length and the arthrotomy extended from the superior pole of the patella to 2 cm below the tibial joint line on the medial side of the knee (Figure 2). The technique required modified instruments that were smaller and designed specifically for the approach[29]. The instruments were unique in design and somewhat unfamiliar to the orthopaedic community (Figure 3). The operation was demanding and required some cadaveric
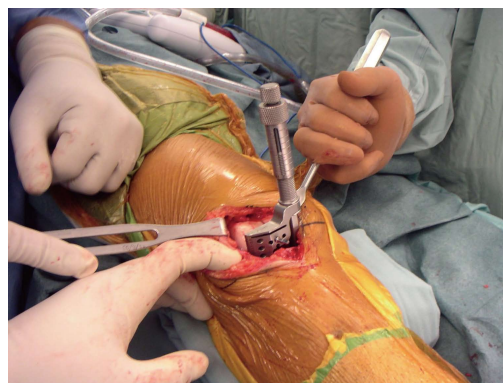
Figure 3 Specially designed instruments for minimally invasive surgery total knee arthroplasty. This instrument resects the anterior aspect of the femur in full extension.

training for most arthroplasty surgeons. The early results were encouraging and the designing surgeons reported a faster recovery, with less blood loss, greater range of motion but somewhat less accuracy for the alignment of the prostheses[5]. During the early period of development there were reports of failures and revisions that were mostly related to technical issues with the compromising surgical technique[9,10]. This was not an operation for all patients or for all surgeons and it became evident that the choice of the patient and the surgical ability of the operating surgeon were both critical to the result.

Some companies modified the prostheses to facilitate insertion by limiting the tibial stem length (Figure 4). Modular designs for both the tibia and the femur were considered but never came to implantation (Figure 5).

Surgeons learned to perfect the approach over the ensuing years and the results of the technique improved[29,30]. Modified instruments along with good patient selection and surgical technique have proven valuable[31].

MINI-MIDVASTUS TECHNIQUE

The midvastus approach to the knee was well established before the MIS surgeries were developed[32]. During the period of time when the quadriceps sparing technique became popular, surgeons looked for a modification that might be easier to apply[6,7]. The midvastus approach divides the vastus medialis in the line of its fibers at the junction of the distal one third and the proximal two thirds of the muscle belly (Figure 6). Limiting this division of the vastus medialis to 2 cm in length and carrying it distal along the medial side of the patella to the tibial joint line produced an approach that was familiar to surgeons and compatible with MIS surgery. This was also an extensile exposure that could be modified if the visualization became too limited. However, extension proximally into the vastus medialis muscle fibers may lead to potential denervation of the distal one third of the muscle and may disrupt the associated vasculature with hematoma formation.

Figure 4 Implants designed specifically for minimally invasive surgery total knee arthroplasty. A: A limited keel on a modified tibial tray for MIS; B: A dropdown stem used with a modular tibial tray.
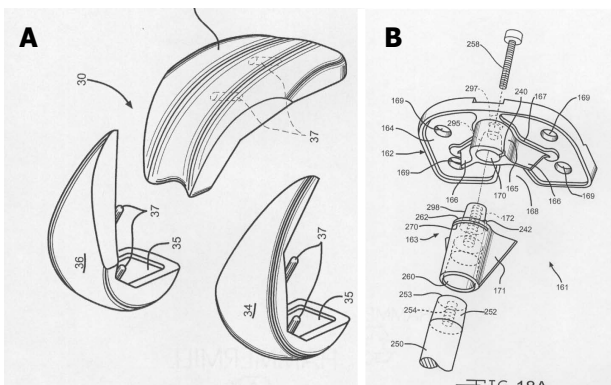
Figure 5 Modular components for minimally invasive surgery total knee arthroplasty. A: Modular femoral component; B: Modular tibial component.

Figure 6 Mini-midvastus arthrotomy. The dotted line shows the medial arthrotomy with the continuation of the incision into the vastus medialis muscle splitting the distal one third of the muscle from the proximal two thirds in the line of the fibers.

The mini-midvastus has become the most popular approach for MIS surgery. It does not require major instrument modification and does permit extension of the arthrotomy to accommodate the more difficult cases. The incision into the vastus muscle does not appear to weaken the quadriceps total muscle strength if the division is kept to 2 cm or less.

MINI-SUBVASTUS TECHNIQUE

The subvastus approach to the knee is another technique that was established in the 1990s, well before the MIS era[33]. The approach is based upon the principle that there is no incision into the quadriceps musculature. The entire quadriceps muscle is lifted across the anterior aspect of the femur and retracted laterally. The arthrotomy incision is made along the inferior border of the vastus medialis and taken distally along the medial side of the patella (Figure 7). The incision along the border of the muscle is critical to the exposure. If the incision is extended proximally beneath the muscle, the penetrating vessels may be divided and can lead to a hematoma, and in extreme cases this can lead to a compartment syndrome in the thigh[34,35]. Any addition bleeding in this area can lead to swelling that may inhibit the range of motion exercises after the operation with a possible contracture.

The original subvastus approach required an extensive exposure[33,36]. The approach was then modified by to limit the exposure and make it more MIS friendly[8]. The technique was difficult to accomplish and required proper patient selection. Larger, more muscular males presented difficult knees for the technique. Moving the entire quadriceps muscle laterally in these cases required significant retraction and manipulation of the knee. The operation did lead to a faster recovery but was much more demanding of the surgeon and did not maintain its popularity.

MINI-MEDIAL PARAPATELLAR TECHNIQUE

Many surgeons looked towards the MIS operations as desirable in themselves but saw the complications and difficulties and looked for a modification of the standard arthrotomy that might afford similar results with less difficulty. The mini-medial parapatellar arthrotomy used the standard median parapatellar approach and limited the incision to 4 cm into the quadriceps tendon[37]. The technique did allow for a less extensive exposure and the results were similar but not identical to the MIS reports. This technique remains useful and allows the surgeon to judge the exposure throughout the operation with minimal to no limitations. The approach can also be limited to even a greater extent with a 2 cm
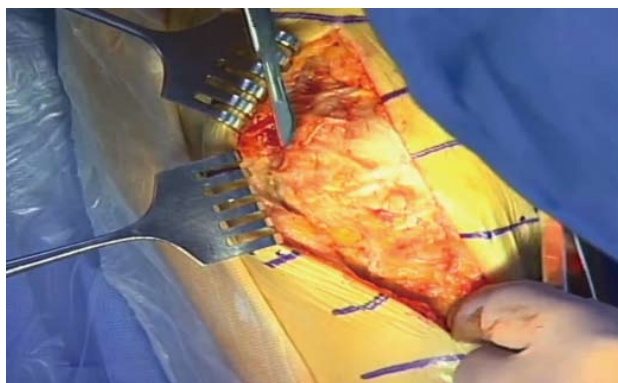
Figure 7 Subvastus arthrotomy. The subvastus incision along the inferior border of the vastus medialis muscle. The scalpel blade is along the inferior edge of the vastus medialis and will extend the arthrotomy from there distally along the medial side of the patella and the patellar tendon.

incision into the quadriceps tendon. This limitation has been compared to the quadriceps sparing technique and found to produce the same clinical result[30].

The mini-medial parapatellar arthrotomy represents a good compromise for the surgeon and the patient. It does allow a truly MIS technique with the 2 cm quadriceps incision but also gives the surgeon some leeway to modify the operation if the exposure starts to limit the operation.

INSTRUMENTATION

The MIS techniques all advocate a more limited exposure to avoid injuring the surrounding soft tissues. The original instruments for replacement were designed without any size limitation. Large instruments do not fit comfortably in a smaller incision and there were reports of malalignment[38]. If the instruments are radically changed, the technique is less familiar to the surgeon and this may also contribute to improper positioning and early failures. Most surgeons advocate modification of existing instruments that will fit in the limited exposure and allow for greater familiarity.

CLINICAL RESULTS OF MIS

The designing surgeons for each technique reported excellent results with short term follow-up. The quadriceps sparing technique was the most difficult surgery and the designers did note that some components were more than 3 degrees from the ideal alignment but this did not lead to clinical failures[5]. The patients did have greater range of motion, less pain, and a faster return to full activities. Other authors compared the technique to the standard one and found no clinical difference with more complications in the quadriceps sparing group[39]. The more recent publications from experienced, non-designing surgeons report less pain, greater range of motion, less blood loss, with a faster overall recovery time than the standard operative technique. They do not report greater

complications or greater incidence of malalignment[40].

The mini-midvastus technique results were equal to the standard from the beginning of the reports. Hass and Laskin were able to perfect the technique with minor instrument modifications and modified patient selection[6,7].

The mini-subvastus approach has had mixed reports in the literature. The developers were able to use the original, standard arthrotomy incision with adequate exposure[33]. However, with the introduction of the smaller incision the technique was more difficult and Boerger *et al*[41] found that the surgical time was greatly increased. Pagnano felt that the technique could be applied to all cases without compromise at all[42]. Most authors advocated the technique for less obese patients with a good range of motion for the involved knee.

The mini medial parapatellar technique is the simplest of the surgeries. The length of the incision into the quadriceps tendon is important and Tanavalee reported improved results that were similar to the quadriceps sparing technique if the quad incision was limited to only 2 cm[30].

PAIN MANAGEMENT TECHNIQUES AND REHABILITATION

The MIS techniques forced surgeons to look at the entire TKA approach for patients. Many criticizers felt that the rapid recovery was not just the operation itself but also the associated pain management and rehabilitation changes that occurred at the same time. Pain management included not only the operation but also preemptive medicating before the surgery and postoperative support[11-13]. Opioids came under scrutiny because of the associated nausea and vomiting. Combinations of drugs that included non-steroidal anti-inflammatories and even steroids were added to protocols.

The anesthetic programs changed with greater emphasis on spinal and epidural techniques to avoid the cardiovascular problems associated with general anesthesia[11]. Peripheral nerve blocks became popular and fit well with early hospital discharge. The blocks had to be modified to avoid injury to the injected nerves and also to try to decrease weakening the quadriceps muscle group after the surgery. This weakening led to a longer period of knee immobilizer usage to avoid inadvertent falls in the immediate postoperative period[43,44]. Femoral and sciatic nerve blocks were replaced with adductor nerve blocks in an attempt to avoid the muscle weakening[45].

Local injections in and around the knee joint became popular when it appeared that the technique could give excellent pain relief with no effect upon the quadriceps muscle group[46,47]. This led to many different preparations and follow up studies that compared local

Figure 8 Cutting blocks for patient specific instrumentation. A patient specific cutting block for tibial resection.

Figure 9 Smart instruments for alignment of total knee arthroplasty cuts. Orthalign™ (Orthalign, Aliso Viejo, California, United States) instrument for femoral and tibial resection.

Figure 10 Sensor devices for total knee arthroplasty. A: Orthosensor™ (Verasense, Orthosensor, Dania Beach, Florida, United States) inserts for the modular trial tibia; B: Pressure recording from the Orthosensor™ plate.

injection to nerve blocks showing the two techniques produced similar pain relief. The addition of steroid to the preparation remains controversial but under consideration[48].

The MIS procedures also included rapid rehabilitation protocols. Patients were mobilized on the day of surgery and were encouraged to return home quickly with earlier discharges from the hospitals[49]. In some cases the procedures were also moved to surgical centers where patients could go home on the same day as the surgery or within 23 h of the operation.

The question with all of these modifications was how much of the changes that occurred were related to the MIS surgical technique itself and how much to the associated changes that were made at the same time? The designing surgeons often took credit for the entire bundle of changes and others who were opposed to the new technology belittled the operative technique as difficult and unrelated to the rapid recovery.

ASSOCIATED TECHNOLOGIES

Once the MIS procedures were fully developed designers continued to make changes to improve the surgical techniques and make them more user friendly for the practicing surgeon. The major criticism for the MIS operations was the accuracy of the component positions. Visualization has always been the chief issue with the operations. Navigational support seemed to be a logical addition but less than 5% of surgeons adhered to this technology. Navigation remains an expensive technology that helps the less experienced surgeon but adds cost and time that is prohibitive. When appropriately applied, navigation does make the surgery more accurate but is still a peripheral item. Patient specific instrumentation (PSI) helps to eliminate multiple surgical steps and does have a place in MIS surgery but it is not reliable in all cases, especially with respect to the tibial resection, and adds another expense to the operation (Figure 8). There are new, so-called "smart instruments," that can be used on a disposable basis to improve implant accuracy. These instruments include dynamic gyros that locate anatomic landmarks in space and guide the cuts (Figure 9). Pressure sensors are also available on a disposable basis that enable the surgeon to evaluate the balance of the knee and improve soft tissue tension (Figure 10).

Finally, robotic appliances have also been improved. The haptic instruments are guided by the surgeon's hand but limit the excursion of the cutting device and the depth of the bone resection. Studies have indicated that these instruments can promote accuracy and decrease outliers especially in a limited surgical incision (Figure 11)[44].

CONCLUSION

MIS knee arthroplasty has changed the way we look at TKA. Initially, the smaller incisions did lead to compromises in the clinical results and to skepticism. While surgeons were learning to improve the exposures and perfect the techniques, rehabilitation programs were modified and the patient's perspective became much more important. Pain management became an integral part of the arthroplasty regimen and comprehensive programs were developed. The MIS techniques have
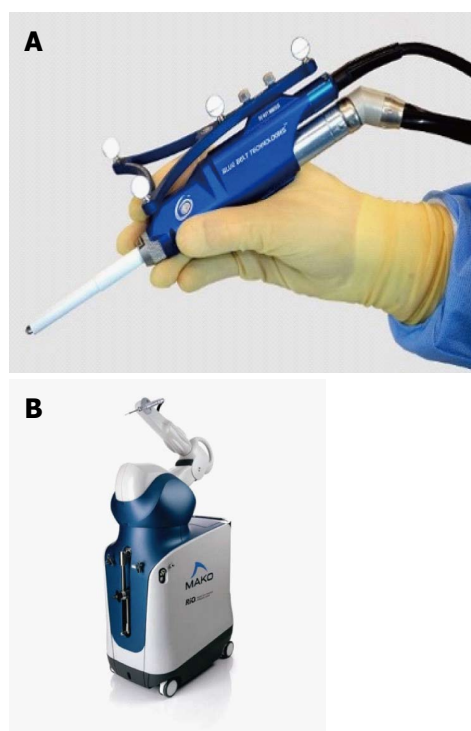
Figure 11 Haptic instrumentation for total knee arthroplasty. A: Navio™ (Blue Belt Technologies, Plymouth, MN, United States) robotic hand piece that is a haptic control. The surgeon moves the cutting instrument and the computer turns the device off if the resection area is exceeded or the depth is too great; B: MAKO™ (MAKO surgical corporation, Fort Lauderdale, Florida, United States) robotic arm. A haptic arm that is moved by the surgeon within the confines of the resection area and within the proper depth.

led to easier recoveries, with less pain, less blood loss, greater range of motion, and more satisfied patients.

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Review on squeaking hips

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Abstract

Squeaking is a well-recognized complication for hard-on-hard bearings. The nature of squeaking is not yet completely understood however it is considered a multifactorial phenomenon. Patient, implant, and surgical factors play a role in squeaking. It is believed that mechanisms damaging the fluid film lubrication in which these bearings function optimally have a critical role. Such mechanisms include edge loading, stripe wear, impingement, third body particles and ceramic fracture. The resonance of metallic parts can produce noise in the human audible range hence the implant metallurgic composition and design may play a role. Implant positioning can facilitate impingement and edge loading enhancing the occurrence of squeaking. The recent introduction of large heads (> 36 mm) 4th generation ceramic-on-ceramic bearing may accentuate the conditions facilitating noise formation; however the current literature is insufficient. Clinically, squeaking may manifest in extreme hip positions or during normal gait cycle however it is rarely associated with pain. Evaluations of patients with squeaking include clinical and radiographic assessments. Computer tomography is recommended as it can better reveal ceramic breakage and implant malposition. The treatments for most squeaking patients include reassurance and activity modification. However for some, noise can be a problem, requiring further surgical intervention. In the occurrence of ceramic fracture, implant failure, extreme components malposition, instability and impingement, surgery should be advised. This review will aim to discuss the current literature regarding squeaking.

Core tip: Ceramic-on-ceramic bearings can reduce osteolysis and wear, however they can make noise. Squeaking is multifactorial phenomenon and is associated with patient, implant and surgical factors. Ceramic-on-ceramic bearings function best under well lubricated conditions and hindrance to these conditions such as edge loading and stripe wear may produce vibrations, which resonate

through the implants metal component producing an audible noise. Mostly, squeaking is a benign phenomenon however it has a psychological effect on patients. Clinical and radiographic evaluations may reveal pathology that requires further surgery however for most, activity modification and reassurance is the treatment.

INTRODUCTION

Total hip arthroplasty (THA) is one of the most successful orthopedic procedures available today. It is estimated that more than 300000 procedures are performed annually in the United States[1] and it is projected that by year 2030 the need for primary and revision THA will increase by 174% and 137%, respectively[2]. The worldwide increase in THA demand together with the improvement in instrumentation, surgical techniques and biomaterials has allowed THA become a common surgical option. Data acquired from the Australian National Joint Registry estimated that 13% of the patients undergoing THA are younger than 55 years[3]. The revision rate in this age group was 11.3% at 12 years, which was the highest rate amongst all age groups. According to this registry, loosening and osteolysis are the leading causes for revision THA[3]. In order to improve implant wear, osteolysis and implant longevity the development of alternative bearings to conventional metal on polyethylene (MoP) were encouraged. These include the improvement in polyethylene processing and development of hard-on hard bearings such as metal-on-metal (MoM) and ceramic-on-ceramic (CoC). The clinical utilization of these hard-on hard bearings has led to the formations of new complications such as metallosis, ceramic fracture and squeaking. However, CoC articulations have excellent tribological properties, biocompatibility, and promise of increased longevity[4]. The progressive improvement in the manufacturing and fabrication processes of ceramics has dramatically decreased the wear and the fracture rate however squeaking is still an ongoing concern[5].

Squeaking is an audible phenomenon almost exclusive to hard-on-hard bearings. Other audible sounds such as clicking, snapping, cracking and grinding are also described in the literature and sometime miss interpreted as squeaking[6-10]. The squeaking rate in MoM and CoC articulation has been reported between 2.9% to 16%[11-14] and 0.3% to 24.6%[9,15], respectively. There are less reports of MoM squeaking relative to CoC. The large variation in squeaking reported in the literature is influenced by the investigators query. Meta-analysis estimated that the rate of self-reported

squeaking was 1.2% while studies evaluating squeaking with specific questionnaire the rate was 4.2%[16]. The presence of other noises such as pops, clicks, grinding was reported at 7.5%[16]. Squeaking can significantly affect patients' quality of life, and may lead to revision surgery[17-19]. Owen *et al*[16] calculated from 43 studies that the overall revision rate due to squeaking was 0.2% in CoC bearings. According to the United Kingdom National Joint Registry there is a decline in the use of CoC bearings in THA. It is possible that squeaking may have led to this trend[20]. The squeaking phenomenon is not completely understood and thought to be multifactorial. The association between squeaking and patients' characteristics, surgical factors, implant positioning and implant types have been studied. However, there is not always uniformity in the results among different studies. The purpose of this review is to provide a summary of the current literature with respect to the squeaking phenomenon.

Mechanism of squeaking

Squeaking defined as a high pitched, audible sound that occurs during movement of the hip joint. It is produced by a forced vibration generated by a driving force resulting in a dynamic response[18]. The driving force is a result of high friction generated in hard-on-hard bearings from a loss of fluid film lubrication (stick slip)[21-24] which can be facilitated in certain conditions such as; edge loading and stripe wear[24-26], rim impingement[18,27], improper liner sitting[18,28], ceramic fracture and third body debris[29]. The dynamic response is the amplification of this vibration. If the amplified impulse occurs at a frequency of an audible range a squeak can be heard.

Vibrations that initiate squeaking are believed to arise from a stick-slip friction. CoC bearings operate best under well lubricated conditions[30]. Ceramics extreme hardness allows the surface to be highly polished and scratch resistant while their hydrophilic character accounts for the formation of a thin fluid film at the articular interface[4]. Loss of the fluid film lubrication results in direct contact between the articulating surfaces reducing sliding and increasing friction[18,25,31]. During hip movement a rotational force overcomes the static frictional joint force resulting in acceleration and deceleration of one articular surface with respect to the other. This produces vibrations within the implant material. Different materials and implant designs carry inherent ability to resonate these vibrations, which can lead to formation of squeak.

Edge loading and stripe wear

During the manufacturing process of grinding and polishing a ceramic acetabular liner a sharp edge is generated inside the rim[25]. When the hip contact force vector moves, the contact patch is over this hard edge (edge-loading). The delicate balance in the articulation fluid film lubrication is disrupted and there is an increase in the frictional forces between the two moving surfaces which can lead to a squeak.
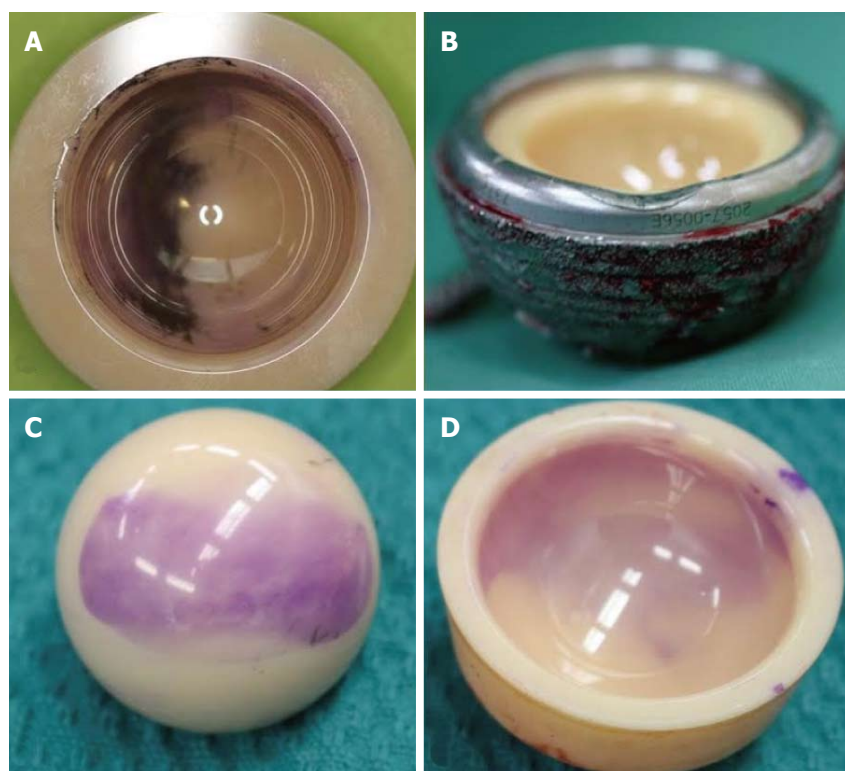
Figure 1 Rim chipping, stripe wear and metallosis. Stripe wear is identified by a purple marking on the ceramic head (A) and liner (B); impingement is identified by a notch created on the acetabular shell (C and D).

Furthermore, both surfaces are damaged secondary to increases in contact stress[32]. This leads to the formation of stripe wear along the femoral head and acetabular cup (Figure 1). Laboratory experiments have demonstrated that edge loading increases friction and leads to squeaking in ceramic bearings[24]. Location of the wear patch may indicate whether the edge loading occurs during deep hip flexion (posterior edge loading) or during walking and hip extension (anterior superior edge lodging)[25]. Another theory describes a micro-separation of the femoral head during swing phase as a possible etiology for stripe wear formation[33]. When this separation occurs, the contact area of the femoral head on the acetabulum liner becomes small leading to the formation of stripe wear. This theory was further demonstrated by 3D modeling and video fluoroscopy[34]. Some patients are clinically pre disposed to micro-separation, such as those with short leg or joint laxity have been shown association to squeaking.

Retrieval analysis of CoC bearings from multiple studies demonstrated the presence of stripe wear[35,36]. A multicenter retrieval study analyzed 12 CoC components from squeaking hips and compared the pattern and wear rate to 33 similar CoC components retrieved from silent hips[35]. All components from the squeaking hips and majority of the components from the silent hips showed edge loading and stripe wear. The retrievals from the squeaking hips had an overall 45 times greater wear rate compared to the retrievals from the control group. The authors suggested that edge loading may represent a normal process in CoC bearing[25,35,37]. Since the majority of the CoC THAs do not squeak, the combination of edge loading and excessive wear rate

may produce squeaking[35]. Clinical and retrieval studies report on the appearance of squeaking after more than six months from the index THA surgery[17,19,25,35-37]. A hip stimulator study did not produce squeaking when the bearing surfaces were in their pristine condition but did at the presence of stripe wear[24]. These observations imply a run out phase in clinical setting before the bearing surface is affected by edge loading and possibly representing the time necessary to produce stripe wear.

Rim impingement and third body particles

Rim impingement is suggested as a possible mechanism in producing squeaking either directly or indirectly. Impingement between the femoral component neck and the acetabular component rim can lever the head out of the acetabular socket leading to squeaking secondary to edge loading and stripe wear. Moreover, direct metal impingement may lead to metal-metal squeaking, metallosis, chipping and other third body particles[18,31,35]. The acetabular component design is a suggested contributing factor to squeaking. Some designs have an elevated acetabular rim to protect the ceramic liner from either chipping or fracturing, however impingement can occur at the rim (Figure 1)[31]. A non-elevated acetabular rim design may allow impingement to occur directly between the neck and the ceramic liner leading to metallosis, and chip fractures at the ceramic rim (Figure 1)[31]. With the introduction of the 3rd and 4th generation of ceramics the risk of ceramic chipping is reduced. Toni *et al*[38] showed that aspirates from squeaking CoC THAs have had high levels of ceramic particles suggestive of third-body wear. Abdel *et al*[29] observed squeaking associated with ceramic fractures.

Dynamic response

In the previous section we discussed possible mechanisms producing forced vibrations in CoC bearings. These vibrations represent excessive energy that the system needs to dissipate; this can be done *via* heat generation or motion[18]. The forced vibrations travel along the system components which can act as an amplifier. Vibrations amplified to a level that can be detected by the human ear (between 20 Hz to 20000 Hz), is recorded as a squeak. An *in vivo* acoustic analysis of 31 patients with squeaking CoC hips demonstrated that squeaking replicated a harmonic wavelength series between the frequency range of 400 Hz and 7500 Hz. Therefore the authors concluded that squeaking sounds are produced by resonance[18]. A modal analysis was conducted to better understand how the parts resonate[18]. That study showed that a ceramic liner whether coupled or isolated with a titanium acetabular shell did not show any relevant modes of resonance[18]. A titanium stem attached to ceramic head showed resonance in multiple modes and planes. An isolated titanium acetabular shell will resonate in an elliptical configuration like a bell. Thus, the metal components are the system amplifiers responsible for squeak propagation. Moreover, if the ceramic acetabular liner is perfectly seated in the metal shell it can potentially prevent the metal cup from resonating hence reducing squeaking. Finite element analysis demonstrated stiffness mismatch between the shell and the liner may cause the liner to tilt out of the shell leading to shell oscillation and squeak formation[18]. An *in vitro* acoustic study determined that neither isolated ceramic components nor perfectly assembled acetabular cup and liner resonate within human audible range. However when the metal acetabular shell or titanium stems were evaluated their resonance frequency falls in whole or in part within the human audible range (from 4300 Hz to 9800 Hz and 1500 Hz-20 kHz, respectively). Additionally it was demonstrated that thinner and larger shells produced a lower frequency[18]. The importance of this data is in the core of understanding that the metal components are a fundamental factor in amplifying the vibration to generate an audible sound heard as a squeak. The implant metallic composition and geometry may influence the resonance propagation affecting the rate of squeaking. From a clinical prospective, it is important to verify and properly secure the acetabular liner in the shell, this can potentially reduce the rate of squeaking as well as the chance to develop backside wear[18,31].

Causes of squeaking

Multiple studies have illuminated that various factors play a role in the formation of squeaking[18,39]. Due to the multifactorial nature of squeaking these factors are integrated and probably cannot be separated, however they can be classified in relation to patient characteristics, surgical factors and implant factors.

Patient's factors and squeaking: Several patients factors such as; age, sex, height and weight may contribute to squeaking as determined by the reporting found in the literature. A study conducted by Sexton *et al*[39]. reported a significantly higher rate of squeaking in taller, heavier and younger patients, however obesity was not shown to be associated with squeaking. Contrary to this, a recent meta-analysis showed that the only significant patient factor was the increase in body mass index[40]. Choi *et al*[41] found that gender was a contributing factor were his study reported males to have a higher occurrence of squeaking. Mai *et al*[10] found that patient height was a contributing factor to the squeaking mechanism. They found that taller patients squeak more. In contrast, Keurentjes *et al*[19] and Restrepo *et al*[36] did not find any correlation between squeaking and these mentioned patients factors. Thus, far patients' factors have mixed results with no specific known indicator relating to the occurrence of squeaking.

In addition to patients demographic factors activity types such as walking, bending, and rising from low sitting position was associated with squeaking[17,31]. This suggests that squeaking is either generated during the normal gait cycle or in extreme flexion. Although extreme positions may be associated with squeaking it is not associated with either hip function or pain as no correlation between squeaking and pain could be demonstrated[10,41,42]. It has been observed that patients with hyperlaxity have a higher rate of squeaking[31,43]. This excessive range of motion can lead to impingement, micro-separation and edge loading, hence resulting in squeaking.

Surgical factors and squeaking: Prosthetic component orientation is considered to play a significant role in noise generation. Improper component position may lead to impingement, edge loading and increased wear. It is believed that the positioning of the acetabular cup can be associated with squeaking. A previous study has shown that an acetabular cup placed within a 25 ± 10 degree of anteversion and 45 ± 10 degree of inclination, will significantly reduce the chance of squeaking[42]. This observation was supported by Sariali *et al*[44]. In contrast, others did not find a similar correlation regarding cup positioning[10,19,36,40,41]. Previous findings showed that anterior edge loading is associated with increased cup anteversion and inclination while posterior edge loading associated with insufficient anteversion and inclination[25,42]. In extreme cup positions squeaking can be generated from direct impingement of the femoral component neck and the cup (titanium squeak) or from edge loading of the head and the ceramic liner (ceramic squeak)[42]. A retrieval analysis of squeaking hips can support this mechanism. A squeaking hip demonstrated marks on the rim of the cup representing impingement whilst the bearing demonstrated stripe wear representing edge loading (Figure 1)[35].

Implant factors and squeaking: Implant design and specific implant coupling may to be linked to squeaking. Acetabular component designed with a raised edge can potentially prevent impingement between the acetabular ceramic liner and the femoral component neck, and consequently prevent ceramic fracture. However, it may increase the risk for MoM impingement hence subsequently squeak[40]. Parvizi *et al*[45] noticed squeaking primarily in patients receiving acetabular system designed with elevated titanium rim (Trident, Stryker Orthopaedics, Mahwah, NJ). On the contrary, Stanat *et al*[40] in a meta-analysis, could not demonstrate a significant relationship between squeaking and elevated cup rim.

Previously, femoral stem design and metallurgy were evaluated as a cause of squeaking. Several studies reported a high rate of squeaking utilizing a thin profile stem and thin neck[10,17,19]. Restrepo *et al*[46] reported that the squeaking rate in patients receiving Omnifit stem (Stryker Orthopeadics) was seven times less than in patients who received an accolade stem (Stryker Orthopeadics). The Omnifit stem made of Titanium - Aluminum - Vanadium alloy with hydroxyapatite coating and has a c-taper neck geometry. The Accolade stem is made of Titanium - Molybdenum - Zirconium - Iron alloy with hydroxyapatite coating and has a V-40-taper neck geometry. The different design factors which can potentially be related to the higher incidence of squeaking produced by the Accolade stem are the stem geometry, taper dimension, and the material composition. The accolade stem alloy composite and geometry creates a more flexible stem with a thinner front to back diameter which has a clinical potential to reduce thigh pain[46], however due to its flexibility it may resonate more hence producing a squeak[18,46]. The V-40 neck has a smaller diameter and should lead to less impingement. However the smaller diameter leads to a lower bending stiffness and lower resonant frequency and is more capable of amplifying vibrations generated by the CoC articulation producing audible squeak[46]. Fan *et al*[47] conducted an *in vitro* study evaluating squeak production in 3 different types of stems in compromised lubrication conditions. Their study showed that stiffer (cobalt chrome *vs* titanium) and smaller stems demonstrated higher critical friction factors which correlates clinically with squeaking. The frequencies captured *in vitro* by Fan *et al*[47] are in agreement with the frequencies measured previously *in vivo* (between 0.4 and 0.75 kHz)[18].

Squeaking in large diameter CoC: Large diameter femoral heads (> 36 mm) have the potential to reduce instability following THA[48]. They provide greater range of motion[49], decrease the component impingement and increase the jump distance that the head must travel before dislocation occurs[50]. Delta Motion (DePuy, Warsaw, Indiana) is a preassembled, monoblock, large diameter, fourth generation CoC (Biolox - Ceramtec) Acetabular cup. The acetabular cup consists of a titanium alloy with thin ceramic liner which can accommodate a large (> 36 mm) ceramic head, optimizing the head-neck ratio.

Recently, Tai *et al*[5] reported on the short term results of large diameter CoC in patients acquiring Delta Motion bearings with a proximally coated titanium stem (Secure Fit, Stryker orthopeadics, Mahwah, New Jersy). In their series, 7.3% (15 of 206 hips) of the hips were recorded as squeaking. The mean postoperative time to onset of squeaking was 1.4 years (range 0.4-3 years). Squeaking was documented only at deep flexion. Although the median femoral component size was larger in the squeaking hips compared to non-squeaking hips (44 mm *vs* 40 mm, respectively), no statistically significant difference in the incidence of squeaking in various head size could be demonstrated. Radiographic analysis did not show statistical significance with respect to acetabular cup inclination, anteversion and correlation to Lewinnek's acetabular safe zone position. Patient demographic characteristics such as height, weight, BMI or range of motion were also not significant between patients with or without squeaking. McDonnell *et al*[43] reported on 208 THA acquiring Delta Motion cups and heads with four different cementless stem designs. They found 31% of the hips producing noise with a squeaking rate of 20.7%. Squeaking almost exclusively occurs during deep hip flexion. Similarly to Tai *et al*[5] they found no relation between squeaking to patient height and weight. However, they found amongst the squeaking hips a statistically significant lower inclination and anteversion angles, increased ligament laxity, and higher rate of squeaking with smaller heads. A possible explanation of the difference in the squeaking rate in-between these studies may be related to the stem design. The predominant stem (151 of 208) used in the series by McDonnell *et al*[43] was Tri-Lock (DePuy) which is a short and narrow stem composed of Titanium - Aluminum- Vanadium. In spite of the high squeaking rate reported the short term clinical results of the Deltamotion/TriLock combination show a low revision rate in the Australian registry data 0.3% at 3 years. Bishop *et al*[30] measured the friction moments of large ceramic (DeltaMotion) and metal bearings in hip simulator with variable cup angles and in both wet/dry conditions. They showed that friction moments were smaller for CoC bearings in lubricated conditions (optimal conditions) but increased over fivefold for 48 mm diameter ceramic bearings in dry conditions (extreme conditions). The combination of a 48 mm ceramic head and an increase in cup inclination angle was associated with increased friction. They concluded that extreme conditions dramatically increase the friction moments in large diameter ceramic bearings, which can amplify the clinical problem of squeaking[30]. Another theory suggested that larger heads have a greater mass which may decrease the frequency of the resonating waves, bringing them into the audible range for humans[5]. Yet other study suggested that since the Delta Motion cup is relatively thin (5 mm) with only 2 mm titanium shell

it is more flexible and can better resonate or amplify vibrations which can produce an audible squeak[51]. In conclusion, a large CoC articulation is a relatively new design, with limited reports in the literature with respect to squeaking. It appears that the rate of squeaking is relatively high however most of the reported series have a benign type of squeaking[5,43]. The biomechanical mechanism which results in larger heads having a higher incidence of squeaking is primarily due to the increase in the total work done at the articular interface, the lowering of the natural frequency of the oscillations, and the increase in the amplitude of oscillations. The work at the bearing surface correlates to the applied normal force, frictional force, and moment arm. Therefore for a given frictional co-efficient and angular rotation the work at the bearing will increase. Therefore, in order to try and reduce the rate of squeaking we can recommend on optimal implant position and implant selection. Currently while implanting DeltaMotion ceramic bearings we use a thick long titanium stem with relatively wide neck (*e.g.*, Secure - Fit, Stryker) which potentially can reduce the vibration propagation and squeaking. Mid and long term outcome studies will be necessary to further understand the possible causes for squeaking in of patients utilizing large CoC bearings.

Clinical assessment and management of patients with squeaking: Patients undergoing hip replacement should be aware of the advantages and the disadvantages of the different bearings for THA. Therefore, the management of patients with squeaking starts with informed consent. We tend to recommend CoC bearings for young active patients as such bearings have shown to have superior wear rate both in laboratory[52-54] and clinical studies[6,55,56]. As squeaking is one of a possible complication utilizing such bearings, patients should understand and agree to the use of ceramic bearings. Owen *et al*[9] reported a squeaking rate of 24.6% in 69 patients undergoing THA with CoC bearing. Only 7.5% of the patients recalled being warned preoperatively of squeak as a possible complication. More than 50% of the squeaking patients were concerned, anxious and embarrassed with their squeak. Therefore, their study further highlights the importance of warning patients from squeaking as a possible surgical complication. This can ultimately better address patient psychological concerns, match patient's postoperative expectation and can prevent litigation against surgeons.

The assessment of patients presenting with a squeaking hip should include clinical and radiographic evaluation. Clinical evaluation should assess whether the squeak is benign or problematic and if it is constant or transitory. Benign squeaking is most likely a result of posterior edge loading and occurs with activities involve deep hip flexion such as squatting or rising from a low chair[25]. This type of squeaking usually related to certain activity or hip movement and can be avoided with activity modification. Problematic squeaking

occurs during normal gait cycle and is relatively rare. It is produced with each step, may be associated with pain, jeopardize hip function and generally created a significant concern to the patient. It is believed that this type of squeak involves anterior edge loading usually as a consequence of components malposition[25]. This type of squeaking is reproducible and usually intolerable by the patients requiring further treatment and surgery. Others types of squeaking such as transitory or single occurrence can be found however their significance is not well understood.

Evaluation of patients with squeaking involves a thorough history and examination. Evaluation should include assessment of patients demographics such as height, weight, age, sex[18,31,39,41] and ligament laxity[43] which may be associated with squeaking. Range of motion assessment may differentiate between benign and problematic squeak and may give further input to the nature of the squeak. For example, squeaking may be associated with component impingement[31] or ceramic component fracture which may be painful and can limit range of motion[29]. After clinical assessment plain radiograph should be performed to evaluate component alignment, implant failure and bone or ceramic fracture. The presence of ceramic fracture should be further assessed with CT it does not always seen in plain x-ray. Moreover, CT scan further assesses component anteversion and inclination. If no abnormal radiographic pathology is observed, the squeaking is activity related, and the patient is pain free reassurance is appropriate and the patient should consult to modify his activities. If the squeaking is problematic then a revision surgery may be performed, however prior to surgery all the possible reasons producing the squeak should be attempted to be understood.

Squeaking and the association with implant failure are not clearly understood. Traina *et al*[57] reported that an audible noise had an association with ceramic fracture. Eighty point seven percent (21 hips) which produced a noise resulted in a fracture compared to the non-audible group which had only 6.1% (3 hips) ceramic fractures. A recent case report has also reported on a ceramic femoral head fracture following squeaking[58]. Due to the multifaceted nature of squeaking it is not clearly understood if squeaking itself is a sole reason to implement ceramic fractures.

While the incidence of revision due to squeaking in CoC bearings has been reported between 0 to 4.7%[16] a recent a meta-analysis estimated the revision rate to be 0.2%[9]. During revision surgery component can be revised to CoC or CoP, while optimization of implant position, soft tissue balance or correcting issues such as bone impingement. Jack *et al*[59] reported on the clinical outcome of 165 revision total hip replacement. During revision surgery a polyethylene liner was replaced with ceramic liner while the femoral head revised to ceramic head with titanium sleeve. At 8.3 years of follow up the implant survival rate was 96.6% and

none of the patient was diagnosed with squeaking.

Squeaking in metal on metal bearing: Being a hard-on-hard bearing MoM articulation, it carries the inherent is ability to produce noise and squeak. Squeaking in MoM bearing has been reported with incidences ranging from 1.5% to 16%[11-13,60]. Limited reports have been found in the literature therefore it is difficult to conclude which risk factors are associated with squeaking in MoM bearings. Bernasek *et al*[60] reported 1.5% squeaking rate in 539 patients undergoing MoM THA. The average time from surgery to onset of squeaking was 23 mo (range 6-84 mo). The authors also observed increased frequency of squeaking among females and in patients having a cup inclination greater than 45 degree. Imbuldeniya *et al*[14] reported squeaking rate of 2.89% in 380 patients undergoing MoM hip resurfacing. Cases were matched for age, gender, BMI and implant to three controls. The mean time for squeaking to appear was 11.3 mo (range 3-22 mo). No correlation was demonstrated to patient demographic characteristics, radiographic cup position and serum chromium or cobalt levels. They found males with head size smaller than 50 mm was associated with squeaking. The theoretical concept of not having a complete thin fluid formation at the bearing interface due to the smaller diameter head which has a less favorable environment to generate a fluid film[61]. The lack of lubrication correlates with a higher frictional coefficient at the surface which can lead to increase wear which can potentially result in squeaking[61]. In the study by Imbuldeniya *et al*[14] 3 of the 11 patients with squeaking had undergone revision surgery. Interestingly, among the patients who did not undergone revision the squeaking spontaneously resolved at a mean of 19.3 mo (range 4-78 mo). This might be explained by a self polishing mechanism which is generally associated as the "running in" period for this bearing[14]. Thus, the authors suggested that squeaking in MoM resurfacing should not be the sole indication for revision surgery and closer patients follow up is advocated[14].

Other noises: While squeaking is concerning as it may be associate with wear and fracture, other noises are more commonly produced following THA[8,10,62]. Schroder *et al*[8] reported an overall noise rate of 11% in patients undergoing CoC THA. The most common type of noise was clicking or snapping. Squeaking was reported only in 1.9% of the patients. A similar trend was observed following CoC THA by Mai *et al*[10] and Jarrett *et al*[17]. Despite that THA related noise is predominantly reported in hard-on-hard bearings, some describe noise generation in hard-on-soft bearings[62]. Wyatt *et al*[62] found that 37.7% of the patients undergoing THA with CoC bearing report noise, while only 12.7% of the patients undergoing THA with Ceramic-on-Polyethylene will experience noise. Jarrett *et al*[17] compared a matched cohort of patients who had CoC THAs to patient receiving MoP THAs showed

noise incidence of 21% and 4% respectively. None of the patients with CoP squeak. It was suggested that the higher incidences of noise, and more specifically click, pop or snap observed in CoC bearing are due to hard on hard bearing loading[17]. Glaser *et al*[63] conducted an *in-vivo* acoustic analysis in combination with fluoroscopic analysis in patients with various THA bearing types. They found distinctive sounds such as popping, snapping, knocking, crunching, granting, cracking and squeaking. The sounds generated were assessed in correlation with the gait cycle and with the bearing surface. They suggested that during the gait cycle there is a separation of the femoral head from the acetabular liner, whilst at heel strike the femoral head returns into position knocking against the acetabular component, which can produce a knocking or popping sound[63]. Other observed sounds are possibly related to soft tissue impingement such as iliotibial band snap, however the etiologies and the consequences of these sounds are poorly understood.

CONCLUSION

Squeaking is a multifactorial, unique phenomenon to hard on hard bearings. Although there is no uniformity in the literature with respect to the etiology of squeaking we believe that there are several factors contributing to its formation. These include patient, surgical and implant factors. Careful patient assessment; particularly the height, weight and hyperlaxity, are important. Meticulous surgical technique which places the components in the right tension and location can potentially reduce the loss of lubrication and pathological edge loading as well as component impingement. Stem design and alloy composite have shown to associate with increased resonance and squeaking. Stem selection is of particular importance when a large ceramic head (> 36 mm) is used as these shown to have relatively high rate of squeaking. While assessing patients with squeaking a differentiation should be made between benign and problematic squeaking. A transitory squeak or squeak that can be reproduced in extreme hip flexion without any radiographic signs of pathology can be managed with patient education and reassurance. Problematic squeaking which occurs during normal gait cycle usually requires further surgical intervention. An important part of patient evaluation is the understanding of the psychological effects of the noise on the life of the patient as this may change the treatment plan significantly. In the recent years due to the clinical failure of the large head MoM bearings in THA, the high reported rate of squeaking in CoC bearings, concerns regarding ceramic fracture and the introduction of highly crossed linked polyethylene, there is a shift from the use of hard-on- hard articulations toward hard on soft bearings. Yet the future is unknown and long term studies will clarify the longevity of such bearings and their ability to reduce the rate of osteolysis and wear in a similar fashion to CoC bearings.

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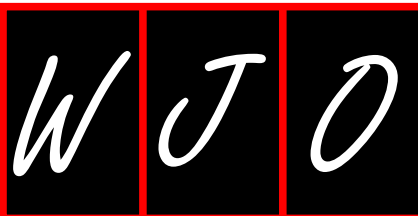
Basic Study

Novel computer-assisted method for revision arthroplasty of the knee

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Abstract

AIM: To introduce the navigation system of software and instruments designed specifically for revision total knee arthroplasty (TKA).

METHODS: We present an imageless navigation system for revision TKA, with optical point and tracker identification to assess kinematic and anatomical landmarks. The system automatically positions the cutting guides with a motorized cutting unit. The cutting unit is placed on the distal femur with a femoral clamp and acts as a rigid body and the base for all femoral cuts. The surgical technique for using the navigation system for revision TKA is based on the technique used in primary TKA. However, there are some important differences. The most notable are: (1) differences in estimation of the position of the primary implant relative to the bone and the mechanical axes; (2) the specific possibilities the revision navigation software offers in terms of optimal joint level positioning; and (3) the suggested "best fit" position, in which the clock position, stem position and offset, femoral component size, and mediolateral position of the femoral component are taken into account to find the optimal femoral component position. We assessed the surgical technique, and accompanying software procedural steps, of the system,

identifying any advantages or disadvantages that they present.

RESULTS: The system aims to visualize critical steps of the procedure and is intended as a tool to support the surgeon in surgical decision-making. Combining a computer-assisted cutting device with navigation makes it possible to carry out precise cuts without pinning. Furthermore, the femoral clamp provides a stable fixation mechanism for the motorized cutting unit. A stable clamp is paramount in the presence of periarticular bony defects. The system allows the position of the primary implant relative to the bone and mechanical axes to be estimated, at which point any malalignments can be corrected. It also offers an optimal joint level position for implantation, and suggests a "best fit" position, in which the clock position, stem position and offset, femoral component size, and mediolateral position of the femoral component are considered. The surgeon can therefore make decisions intraoperatively to maximise alignment and, hence, outcomes. Based on the intraoperative findings of joint stability, the surgeon can modify the preoperative plan and switch from a constrained condylar system to a hinged version, or vice versa.

CONCLUSION: The system is flexible and easy to learn and allows improvements in workflow during TKA.

Key words: Knee; Navigation system; Revision total knee arthroplasty; Computer-assisted surgery; Surgical technique

Core tip: The obscuring of bony landmarks by the previous implant, scar formation, the loss of bone stock and ligamentous insufficiency, make revision total knee arthroplasty very demanding. Current navigation systems do not typically allow reconstruction of the anatomic joint line, which is an important factor in implant survival, or compensation for the absence of classical landmarks. We present an imageless navigation system for revision total knee arthroplasty. The system automatically positions the cutting guides with a motorized cutting unit. We assessed the surgical technique, and accompanying software procedural steps, of the system, identifying any advantages or disadvantages that they present.

INTRODUCTION

Primary total knee arthroplasty (TKA) is generally a successful procedure[1], but the lifespan of the prosthesis is finite[2]. Patients may require revision TKA due to mechanical wear, aseptic loosening, infection, instability, or malalignment, among other reasons[2,3]. Implant positioning is closely linked to outcome in primary and revision TKA, and the criteria for an acceptable result include restoration of physiological joint line position and correct implant component position in the sagittal, coronal and transverse planes[4]. Patients have been shown to have better functional outcomes when coronal alignment is within 3° of neutral alignment[5-9]. Proper rotational alignment is particularly important for successful flexion gap stability, and affects patellofemoral mechanics during knee flexion[10-13]. Rotational malalignment has been associated with postoperative pain in primary TKA[14,15].

Successful revision TKA relies upon achieving the same results as a primary TKA[16,17]. Nevertheless, revision TKA is an even more demanding procedure than primary TKA due to previous implants hiding commonly used anatomical landmarks, scar formation, the loss of bone stock, and the frequent presence of osteolytic lesions, severe osteoporosis, lack of anatomical bony landmarks and ligamentous insufficiency that are often seen after the removal of the failed prosthesis[4,18-20]. A further complicating factor is that the patient's bone may provide insufficient stability for the resection guides, due to the underlying osteoporosis and the presence of bone defects. Ligamentous tissue may also be distended, destroyed or retracted as a result of bone degradation, surgical over-exposure, or fibrous scars from previous procedures[4].

In revision TKA, implants with an intramedullary stem are typically used. The angle between the surface of the femoral prosthesis and the femoral stem, which is given by the manufacturer, limits the possibility to align the femoral implant in the coronal plane. This can be a further restricting factor during surgery to achieve correct alignment.

It is therefore unsurprising that revision TKA is less successful at producing high quality outcomes than primary TKA[21]. Currently, 10-year survival following revision TKA is estimated at 74%[22], substantially less than the expected survival rate after primary TKA[23].

Stability in revision TKA is achieved through the balance of collateral ligaments, the peripheral capsule, tendons, and other elements[4], and cannot rely simply on the stabilisation mechanism of the implant[24]. Accurate soft tissue balancing, proper three-dimensional restoration of limb alignment and joint line height, correct alignment of the patella, and a functional extensor mechanism are all important factors to achieve a successful functional outcome and long-term implant survival[25-29].

An anatomic joint line must be restored at the time of revision surgery[4,27]. Due to the frequent absence of the classical landmarks, this objective may be difficult to achieve. It cannot be assumed that an
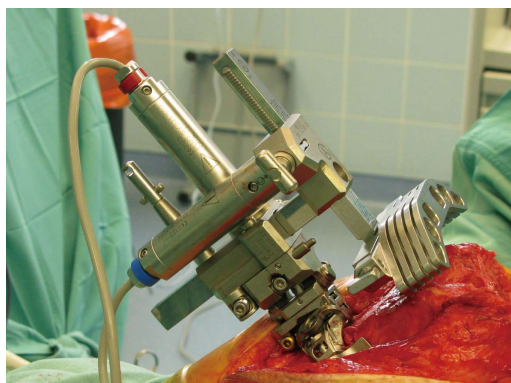
Figure 1 Revision total knee arthroplasty performed using the PiGalileo Revision Navigation instruments.

Figure 2 Centre of rotation using the PiGalileo Revision Navigation software. Kinematic analysis of the centre of rotation of the hip using 6 leg positions in different conditions of flexion and add/abduction.

appropriate joint line was established at the primary surgery. In fact, it may be that an inappropriate joint line may have contributed to the failure of the primary arthroplasty[27].

Standard navigation software can significantly improve the accuracy of prosthesis implantation[30]. However, the use of systems designed primarily for primary TKA may be of limited benefit in a revision setting[31]. Dedicated software potentially allows the specific aspects of revision TKA to be addressed. The software aims to assist the surgeon with three dimensional implant alignment, medio-lateral positioning and antero-posterior shift, offset of the femoral component, and joint line reconstruction[30].

Here, a recently introduced navigation system for revision TKA is presented. The revision navigation software and instruments aim to guide surgeons through revision TKA. They have been designed for use with a dedicated constrained condylar knee system, and with a rotating hinged revision system. In this paper, the system, the surgical technique, and the potential advantages and disadvantages of the system are discussed.

MATERIALS AND METHODS

System description
The navigation system for revision TKA (PiGalileo, Smith and Nephew Orthopeadics, Aarau, CH) is an imageless navigation system for revision TKA, with optical point and tracker identification to assess kinematic and anatomical landmarks. The system automatically positions the cutting guides with a motorized cutting unit. The cutting unit is placed on the distal femur with a femoral clamp and acts as a rigid body and the base for all femoral cuts (Figure 1).

The basic surgical technique for using the navigation system for revision TKA is based on the technique used in primary TKA described by Hoffart *et al*[32] and Matziolis *et al*[33]. While there are many similarities between the techniques used in primary and revision TKA, there are some important differences. The most

notable are: (1) differences in estimation of the position of the primary implant relative to the bone and the mechanical axes; (2) the specific possibilities the revision navigation software offers in terms of optimal joint level positioning; and (3) the suggested "best fit" position, in which the clock position, stem position and offset, femoral component size, and mediolateral position of the femoral component are taken into account to find the optimal femoral component position.

Surgical technique
Once the computer-assisted saw guide unit and femoral clamp have been assembled and fixed flush to the ventral aspect of the distal femoral corticalis, the center of rotation of the hip is determined (Figure 2). This is performed through kinematic assessment of the lower extremity. The existing implant remains in situ at this point. The distal definition of the femoral mechanical axis is pinpointed by identifying the most dorsal part of the trochlea above the intercondylar notch on the implant or at the medial insertion point of the posterior cruciate ligament (Figure 3). Next, the medial and lateral epicondyles are identified.

On the tibial implant, the intersection point of the mechanical axis on the old implant is measured, and the location of the medial and lateral deepest points of the existing tibial plateau identified. The direction of tuberosity, aligned parallel to the tibial plateau, is determined, and the position of the medial and lateral malleoli is identified. These latter measurements represent the distal definition of the tibial mechanical axis (Figure 4). The stability of the existing implantation is tested *via* the varus/valgus in extension/flexion to establish an early range of motion. This gives the surgeon an overview of the existing implant malalignment and stability of the knee, including the status of the ligaments. Consequently it offers the surgeon the opportunity to choose an alternative implant before any surgical steps with the original implants have been carried out. This early range of motion assessment is stored in a final report, thus giving evidence in case of
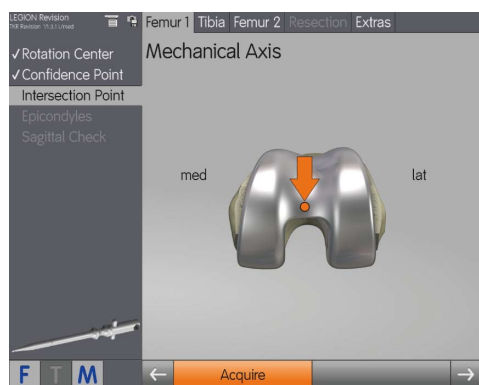
Figure 3 Mechanical axis - femur. The distal definition of the femoral mechanical axis using the PiGalileo Revision Navigation software.
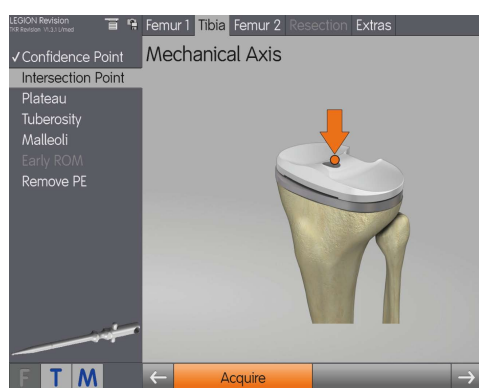
Figure 4 Mechanical axis - tibia. This measurement determines the tibial mechanical axis and therefore the extension of the mechanical axis, as defined for the femur.

Figure 5 Early range of motion. Encompassing varus/valgus, in extension/flexion, this measurement tests the "initial stability" of the existing implant to establish a "before" and "after" illustration.

any previous malalignment and instability (Figure 5).

The existing polyethylene is then removed to create space for the subsequent measurements. Next, further femoral landmarks are measured on the original implant and on the existing bone. The whiteside line and distal and posterior condyles of the original implant are measured. The condylar width is determined by identifying the medial and lateral edge of the medial condyle on the bone. The endpoint of the anterior shield of the implant on the anterolateral cortex is then pinpointed.

Next, the implants are removed, and the intramedullary canal is opened and reamed until a stable reaming can be achieved. The orientation of the last reamer is also measured to identify the anatomical axes. The motorized cutting unit is then placed and calibrated.

The surgeon now aligns the cuts and plans the implant position. The alignment of the mechanical axes can be performed by using either an anatomical axes orientation or a mechanical orientation, depending on the length of the chosen stem.

Before cutting, the position is checked and shifted, if necessary, in 0.5 mm steps distally or proximally to achieve minimal bone resection. Additionally the cutting block is raised or lowered closer to the bone to minimize saw blade twisting. The resection is performed through the 0 cut slot, or the -5, -10 or -15 cut slot if wedges are required.

The system then presents a "best fit" position, which includes size, offset and position of the intramedullary stem, medio-lateral implant position, and clock position. The surgeon then assesses these parameters, including in rotation, and then performs the anterior resection. The motorized unit also allows anteroposterior adjustment in 0.5 mm increments.

Posterior and anterior chamfer resections are performed next, followed by the posterior chamfer cut and reaming of the intramedullary canal, with the guide moved to the correct mediolateral position beforehand. The cutting guide/block is then removed, before returning the motorized cutting unit to the zero position.

The tibial procedure is similar, with the intramedullary rod inserted through the intramedullary adaptor and into the tibial canal. The anatomical and mechanical axis is displayed on-screen for both varus/valgus and flexion/extension. This helps to determine the optimal varus/valgus alignment of the resection. The tibial resection is performed with the existing tibia cut block used for the revision implant. For proper alignment, resection height, varus/valgus and slope are checked. After implantation of the trial components, the range of motion can be measured to assess the stability of the joint and correct the polyethylene height, if necessary.

RESULTS

This navigation system for revision TKA consists of two elements: a bone referencing imageless navigation system and a computer-assisted cutting device. It has been designed to cope with a number of surgical issues that are specific for revision knee arthroplasty.

The system aims to visualize critical steps of the procedure and is intended as a tool to support the surgeon in surgical decision-making. Combining a
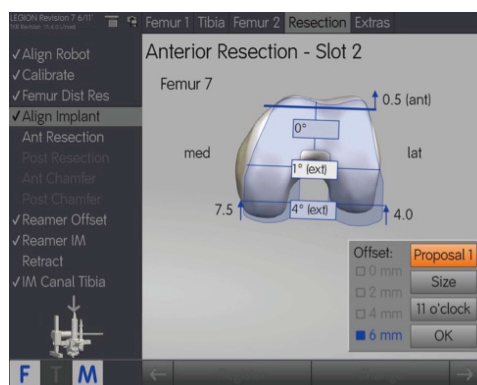
Figure 6 Presentation of a "best-fit" proposal.

computer-assisted cutting device with navigation makes it possible to carry out precise cuts without pinning. Furthermore, the femoral clamp provides a stable fixation mechanism for the motorized cutting unit. A stable clamp is paramount in the presence of periarticular bony defects.

As the position of the primary implant is measured first, the surgeon should correct for any malalignments, including rotational, that occurred with the primary implant. In standard revision TKA, the commonly used anatomical landmarks disappear once the implants have been removed, making correct placement of the prosthesis, especially in the presence of pre-existing malalignments, extremely challenging.

Based on the intraoperative findings of joint stability (status of joint capsule and ligaments), the surgeon can modify the preoperative plan and switch from a constrained condylar system to a hinged version, or vice versa.

Joint-level planning can be based on the old prosthesis or on a calculated algorithm based on the relationship between epicondylar distance to the medial and the lateral condyles developed by Romero *et al*[34].

In revision TKA, implants with an intramedullary stem are typically used. The angle between the surface of the femoral prosthesis and the stem generally measures 6° of valgus. Using such an implant will result in a perpendicular angle of the mechanical axis to the joint surface of the knee. The implant itself therefore has a restricted guidance and the surgeon has limited opportunities to change the alignment in the varus/valgus direction (In the tibia, the anatomical and mechanical axis typically coincide.). When using a short stem, the navigation software offers the possibility, alongside intramedullary and mechanical axis alignment, of an alignment "in between" the optimal anatomical and mechanical alignment, achieving an ideal implant position based on the given anatomical constraints of the individual patient.

As implant sizing and positioning is difficult to achieve in revision TKA, the navigation system calculates the optimal position of the femoral implant based on size, the anteroposterior and mediolateral dimensions,

and the clock position of the offset. In addition, the software gives the optimal configuration for the chosen implant. Based on this algorithm, the best six options with regard to implant configuration (including clock position and offset), component size, position, and stem position, depending on the stem offset, are suggested to the surgeon (Figure 6).

The workflow of the surgery may be adapted to personal preferences or surgical requirements by rearranging individual functional sections or "blocks" of the surgical workflow, *via* drag and drop. Some changes are possible even during the procedure. However, the system also was designed to refuse modifications if a specific workflow is not possible for safety or technical reasons. This offers the opportunity for the surgeon to examine the consequences of each decision taken, and to assess different implant solutions, and, if ultimately, an intraoperative switch to another implant.

For these reasons, the authors believe the system is suitable to serve as a teaching tool for understanding revision TKA.

DISCUSSION

Revision TKA is frequently a highly complex and difficult procedure, as commonly used anatomical references are hidden by previous implants and disappear after the failed implants are removed. Some degree of bone loss is typically encountered in all cases during revision surgery, and may often be underestimated[35] Causes of bone loss include stress shielding, osteolysis, infection, mechanical bone loss generated from a loose implant, and iatrogenic loss during implant removal[36-42]. Additionally, decreased bone mineral density is observed[35], which compromises pin fixation and promotes fractures. The degree of bone loss is variable, ranging from situations in which the epicondyles remain in situ to massive bone loss where the traditional bony landmarks are no longer available. Consequently, exact positioning of the revision cutting devices is aggravated[43].

During revision surgery, osteoporosis and bony defects at the distal femur can lead to suboptimal positioning of the pins and, hence, the cutting blocks. In addition, inadequate rigid fixation of the cutting blocks to osteoporotic bone may cause oscillations of the sawblades that change the position of the cutting blocks. This may result in discordant cutting planes on the condylar back surfaces of the implant, thus jeopardizing implant bone contact and, potentially, implant longevity.

In contrast, the presented navigation system offers rigid fixation of the cutting blocks, as the motorized block is secured on the distal femur corticalis with a clamp. The construct remains stable even in the presence of bony defects. From our initial experience, the rigidity leads to precise cuts, with good contact between the bone cuts and the prosthesis. A disadvantage is that the femoral clamp needs some space in region of the suprapatellar

pouch. Even if the brackets of the clamp are provided with spaces for fixation in the cortical bone, the clamp can compress the periosteum/soft tissue around the bone.

The additional fine adjustment of the distal and posterior cutting planes in 0.5-mm increments allows further adaptation of the flexion and extension gap. In the presence of distal and dorsal bone defects, it is paramount that the surgeon is able to resect as little bone as possible.

A known issue associated with conventional instrumentation in TKA revision is joint line proximalization. There is always distal femoral bone loss during revision surgery, and there is a tendency to undersize the femoral component. In addition, there is usually a relatively large flexion space after component removal compared to the extension space[25]. To compensate for this, the surgeon frequently fills the flexion space with a thicker inlay to balance the flexion and extension gaps. This, however, comes at the price of an elevated joint line.

It is also possible that the joint line was already elevated during primary surgery. In that case, radiographs of the primary TKA may not reflect the true anatomical position before primary TKA[34]. Thus, the restoration of the anatomical joint line in revision TKA is challenging, especially in the presence of preoperative deviations. The presented navigation system implements the findings of Romero *et al*[34], who described an algorithm to calculate the position of the joint line that can be used even in absence of classical landmarks. They used the linear correlation between epicondylar width and the perpendicular distance from the medial and lateral epicondyle of the joint-line tangent. Consequently, the joint line in revision TKA can be determined accurately and can be compared on-screen with the former joint line. Based on our initial experiences, we believe this feature will be helpful as further guidance to achieve an anatomic joint-line reconstruction.

Another consideration is that standard revision TKA surgery, and surgeries using navigation systems originally developed for primary TKA, rely on anatomical landmarks that are frequently no longer present. In such situations, anatomical references need to be taken from preoperative X-rays or be acquired from implant components that are to be removed[18]. This may result in suboptimal implant positioning and joint line restoration (as mentioned above)[4,30], and indicates that native anatomy should be taken into account. It has also been observed that primary navigation systems used in revision TKA lack the flexibility to cope with mismatches between stem alignment and the articular resection. In such instances, the implanted prosthesis may be forced in the direction of the diaphyseal axis[30].

The current system, however, identifies the anatomical and mechanical axes to achieve optimal implant alignment, to a feasible extent. This gives surgeons a range of options, depending on the implants to be used. For example, when using a long femoral stem, the system allows alignment from the endosteal cortex of the intramedullary canal, which is a reliable method of achieving satisfactory alignment in most, but not in all, revision TKAs[44]. In cases where satisfactory alignment cannot be obtained, the use of short femoral stems will be beneficial. The navigation systems for revision TKA allows the surgeon to compromise between neutral anatomical and mechanical alignment, which may be valuable in femoral alignment.

The navigation system we describe is based on a bone-referencing technique. Future enhancements with the possibility of ligament balancing are currently being developed. At present, our experience indicates that a good estimate of stability is obtained after three passes of early ROM with the system. The first reading is performed under application of a valgus stress, the second with varus stress and the third with a spontaneous ROM as a reference. As a result, the surgeon has a good indication of the stability of the joint and ligaments, and the required level of constraint from the implant (*i.e.*, a hinged design or a constrained condylar design). The decision can then be made intraoperatively to go ahead with the planned implant or change the implant type. Overall, this is only the first attempt at including soft tissue balancing in the navigation algorithm and will be developed further.

For the surgeon experienced in revision TKA, the software is easy to use and, by providing a number of choices, ensures that they are in control of the procedure while being guided on a step-by-step basis. However, it should be seen as a tool to facilitate the execution of thorough preoperative planning, instead of replacing it. The system facilitates precise implementation of a thoroughly prepared preoperative plan, and allows the surgeon to intraoperatively adapt the preoperative plan if necessary, based on feedback and feed-forward provided by the system.

Based on a complex measurement algorithm, the system visually and numerically presents six proposals of femoral implant configurations to the surgeon. These configurations contain details on implant size, offset and position of the intramedullary stem, medio-lateral implant position, and clock position that is adaptable by the surgeon, based on his experiences and preferences.

The system also allows the location of the primary implant to be documented at the time of revision, which may be beneficial in medico-legal situations.

The presented navigation system aims to further improve surgical strategy and accuracy over navigation systems designed solely for primary TKA. The system requires validation for accuracy and reproducibility in a variety of clinical settings, both in comparison with standard surgical approaches and with more traditional assisted navigation systems. The intraoperative advantages highlighted above must be carefully weighed against the expected increase in surgical time. Radiographic evidence from robust clinical studies will

also be needed to prove that the current navigation system leads to improved implant alignment. Femoral component alignment in the coronal plane is largely determined by the stem component and the femoral diaphysis. For this reason, surgical navigation may not necessarily improve alignment in the coronal plane. The use of shorter stem components, as suggested in this paper, will offer additional possibilities to align the femoral component. In practice, this may be of marginal benefit, as this strategy is also at the disposal of the experienced surgeon who uses standard instrumentation. In addition, the additional flexibility of femoral component positioning must not be at the cost of implant fixation.

Once early results with this system for revision TKA will become available, it will doubtless present some limitations. For example, surgeons will be required to undergo training in order to be able to use the technology correctly and effectively, both in terms of accurate and careful data acquisition and use of the computer-assisted saw guide. Nevertheless, the system has been designed with this specifically in mind, with an in-depth of set of on-screen instructions and procedure guides. It is therefore anticipated that, for experienced surgeons, the learning curve will be no greater than in taking up a standard computer-assisted navigation system for primary TKA, and will assist surgeons in taking on more complex revision TKA procedures.

In summary, revision TKA is a demanding procedure, and current computer-assisted navigation systems typically do not allow surgeons to identify the pre-primary TKA anatomical and mechanical axes in order to arrive at the optimal revision implant position. The presented system for revision TKA is thought to offer surgeons a tool to improve workflows for total knee revision arthroplasty.

ACKNOWLEDGMENTS

COMMENTS

Background

Revision total knee arthroplasty (TKA) is a demanding procedure due to previous implants hiding commonly used anatomical landmarks, scar formation, the loss of bone stock, and the frequent presence of osteolytic lesions, severe osteoporosis, lack of anatomical bony landmarks and ligamentous insufficiency that are often seen after the removal of the failed prosthesis. A recently introduced navigation system for revision TKA is presented. The revision navigation software and instruments aim to guide surgeons through revision TKA. In this paper, the system, the surgical technique, and the potential advantages and disadvantages of the system are discussed.

Research frontiers

Revision TKA is less successful at producing high quality outcomes than primary TKA. Currently, 10-year survival following revision TKA is substantially less than the expected survival rate after primary TKA. Current computer-assisted navigation systems typically do not allow surgeons to identify the pre-primary TKA anatomical and mechanical axes in order to arrive at the optimal

revision implant position.

Innovations and breakthroughs

The current system for revision TKA is thought to offer surgeons a tool to improve workflows for total knee revision arthroplasty. The current navigation system aims to further improve surgical strategy and accuracy over navigation systems designed solely for primary TKA.

Applications

The intraoperative advantages must be carefully weighed against the expected increase in surgical time. The system requires validation for accuracy and reproducibility in a variety of clinical settings, both in comparison with standard surgical approaches and with more traditional assisted navigation systems.

Terminology

Computer-assisted revision arthroplasty described in the papers uses an imageless navigation system for revision TKA, with optical point and tracker identification to assess kinematic and anatomical landmarks. The system automatically positions the cutting guides with a motorized cutting unit.

Peer-review

Interesting topic, well written article.

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ORIGINAL ARTICLE

Retrospective Study

Modified porous tantalum rod technique for the treatment of femoral head osteonecrosis

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Abstract

AIM: To study a modified porous tantalum technique for the treatment of osteonecrosis of the femoral head.

METHODS: The porous tantalum rod was combined with endoscopy, curettage, autologous bone grafting and use of bone marrow aspirates from iliac crest aspiration in 49 patients (58 hips) with a mean age of 38 years. The majority of the patients had idiopathic osteonecrosis, followed by corticosteroid-induced osteonecrosis. Thirty-eight hips were of Steinberg stage Ⅱ disease and 20 hips were of stage Ⅲ disease. Patients were followed for 5 years and were evaluated clinically with the Merle D'Aubigne and Postel score and radiologically. The primary outcome of the study was survival based on the conversion to total hip arthroplasty (THA). Secondary outcomes included deterioration of the osteonecrosis to a higher disease stage at 5 years compared to the preoperative period and identification of factors that were associated with survival. The Kaplan-Meier survival analysis was performed to evaluate the survivorship of

the prosthesis, and the Fisher exact test was performed to test associations between various parameters with survival.

RESULTS: No patient developed any serious intra-operative or postoperative complication including implant loosening or migration and donor site morbidity. During the 5-year follow up, 1 patient died, 7 patients had disease progression and 4 hips were converted to THA. The 5-year survival based on conversion to THA was 93.1% and the respective rate based on disease progression was 87.9%. Stage Ⅱ disease was associated with statistically significant better survival rates compared to stage Ⅲ disease (P = 0.04). The comparison between idiopathic and non-idiopathic osteonecrosis and between steroid-induced and non-steroid-induced osteonecrosis did not showed any statistically significant difference in survival rates. The clinical evaluation revealed statistically significantly improved Merle d'Aubigne scores at 12 mo postoperatively compared to the preoperative period (P < 0.001). The mean preoperative Merle d'Aubigne score was 13.0 (SD: 1.8). The respective score at 12 mo improved to 17.0 (SD: 2.0). The 12-mo mean score was retained at 5 years.

CONCLUSION: The modified porous tantalum rod technique presented here showed encouraging outcomes. The survival rates based on conversion to THA are the lowest reported in the published literature.

Key words: Avascular necrosis; Femoral head; Tantalum rod; Survival; Bone grafting

Core tip: In the present study, we present the results of a modified porous tantalum technique for the treatment of femoral head avascular necrosis. The porous tantalum rod was combined with endoscopy, curettage, autologous bone grafting and use of bone marrow aspirates from iliac crest aspiration in 58 hips. The 5-year survival based on conversion to total hip arthroplasty was 93.1% and the respective rate based on disease progression was 87.9%. Stage Ⅱ disease was associated with statistically significantly better survival rates compared to stage Ⅲ disease, while no other factor was found to be associated with outcomes.

INTRODUCTION

Osteonecrosis of the femoral head is an increasing cause of musculoskeletal disability, and it poses a major diagnostic and therapeutic challenge. It is a progressive disease that may lead to deterioration of the hip joint even with optimal treatment, and mostly occurs in the young and previously fit population (usually between the third and the fifth decade of life). It is estimated that approximately 10% of the performed total hip arthroplasties (THA) are due to osteonecrosis[1].

Investigators have not yet agreed on the exact pathogenetic mechanisms that contribute to the disturbance of blood supply to the bone. However, various factors such as trauma, alcoholism, blood cell diseases, corticosteroid administration, pregnancy, collagen disorders (especially lupus), adipogenesis of bone marrow, colon disorders and factors or diseases, which cause immune deficiency, have been reported as etiologic factors for the disease[2,3]. It is also proposed that hypercoagulability may be a major pathway by which the above-mentioned abnormalities lead to impairment of the vascular supply[4]. In many cases, osteonecrosis can be characterized as idiopathic since the patients do not have any risk factor.

While efforts are being made to find ways to prevent and reverse the course of the disease, the main goal of current treatment is to preserve the integrity of the femoral head, before it collapses and leads to hip joint degeneration. In late stages of osteonecrosis in which the subchondral bone is fractured and the collapse of the articular surface leads to arthritic alterations, surface replacement[5] or THA[6] is inevitable. It is therefore critical to treat osteonecrosis in early stages, to delay or possibly prevent the finality of total hip replacement, especially in the young population where poorer long-term outcomes have been reported[7]. Various therapeutic procedures depending on the degenerative stage of the necrosis have been implemented and include restricted weight bearing, osteotomies, core decompression, non-vascularized and vascularized bone grafting[8,9]. However, most of these methods did not show satisfactory clinical outcomes and were associated with either prolonged surgical times due to the complex surgical procedure, or high donor-site morbidity and prolonged rehabilitation.

The need for an easy, effective and safe way to support the subchondral bone has led to the use of porous tantalum rods, firstly described by Pedersen *et al*[10] in 1997. Tantalum rods have high volumetric porosity, providing excellent osteoconductive properties, while their elastic modulus is similar to bone and they have exceptional biocompatibility[11,12]. They provide structural support like that of bone graft and avoid the risks associated with bone grafting. The surgical technique is simple and safe, with short operative time and minimal blood loss. Short and mid-term results can be satisfactory, especially in the early stages of the disease (pre-collapse and early post-collapse), but it is essential that particular attention is given to careful

patient selection and exact positioning of the rod into the necrotic lesion and the subchondral bone.

The present retrospective study represents a bi-centre trial that reports on the clinical outcomes of porous tantalum rod for the treatment of femoral head osteonecrosis. The technique used in our study is a variation of the classical technique, since the tantalum rod is combined with endoscopy, lesion curettage, autologous bone grafting and use of bone marrow aspirates.

MATERIALS AND METHODS

Biomechanical characteristics of tantalum rods

Porous tantalum rods were designed to support the subchondral plate of a necrotic human femoral head. The implant is entirely made of porous tantalum metal which is currently used in a variety of hip, knee and spine components[11]. Tantalum biomechanical characteristics such as porosity and mean pore size have been earlier reported[13]. The rod has a 10-mm-diameter cylindrical shape with length options ranging from 70 to 130 mm (in 5-mm increments). There is also a threaded section which engages the lateral cortex of the femur and a hemispherical tip which supports the subchondral plate. Through mechanical experimentation, Tsao *et al*[12] identified the ability of this implant to support the articular surface. It is also possible that the tantalum induces bone formation without bone grafting, which has been reported in animal models by Bobyn *et al*[11,13].

Patients

Between 2001 and 2010, 49 patients with osteonecrosis of the hip were treated with a porous tantalum rod in the Department of Orthopaedic Surgery of the University Hospital of Ioannina (24 patients) and the Department of Orthopaedic Surgery of the University Hospital of Patras (25 patients). The study was approved by the Institutional Review Board of both participating institutions. Nine patients had bilateral osteonecrosis of the hip that was treated with tantalum rod at separate stages. The classification of osteonecrosis was performed using the Steinberg classification system[14]. Patients with serious subchondral collapse and/or destruction of the hip joint (Steinberg stage IV or higher) were excluded from the present study. We have also excluded patients with previous surgical management of osteonecrosis (*i.e.*, core decompression, osteotomy, bone grafting). Overall, 21 female patients and 28 male patients with 58 affected hips and a median age of 38 years (range 22-55) were included in the study. Thirty-nine patients had the right hip affected.

Twenty-two patients (45%) were diagnosed with idiopathic osteonecrosis, 16 patients had corticosteroid-induced osteonecrosis, 3 patients had primary diagnoses of leukemia and developed osteonecrosis due to a combination of chemotherapy and corticosteroid treatment, 2 patients had osteonecrosis secondary

to bowel disease, 2 patients had alcohol-induced osteonecrosis, 2 patients had dyslipidemia, 1 patient developed osteonecrosis after labor and 1 patient had polycythemia vera. The grade of osteonecrosis was determined with a combination of plain anteroposterior (AP) and lateral radiographs as well as magnetic resonance imaging (MRI) imaging. Among the 58 hips included in the study, 38 hips were of Steinberg stage 2 (6 hips 2a, 22 hips 2b, 10 hips 2c) and 20 hips of Steinberg stage 3 (20 hips 3a).

Surgical technique

All operations were performed by the senior authors (Megas P, Xenakis TA). Under general anesthesia, the patient was positioned supine on the fracture table and internal rotation was applied to the affected lower limb. Under fluoroscopic control, a guide pin was placed over the skin directed to the exact place of the necrotic area in order to mark the skin incision at the greater trochanter. A lateral lengthwise 1.5-cm incision was performed and the subcutaneous soft tissue, the fascia lata and the vastus lateralis muscle were blindly dissected. Under fluoroscopic control, a 3.2-mm guide pin was inserted at the level of the upper margin of the lesser trochanter with the goal to place the guide pin exactly within the necrotic region and 5 mm from the subchondral surface of the femoral head. The core was progressively reamed with cannulated reamers up to 10 mm in diameter. At a second stage, an endoscopy was performed through the canal in order to evaluate the posterior aspect of the osteonecrosis (Figure 1). The posterior aspect of the osteonecrotic lesion was the only visible area, since the endoscopy was performed through a narrow canal. A partial curettage of the osteonecrotic lesion was then performed, with meti-culous care in order not to invade the cartilage. The curettage was performed with small drills into the necrotic lesion using a threaded flexible Ø3.2 × 450 mm Kirschner wire through the canal.

The next step involved bone marrow aspiration from the ipsilateral anterior iliac crest. A 5-mm incision was performed approximately 3-4 cm posterior to the anterior superior iliac spine directly on the crest. A 16-gauge aspiration needle was advanced into the bone marrow with an angle of 15 degrees cephalad by rotating it in an alternating clockwise/counter clock-wise motion. The needle was advanced approximately 4–6 cm into the cancellous bone. The stylet/trocar was removed and a heparin-coated 30-mL syringe was adjusted onto the needle. Aspirates of 30 mL of bone marrow were obtained. If no bone marrow was obtained, the needle was reoriented within the ilium, and the aspiration was repeated.

The aspirates were divided in 2 equal parts. The first part was mixed with the morselized bone graft from the canal reaming and was then placed into the canal and was pushed to reach the necrotic area. Finally, the tantalum rod (Zimmer, Inc., Warsaw, IN,
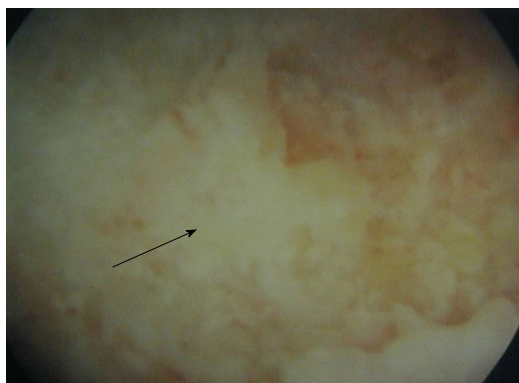
Figure 1 Endoscopic view of the osteonecrotic lesion. View obtained from the endoscopy through the canal. The posterior aspect of the osteonecrotic lesion is seen at the center of the image (arrow) as a white non-vascularized area, surrounded by normal purple-coloured bone (vascularized bone).

Figure 2 Tantalum rod. The tantalum rod used in the present series, manufactured by Zimmer (Zimmer, Inc, Warsaw, IN, United States). The rod was impregnated with bone marrow aspirates obtained from iliac crest aspiration.

United States) was impregnated with the second part of bone marrow aspirates (Figure 2). The impregnation was performed by immersing the rod into the aspirates for 5 min.

Although the initially described technique involved the measurement of the canal and the placement of the lateral part of the rod at the lateral femoral cortex, we used shorter rods in the majority of the patients so that the rod ended distally at the cancellous bone of the trochanteric area. This method enabled the easier removal of the rod (the lateral edge of the rod was at the level of femoral head osteotomy) and the filling of the cortical defect with bone in case of future arthroplasty.

Prophylactic antibiotics (second generation cephalosporins) were administered intravenously for 1 d post-operatively, while thromboprophylaxis with low molecular weight heparin according to the body mass index was administered subcutaneously for 4 wk. Postoperative pain was treated with paracetamol and pethidine. All patients followed the same routine rehabilitation program that included mobilization on the 2nd postoperative day with the help of a specialized physiotherapist, partial weight bearing on the operative side with 2 crutches for 6 wk, and then full weight bearing with 1 crutch for another 6 wk. No patient required intensive physiotherapy.

Postoperative evaluation

Patients were evaluated clinically and radiologically in the postoperative period. The clinical evaluation was based on the Merle D'Aubigne and Postel score[15] and was performed at 6 mo, 1 year and 5 years postoperatively. The Merle d'Aubigne and Postel score evaluates pain, gait and mobility, on a scale of 1 to 6 for each item, where 1 indicates the worst and 6 the best state of the patient. The total minimum score reached is 3, and the maximum is 18. Scores were compared with those from the immediate preoperative period. All intra-operative and postoperative complications were recorded. The radiological evaluation was performed at 1.5, 3, 6 and

12 mo postoperatively and annually thereafter till the 5th year. The postoperative radiological evaluation included the restaging according to the Steinberg staging system[15] based on plain X-rays and MRI on indication. Post-operative follow-up examinations were performed by two independent investigators who reached consensus on all patients.

Statistical analysis

The follow-up time was calculated from the day of operation. Primary endpoint of the study was the 5-year survival of the hip joint defined as hips that did not undergo total hip arthroplasty. Secondary outcomes included deterioration of the osteonecrosis to a higher disease stage at 5 years compared to the preoperative period. Finally, we tested for associations between disease stage and etiology of osteonecrosis and survival.

A Kaplan-Meier survival analysis was performed to evaluate the survivorship of the prosthesis. A Fisher exact test was performed to test associations between various parameters with survival. A t test for independent samples was used to determine whether there was a significant difference in mean values of the clinical scores or not. P values < 0.05 were considered statistically significant; all P values were two-tailed. All statistical analyses were performed using the Statistical Package for Social Sciences (SPSS 22.0, Chicago, IL, United States).

RESULTS

The median duration of operation was 40 min (range 35-50 min). One patient had a superficial wound infection at 5 d postoperatively and was treated with oral antibiotic therapy for 1 wk without further evidence of infection. No other patient developed any intraoperative (*i.e.,* fat embolism) or postoperative complication. No patient developed any loosening or migration of the tantalum rod. No patient reported any donor site morbidity from the ipsilateral iliac crest. The mild pain or irritation at the iliac crest was not retained for more than 6 wk.

All patients except one were available for follow up for up to 5 years (Figures 3 and 4). One 38-year-old patient with unilateral osteonecrosis of stage 3b
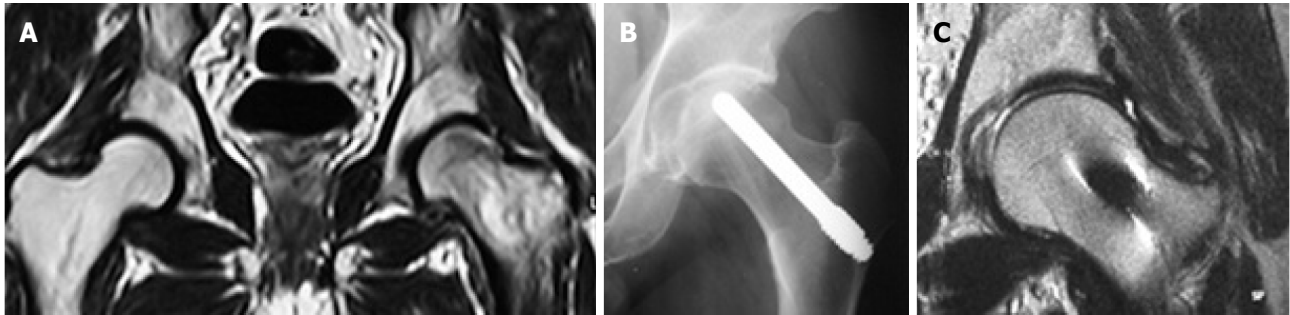
Figure 3 Pre- and post-operative imaging of femoral head osteonecrosis. Imaging of a 42-year-old patient with corticosteroid-induced osteonecrosis of the femoral head treated with porous tantalum. A: Preoperative MRI of Steinberg stage II osteonecrosis of the left femoral head; B: One-year postoperative X-ray after the implantation of the tantalum rod. No pathological findings are seen; C: Five-year postoperative MRI of the left hip with absence of pathological findings. MRI: Magnetic resonance imaging.

Figure 4 Pre- and postoperative X-rays of osteonecrosis of the femoral head. X-rays of a 47-year-old patient with idiopathic osteonecrosis of the femoral head. A: Preoperative X-ray with Steinberg stage II osteonecrosis; B: Six-month postoperative X-ray showing no disease deterioration; C: Five-year postoperative X-ray of the same patient with no pathological findings.
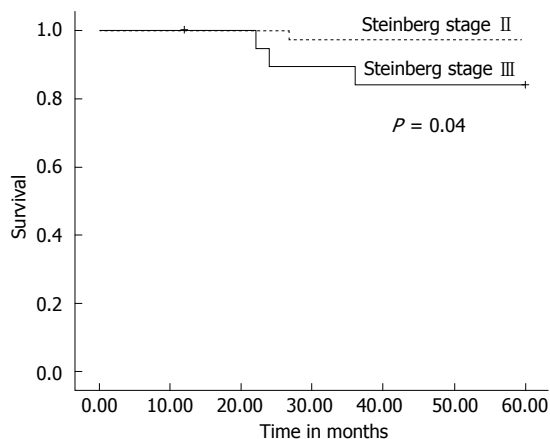
Figure 5 Survival plots for patients with stage II and stage III disease. Within the 5-year follow up period, 4 patients with osteonecrosis treated with tantalum rod were converted to total hip arthroplasty. One patient had Steinberg stage II disease and 3 patients had Steinberg stage III disease. Patients with stage III disease had increased risk to undergo total hip arthroplasty. The difference was statistically significant ($P = 0.04$).

due to leukaemia died 12 mo postoperatively with no apparent sign of disease deterioration. During the 5-year follow up, the radiographic evaluation showed increase of the Steinberg stage in 7 patients. Four hips developed advanced osteoarthritic changes of Steinberg stage V and were converted to THA within a mean time of 27.5 mo (SD: ± 6.2 mo). The 5-year survival was 93.1% (95%CI: 83.3%-98.1%). Patients

with stage III disease had increased risk to undergo THA and the difference was statistically significant ($P = 0.04$) (Figure 5).

In 2 of the hips that were converted to THA, the removal of the tantalum rod was easily performed due to the fact that the rod was shorter, ending distally at the cancellous bone of the trochanteric area at the level of femoral head osteotomy. In two patients where the lateral part of the rod was placed at the lateral femoral cortex, the conversion was performed with the osteotomy cut through the rod (Figure 6A), and the lateral part of the rod was carefully removed with the use of a lexer chisel. No trochanteric fracture was noticed. The trochanteric hole was filled with morselized bone graft from the femoral head and the 6-wk postoperative X-rays showed callous formation (Figure 6B). The 12 and 24 mo postoperative X-rays in these patients did not show any apparent change.

Among the hips that underwent THA, 1 was of stage IIa and 3 were of stage IIIa. Three hips had disease progression with no conversion to THA. One of these hips was initially of stage IIc and was restaged as stage IIIb at 24 mo postoperatively. Two hips of initial stage IIIa were restaged as stage IV at 12 and 60 mo, respectively (Figure 7). The 5-year survival defined as disease deterioration and increase of osteonecrosis stage was 87.9% (95%CI: 76.7%-95.0%). Again, patients with stage III disease had increased risk to deteriorate ($P = 0.02$).
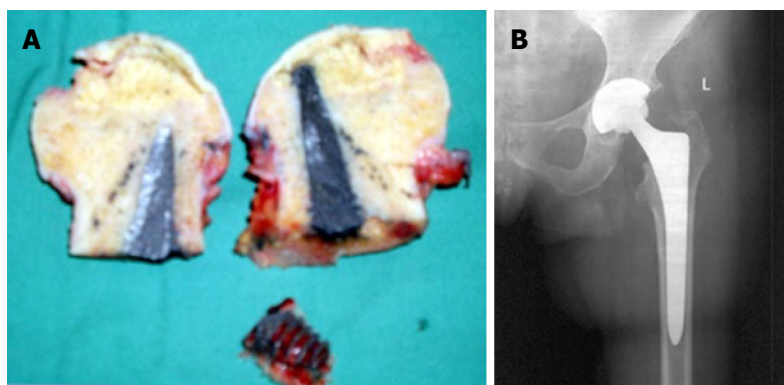
Figure 6 Conversion of tantalum rod to total hip arthroplasty. A: The osteotomised femoral head with the tantalum rod in a 55-year-old patient who underwent THA due to disease deterioration. The osteotomy of the femoral neck was performed through the tantalum rod; B: Six-week post-THA X-ray of the same patient. The X-ray shows callous formation within the trochanteric hole. THA: Total hip arthroplasty.
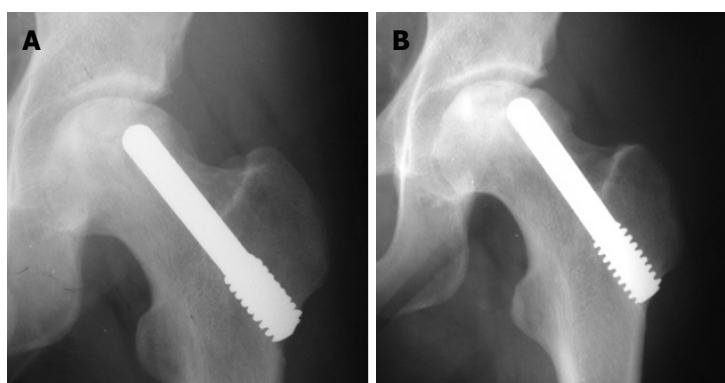
Figure 7 Disease progression after tantalum rod implantation. Thirty-eight-year old female patient with osteonecrosis of the left femoral head due to leukemia. A: The immediate postoperative X-ray after the implantation of tantalum rod showing Steinberg stage III osteonecrosis; B: X-ray of the same patient showing deterioration to Steinberg stage IV osteonecrosis 12 mo after the implantation of tantalum rod.

Among the hips that were converted to THA 2 that had idiopathic osteonecrosis, in one case the osteonecrosis was due to corticosteroid use and 1 patient had combined chemotherapy and steroid treatment for leukaemia. No significant association was observed between the etiology of osteonecrosis and the 5-year survival ($P = 0.31$ for the comparison between idiopathic osteonecrosis and non-idiopathic osteonecrosis). Similarly, no significant difference was observed in survival rates between steroid-induced and non-steroid-induced osteonecrosis ($P = 0.28$).

All patients had available clinical evaluation preoperatively, at 12 mo postoperatively and at 60 mo postoperatively. Patients that had THA were excluded from the 60-mo clinical evaluation. The postoperative clinical evaluation of the patients showed significant improvement compared to the preoperative period. All but 1 patient reported apparent pain relief at 6 wk postoperatively. The mean preoperative Merle d'Aubigne score was 13.0 (SD: 1.8). The respective score at 12 mo improved to 17.0 (SD: 2.0). The difference was highly statistically significant ($P < 0.001$). The improved clinical scores were retained till the final follow up at 5 years where the mean score was 16.8 (SD: 1.5).

DISCUSSION

Management of femoral head osteonecrosis in young adults where THA does not represent the ideal solution is challenging. Indeed, the survival duration of a THA in a young patient and the need for future revision favours joint-preserving techniques for femoral head osteonecrosis. In our study, we report on the clinical and radiological outcomes of a novel variation of the classical porous tantalum rod technique that was combined with canal endoscopy, curettage of the lesion, impaction of autologous bone graft mixed with bone marrow aspirates from the iliac crest and impregnation of the rod with these aspirates. This technique showed encouraging outcomes for the treatment of osteonecrosis of the femoral head. The 5-year survival defined as conversion of the tantalum rod to THA was 93.1%. The 5-year survival defined as disease deterioration and increase of disease stage was 87.9%. Both survivals were statistically significantly associated with the disease stage, since patients with stage II disease had increased survival rates compared to patients with stage III disease.

One treatment option for osteonecrosis of the femoral head is free vascularized fibula grafting (FVFG). This technique was introduced approximately 40 years ago and has shown efficiency in preserving the hip joint[16,17]. The popularization of the technique highlighted that there are certain indications for its application and its efficiency is dependent on proper patient selection[18,19]. Several disadvantages of FVFG have been also highlighted, such as long surgical time, demanding operative technique and donor morbidity[20-22]. These limitations make tantalum core decompression an attractive option for femoral head osteonecrosis.

Several studies have evaluated the efficacy of the porous tantalum rod in the treatment of femoral head osteonecrosis, with controversial outcomes. In

the majority of these studies the porous tantalum rod has proven an effective and safe management for osteonecrosis of femoral head[23-25]. However, other studies showed poor outcomes with high rates of conversion to THA[26]. A recent meta-analysis showed that porous tantalum rod application was associated with higher improvement in Harris Hip Score as well as better survivorship and complication rate in comparison to bone grafting techniques[25,27]. Specifically, femoral collapse occurred in approximately 6% of the patients, which was significantly lower when compared to 28% in the bone grafting group[27]. Tantalum rod results in less bleeding, fewer transfusions, and shorter hospitalization[27]. Our findings confirm the effectiveness and safety for the porous tantalum rod in these patients. Our series, utilizing a modified technique of porous tantalum rod, shows improved effectiveness compared to the published literature. Conversion to arthroplasty within the 5-year follow up period was performed in 7% of our patients, which represents the lowest rate up to date in such a long term period.

The effectiveness of the porous tantalum rod in osteonecrosis treatment may be correlated with the material properties of the tantalum. Porous tantalum has a porosity of 75%-80% and allows more than 40% of bone ingrowth within the first 4 wk of implantation and up to 80% at a later stage[13]. Recently, reports of new bone ingrowth with associated small blood vessels at the bone/tantalum interface highlighted the biocompatibility of the material[28]. At the same time, it is less stiff than the traditional tantalum, with a stiffness that approximates that of the subchondral bone[13]. Thus, it provides an environment that favours bone remodelling, which is critical in femoral head osteonecrosis.

Porous tantalum insertion at the femoral head removes the necrotic lesion, forms a decompression zone, and provides support to the subchondral bone. Core decompression has been reported to be an effective method in preventing the progression of osteonecrosis[29,30]. However, it was proven that it offers more symptomatic relief rather than delay in the natural history of femoral head osteonecrosis and subsequent collapse and degeneration[31]. Furthermore, it has been suggested that decompression alone may weaken the cancellous bone in an area adjacent to the necrotic area with obvious disadvantages[8]. Therefore, porous tantalum offers mechanical support to the subchondral bone, which not only addresses the concern of bone weakening, but also may represent a key intervention for osteonecrosis progression[12,32].

In our series, the porous tantalum rod has been combined with other techniques in an attempt to increase its efficiency. An endoscopy of the lesion through the canal was performed in order to evaluate the situation of the subchondral bone. Consequently, curettage of the lesion was performed in order to remove the necrotic bone and to create sockets which

the morselized bone graft and the new bone would fill. Finally, in order to enhance new bone formation from the tantalum rod, the rod was impregnated with bone marrow aspirates before implantation. This the first time in the published literature that such a combination was used. Moreover, the outcomes of the present study confirm all previous published studies that improved survival rates are associated with an earlier disease stage. Finally, associations of factors such as corticosteroid use or chronic systemic disease that were previously reported to correlate with higher failure rates[24] were not found in the present study. Previously reported complications from the use of the tantalum rod such as fat embolism[33] and subtrochanteric fractures[34] were not seen in our series.

Porous tantalum implantation appears to play a prominent role in the treatment of osteonecrosis of the femoral head, especially when combined with other techniques that can increase its effectiveness and applicability. The combination of tantalum rod insertion with vascularized iliac grafting has shown a survival rate of more than 90% for stage II and III osteonecrosis[35]. Recently, in a randomized control trial, Mao *et al*[36] have reported the combination of a tantalum rod with targeted intraarterial infusion of peripheral blood stem cells, with improved survival compared to the control group (6.5% conversion to THA in the combined group). Another recent study where a tantalum rod was combined with curettage of the sequestrum and insertion of nano-hydroxyapatite/polyamide 66 material showed 19.3% conversion to THA in 45 mo[37]. Finally, the porous tantalum rod may be used in combination with low intensity ultrasound in order to promote bone ingrowth into the porous implant that could enhance the effectiveness of this technique[38].

In conclusion, the modified porous tantalum rod technique that was applied to our series is a safe and quick method that showed encouraging outcomes and improved survival rates compared to previous reported techniques. The limitations of the present study include the retrospective design, the limited sample size, the inhomogeneous group of eligible patients, the absence of control groups and the absence of long term survival outcomes exceeding 10 years. These limitations should be considered in future study designs.

COMMENTS

Background
Osteonecrosis of the femoral head is an increasing cause of musculoskeletal disability, and it poses a major diagnostic and therapeutic challenge. Although various factors have been reported as etiologic factors, the exact pathogenetic mechanism of the disease is unknown. The goal of current treatment modalities is to preserve the integrity of the femoral head and prevent hip joint degeneration and eventually total hip arthroplasty (THA). Various therapeutic procedures depending on the degenerative stage of the necrosis have been implemented and include restricted weight bearing, osteotomies, core decompression, bone grafting (either non-vascularized or vascularized) and the use of porous

tantalum rods. In this study the authors evaluated the efficacy of a modified porous tantalum rod technique where the tantalum rod was combined with endoscopy, lesion curettage, autologous bone grafting and use of bone marrow aspirates.

Research frontiers

The surgical technique of porous tantalum is simple and safe, with short operative time and minimal blood loss. The majority of the published literature has shown promising clinical outcomes with low rates of conversion to THA, especially in the early stages of the disease. The results of the present study where a modified technique is used contribute to further improvement of clinical outcomes, by lowering the rates of conversion to THA.

Innovations and breakthroughs

In this study, the modified porous tantalum technique showed increased 5-year survival rates compared to the published literature. The 5-year survival defined as conversion of the tantalum rod to THA was 93.1%. The 5-year survival defined as disease deterioration and increase of disease stage was 87.9%. Patients with stage II disease had increased survival rates compared to patients with stage III disease, in concordance with the published literature.

Applications

The modified porous tantalum rod technique that was applied to the authors series is a safe and quick method that showed encouraging outcomes and improved survival rates compared to previous reported techniques. The use of the authors technique can lower the conversion to THA.

Peer-review

The authors of this paper evaluated the use of a modified porous tantalum technique in the treatment of femoral head osteonecrosis of 58 hips that were followed for 5 years. They describe a novel technique with good results which has potential to be adopted by other surgeons.

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META-ANALYSIS

Operative *vs* non-operative management of displaced proximal humeral fractures in the elderly: A systematic review and meta-analysis of randomized controlled trials

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Abstract

AIM: To perform a systematic review and meta-analysis comparing operative *vs* non-operative treatment of displaced proximal humerus fractures in elderly patients.

METHODS: A systematic literature search was performed using EMBASE and MEDLINE through the OVID interface, CINAHL, the Cochrane Central Register of Controlled Trials (CENTRAL), Proquest, Web of Science, SAE digital library, and Transportation Research Board's TRID database. Searches of conference proceedings were also conducted. All available randomized controlled trials comparing operative *vs* non-operative management of displaced three- and four-part proximal humerus fractures in elderly patients were included. The primary outcomes measures included physical function, pain, health related quality of life, mortality, and the re-operation rate.

RESULTS: Six randomized controlled trials (*n* = 287) were included. There was no statistically significant difference in function (MD = 1.72, 95%CI: -2.90-6.34, *P* = 0.47), as measured by the Constant score, between the operative and the non-operative treatment groups. There was no statistically significance difference in

secondary outcomes of health related quality of life (standardized MD = 0.27, 95%CI: -0.05-0.59, P = 0.09), and mortality (relative risk 1.29, 95%CI: 0.50-3.35, P = 0.60). Operative treatment had a statistically significant higher re-operation rate (relative risk 4.09, 95%CI: 1.50-11.15, P = 0.006), and statistically significant decreased pain (MD = 1.26, 95%CI: 0.02-2.49, P = 0.05).

CONCLUSION: There is moderate quality evidence to suggest that there is no difference in functional outcomes between the two treatments. Further high quality randomized controlled trials are required to determine if certain subgroup populations benefit from surgical management.

Key words: Proximal humerus fracture; Outcomes; Operative treatment; Non-operative treatment; Meta-analysis

Core tip: Our systematic review and meta-analysis found a lack of high quality evidence to determine the effects of operative *vs* non-operative treatment on patient-important outcomes among elderly patients with three- or four-part proximal humeral fractures. There is moderate quality evidence to suggest that there is no difference in functional outcomes between the two treatments.

INTRODUCTION

Proximal humerus fractures are the third most common fragility fracture and they are associated with a substantial burden of disability and impaired quality of life. Optimal treatment in elderly patients remains controversial, and an evidence-based approach is critical to improve patient outcomes and allocate limited health care resources[1-4].

Fracture treatment depends on the type of fracture, the degree of fragment displacement, and fracture stability[5]. Most proximal humeral fractures are non-displaced or minimally displaced and are usually treated successfully non-operatively, but the optimum treatment becomes less clear in more complex, displaced fracture patterns[6,7]. Three- and four-part fractures account for 13% of proximal humerus fractures, and are regarded as the most challenging to treat[7]. Surgical interventions

are associated with good functional outcomes in young adults, but provide varying results and high complication rates in the elderly population[8]. There is little evidence to support that surgical treatment of three- and four-part fractures in elderly patients is more effective than non-operative treatment[9].

Previous systematic reviews have attempted to compare operative and non-operative management of these fractures, but were limited to specific surgical techniques or did not include recently published relevant trials[10-12]. More importantly, most reviews do not use statistical techniques to appropriately pool the heterogeneous proximal humerus fracture literature. Substantial diversity in treatment options and the quality of comparative trials is well known in the management of these fractures, and failure to account for this heterogeneity may lead to incorrect conclusions or biased effect size estimates. In addition, further efforts to systematically assess the individual studies included in pooled analysis are necessary to protect the validity of conclusions and facilitate interpretation of the statistical results. To date, no previous proximal humerus fracture reviews have incorporated the Grading of Recommendations Assessment, Development, and Evaluation (GRADE) to summarize evidence[13].

This systematic review and meta-analysis aimed to overcome the limitations of previous pooled analyses and determine whether operative treatment of displaced three- and four-part proximal humerus fractures in elderly patients improves physical function, pain, health related quality of life, mortality, complications and re-operation rate in comparison to non-operative treatment.

MATERIALS AND METHODS

This review was conducted according to the Cochrane Handbook and is reported according to the Preferred Reporting Items for Systematic Reviews and Meta-Analysis guidelines[14,15].

Eligibility criteria for study selection

All randomized controlled trials that compared at least one operative intervention to a non-operative intervention for management of three- or four-part fractures of the proximal humerus in elderly patients were eligible for inclusion in this review. We excluded retrospective and prospective observational studies, case-reports, case-series, and reviews and studies including nondisplaced fractures or two part fractures. There was no restriction on the type of surgical technique or the non-operative treatment. We did not apply language or publication restrictions[16].

Identification of studies

The following electronic databases were searched for articles published up to February 20th, 2014: EMBASE and MEDLINE through the OVID interface, CINAHL, the Cochrane Central Register of Controlled Trials

(CENTRAL), Proquest, Web of Science, SAE digital library, and Transportation Research Board's TRID database. Combination of keywords and MeSH terms related to proximal humeral fractures were used and no language restrictions were applied (Appendix 1). The WHO International Clinical Trials Registry Platform Search Portal and Current Controlled Trials were searched to identify current and ongoing trials.

We also searched conference proceedings archives for the Canadian Orthopaedic Association, American Academy of Orthopaedic Surgeons, and Orthopaedic Trauma Association for the past seven years. We further conducted hand searches of the major orthopaedic journals in the *Journal of Bone and Joint Surgery* (American and British volumes) and Journal of Shoulder and Elbow Surgery for the same time frame. Reference list of eligible articles were searched to identify any relevant trials.

Assessment of eligibility and methodological quality

Two reviewers conducted title and abstract screening independently and disagreements were resolved by consensus through discussion between the two reviewers. Both reviewers also independently assessed the studies for final eligibility based on full text screening.

The two reviewers independently assessed the studies for risk of bias using the Cochrane Collaboration's Risk of Bias Tool[14]. Developed by Cochrane, this quality assessment tool is designed to report the adequacy of patient allocation, allocation concealment, blinding, clarity of outcome data, the potential for selective outcome reporting, and any other sources of bias for each study included in a systematic review. One reviewer used the GRADE system to assess each outcome measure identified in this review and a second reviewer verified the assessments. When used in the context of a systematic review, the GRADE system is designed to rank the overall quality of included studies for a given outcome from "strong" to "weak" evidence[13]. Data from randomized controlled trials is inherently considered high quality or "strong". Five limitations that can downgrade the quality include study limitations, inconsistency of results, indirectness of evidence, imprecision, and publication bias[13]. Moderate, low or very low quality evidence can be upgraded if there is a large magnitude of effect, a dose-response gradient, or if all plausible biases would not undermine the conclusions[13]. Rater differences in the assessment were discussed and resolved by consensus.

Data abstraction

A data abstraction form was developed and piloted. The following data was abstracted from each included trial: funding source, diagnostic classification system, mean age, gender, sample size, intervention methods, study duration, length of follow-up, physical function, pain, health related quality of life, mortality, and complication and re-operation rates. Outcome measurements within the first 6 mo after the intervention were considered short term and measurements beyond 12 mo were considered long term. One reviewer independently completed data abstraction for each of the included trials and the second reviewer verified the data abstraction.

Statistical analysis

Inter-observer differences for study eligibility and risk of bias assessment were measured using Cohen's kappa statistic[17,18]. The following criteria for the kappa values were set a priori: 0.40 to 0.59 reflects fair agreement, 0.60 to 0.75 reflects good agreement, and 0.75 and higher reflects excellent agreement[14,19].

Function, pain, and health related quality of life were summarized using mean differences (MDs) or standardized mean differences when different instruments were used, and were weighted according to the inverse variance method[20,21]. Missing SDs were derived from CIs and P values[22,23]. Mortality and re-operation rate were summarized using risk ratios calculated using the Mantel-Haenszel method[14]. All comparisons were made for surgical fixation vs non-operative management; therefore, positive pooled estimates represent higher outcomes in the operative group. All tests for statistical significance were two tailed, and a P value of 0.05 or less was considered significant.

Heterogeneity was measured using the I^2 statistic[14]. Surgical technique was defined as an a priori subgroup hypothesis to explain potential heterogeneity. Sensitivity analyses were conducted to test the effect of excluding outdated surgical methods, and to compare open reduction and internal fixation (ORIF) trials or hemiarthroplasty trials alone. Publication bias was assessed by generating a funnel plot for studies measuring longterm function[14]. Outcomes were pooled using the fixedeffects model and if heterogeneity exceeded 40%, the random-effects model was used. Funnel plot and forest plots were generated using Review Manger 5.2.

RESULTS

Study selection

Our literature search identified 6473 titles for consideration for inclusion in this review. Agreement between reviewers for title and abstract eligibility was excellent (kappa= 1.0). Fourteen full-text articles were assessed for eligibility. Six randomized controlled trials (n = 287) met the eligibility criteria and are included in this review (Figure 1).

Study characteristics

All included trials were published between 1984 and 2012 (Table 1)[24-29]. All of the trials were conducted in Europe across four countries (Sweden, Norway, the Netherlands, and the United Kingdom). Three of the studies were government funded, one study was funded by industry, and two studies did not disclose a funding source.
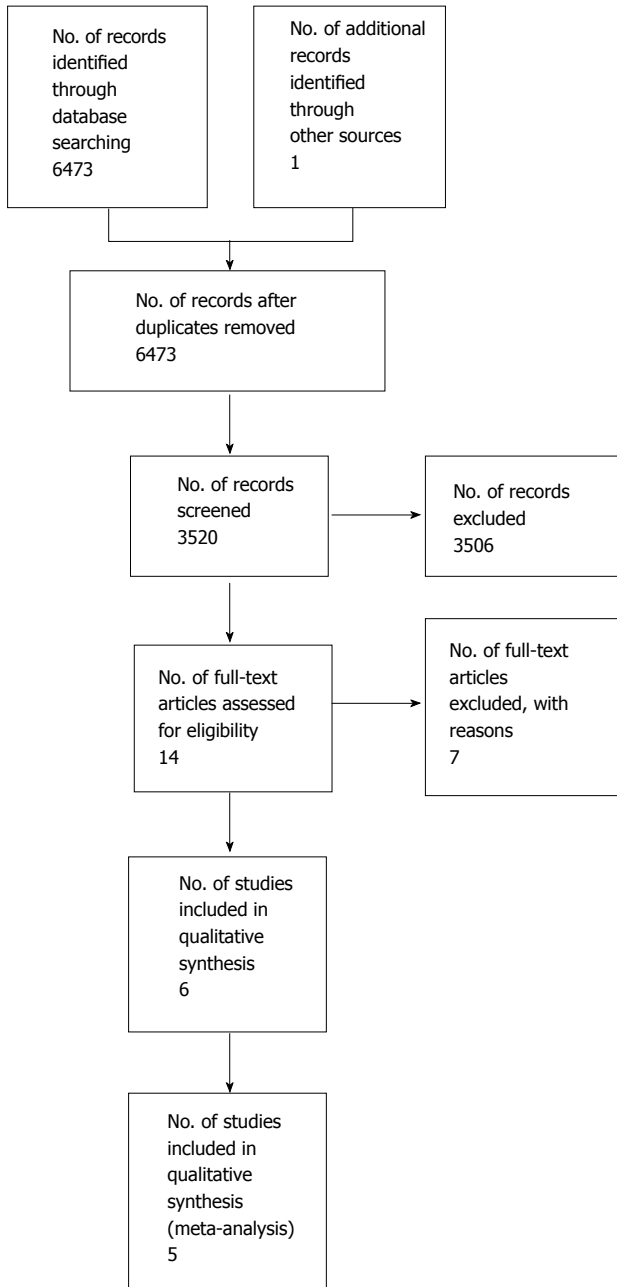
Figure 1 Study flowchart.

Figure 2 Risk of bias summary.

a Visual Analog Scale in one trial.

Risk of bias

Four of the included trials had inadequate or unclear random sequence generation and allocation concealment was inadequate or unclear in two studies (Figure 2). Blinding of patients and outcome assessor bias was high in all studies. Agreement between the two reviewers for the risk of bias assessment was good (kappa = 0.635). The funnel plot is fairly symmetric; however, due to the low number of yielded studies, it is inefficient to clearly assess publication bias (Figure 3).

Functional outcome

Short term physical function was measured by the Constant score in three of the included trials (n = 156). The pooled estimate did not demonstrate any difference (MD = -2.79, 95%CI: -8.66 to 3.09, P = 0.35, I^2 = 42%). Long term physical function measured by the Constant score was measured in five of the included trials (n = 228). The pooled estimate did not demonstrate any difference (MD = 1.63, 95%CI: 2.90, to 6.34, P = 0.47, I^2 = 0%) (Figure 4A). The findings were robust to sensitivity analysis that tested the effect of excluding outdated surgical techniques (MD = 2.78, 95%CI: -2.20 to 7.75, P = 0.27, I^2 = 0%), and they were robust in subgroup analyses that included either ORIF trials alone (MD = 3.25, 95%CI: -4.61 to 11.11, P = 0.42, I^2 = 0%), or hemi-arthroplasty trials alone (MD = 2.46, 95%CI: -3.96 to 8.88, P = 0.45, I^2 = 0%).

Trial sample sizes ranged from 32 to 60 patients. All trials included patients over the age of 52 years and the mean ages ranged from 67.9 to 79.9 years. Fracture type was either classified by Neer's classification (five trials), or OTA (one trial). The operative treatments included: Hemi-arthroplasty, ORIF with locking plate and cerclage wires, ORIF with a locking plate, and ORIF with tension band technique and Neer's prosthesis. Non-operative treatment consisted of immobilization of the shoulder in all trials. Five trials reported short term and long term physical function measured by the Constant score (n = 228). Three trials reported health related quality of life, all six trials reported complications (mortality and re-operation), and pain was reported as a component of the Constant score in four trials and as

Table 1 Characteristics chart of included studies

Ref.	Year	Country	Funding	Size	Age (mean)	Male (%)	Fracture classification system	Fracture type	Operative intervention	Non-operative intervention	Short term follow-up (mo)	Long term follow-up (mo)
Boons *et al*[24]	2012	The Netherlands	Industry funding	50	79.9	2	Neer	3 or 4 part fractures	Hemiar-throplasty	Immobilization of the shoulder	3	12
Fjalestad *et al*[9,25]	2010	Norway	Government funding	50	72.7[1]	12	OTA	3 or 4 part fractures	ORIF with locking plate	Immobilization in a modified Velpeau bandage	3	12
Olerud *et al*[26]	2011	Sweden	Government funding	55	76.7[1]	14.5	Neer	4 part fractures	Hemiar-throplasty	Immobilization by slings	4	12
Olerud *et al*[27]	2011	Sweden	Government funding	59	73.9[1]	18.6	Neer	3 part fractures	ORIF-locking plate	Immobilization by slings	4	12
Stableforth[28]	1984	England	Not reported	32	67.9[1]	21.9	Neer	4 part fractures	Neer prosthesis	Closed manipulation	Not applicable	Not applicable
Zyto *et al*[29]	1997	Sweden	Not reported	40	74	12.5	Neer	3 or 4 part fractures	ORIF-tension band technique	Immobilization by sling	No short term follow-up	50

[1]Average weighted mean of the two arms. ORIF: Open reduction and internal fixation.
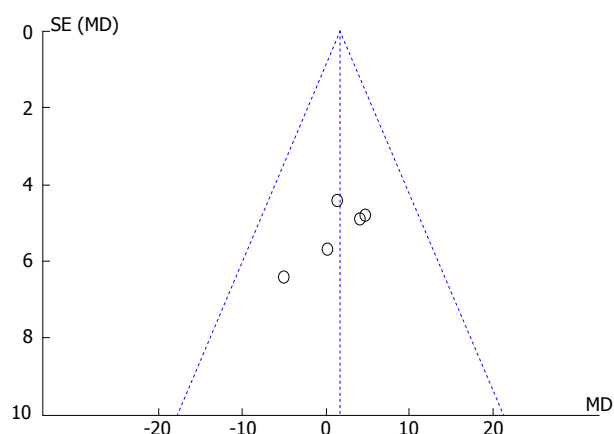
Figure 3 Funnel plot.

Pain

Pain was measured as an individual outcome in one of the studies using the Visual Analog Scale and, was measured as a component of the Constant score in five studies. The short term pooled estimate for the Constant pain score did not demonstrate any difference (MD = 0.77, 95%CI: -0.63 to 2.16, P = 0.28, I^2 = 42%). The long-term pooled estimate was statistically significant and pain was lower in the operative group (MD = 1.26, 95%CI: 0.02 to 2.49, P = 0.05, I^2 = 51%) (Figure 4B). However, pain was not statistically significant when sensitivity analysis was conducted that tested the effect of excluding outdated surgical techniques (MD = 1.10, 95%CI: -0.39 to 2.59, P = 0.15, I^2 = 61%), and no difference was found in subgroup analyses that included either ORIF trials alone (MD = 0.37, 95%CI: −1.49 to 2.23, P = 0.70, I^2 = 51%), or hemi-arthroplasty trials alone (MD = 1.84, 95%CI: -0.51 to 4.19, P = 0.08, I^2 = 67%).

Health related quality of life

Health related quality of life was reported in three of the included trials (two studies used the EQ-5D and one study used the 15D instrument). The short and long term pooled estimates did not demonstrate any difference (SMD = 0.26, 95%CI: -0.06-0.57, P = 0.11, I^2 = 0% and SMD = 0.27, 95%CI: -0.05-0.59, P = 0.09, I^2 = 0%, respectively).

Complications and re-operations

The pooled estimate of mortality did not demonstrate any difference [relative risk (RR) 1.29, 95%CI: 0.50 to 3.35, P = 0.60, I^2 = 0%] (Figure 5A). The re-operation rate was reported in five studies and was significantly higher in the operative group (RR 4.09, 95%CI: 1.50-11.15, P = 0.006, I^2 = 0%) (Figure 5B). The rates of infection (RR 4.43, 95%CI: 0.78-25.18, P = 0.08, I^2 = 0%), avascular necrosis (RR 0.63, 95%CI: 0.35-1.14, P = 0.13, I^2 = 0%), nonunion (RR 0.45, 95%CI: 0.14-1.43, P = 0.18, I^2 = 0%), and post-traumatic osteoarthritis (RR 0.60, 95%CI: 0.22-1.64, P = 0.32, I^2 = 36%) did not differ significantly between the operative and non-operative treatment groups (Table 2).

GRADE quality assessment

Physical function as measured by the Constant score, long term health related quality of life, and mortality were deemed to be of moderate quality by the GRADE quality system due to the risks of bias associated with the trial design and conduct (Table 3). This finding indicates that further research is likely to have an important impact on our confidence in the estimate of effect and may change the estimate. Long term pain and re-operation received a low quality score which indicates that further research is very likely to have an

A

Study or subgroup	Operative			Non-operative			Weight	Mean difference IV, fixed, 95%CI
	Mean	SD	Total	Mean	SD	Total		
Boons *et al*[24]	64	15.8	24	60	17.6	23	21.8%	4.00 [-5.58, 13.58]
Fjalestad *et al*[9,25]	52.3	20.8125	23	52.2	18.4118	25	16.1%	0.10 [-11.06, 11.26]
Olerud[a] *et al*[26]	48.9	14.6	26	47.7	16.8	25	26.7%	1.20 [-7.45, 9.85]
Olerud[b] *et al*[27]	61.5	18.4	27	56.8	16.8	27	22.6%	4.70 [-4.70, 14.10]
Zyto *et al*[29]	60	19	14	65	15	15	12.8%	-5.00 [-17.52, 7.52]
Total (95%CI)			114			115	100.0%	1.63 [-2.84, 6.11]

Heterogeneity: $\chi^2 = 1.80$, df = 4 ($P = 0.77$); $I^2 = 0\%$
Test for overall effect: Z = 0.72 ($P = 0.47$)

B

Study or subgroup	Operative			Non-operative			Weight	Mean difference IV, fixed, 95%CI
	Mean	SD	Total	Mean	SD	Total		
Boons *et al*[24]	10	5	24	12	3	23	17.3%	-2.00 [-4.35, 0.35]
Fjalestad *et al*[9,25]	11.9	3.2	23	10.6	3.5	25	21.6%	1.30 [-0.60, 3.20]
Olerud[a] *et al*[26]	11.2	3.3	26	10.6	3.9	25	20.7%	0.60 [-1.39, 2.59]
Olerud[b] *et al*[27]	11.1	3.25	27	11.7	3.55	27	22.5%	-0.60 [-2.42, 1.22]
Zyto *et al*[29]	12	2.6	14	10	3.6	15	17.9%	2.00 [-0.27, 4.27]
Total (95%CI)			114			115	100.0%	0.28 [-1.01, 1.57]

Heterogeneity: Tau^2 = 1.07; $\chi^2 = 7.49$, df = 4 ($P = 0.09$); $I^2 = 50\%$
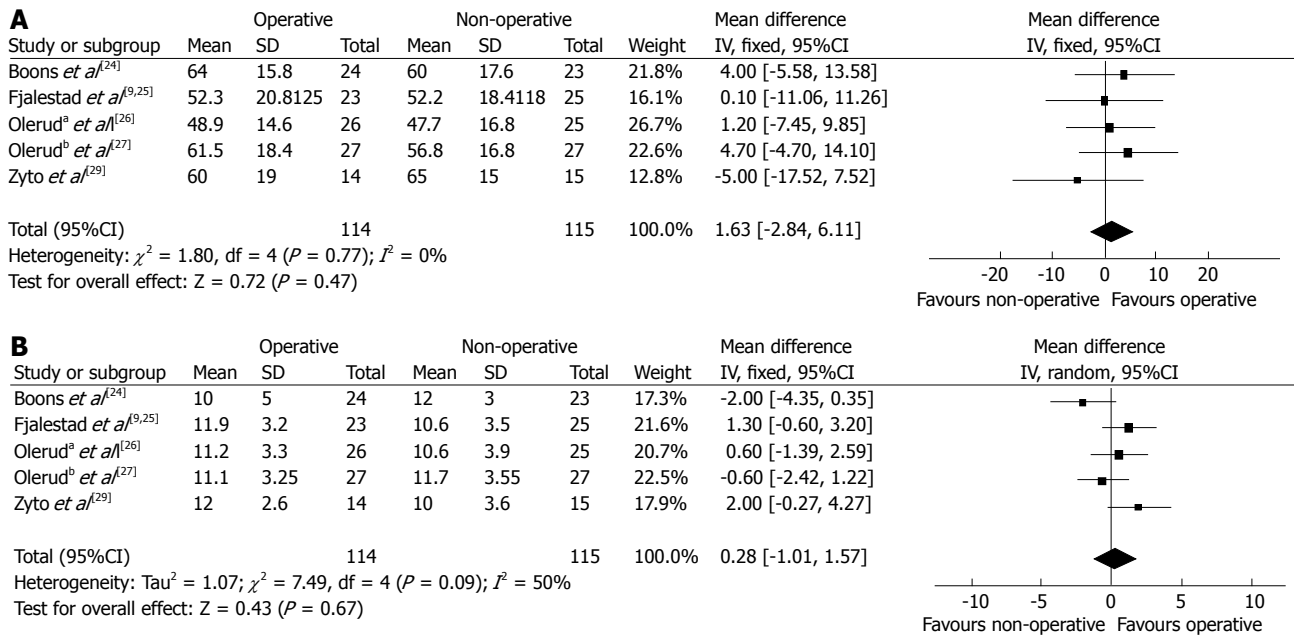Test for overall effect: Z = 0.43 ($P = 0.67$)

Figure 4 Pooled estimate of physical function according to the Constant score at a minimum of one year follow-up (A) and pain according to the Constant score component at a minimum of one year follow-up (B).
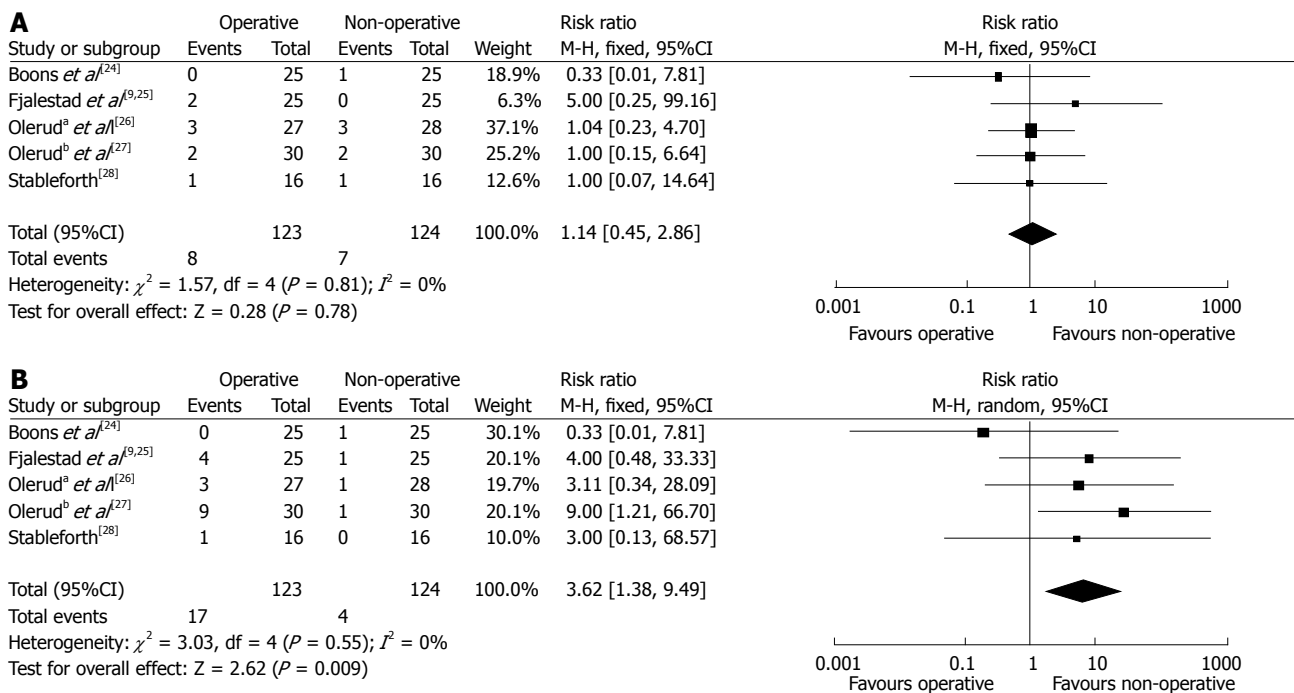
A

Study or subgroup	Operative		Non-operative		Weight	Risk ratio M-H, fixed, 95%CI
	Events	Total	Events	Total		
Boons *et al*[24]	0	25	1	25	18.9%	0.33 [0.01, 7.81]
Fjalestad *et al*[9,25]	2	25	0	25	6.3%	5.00 [0.25, 99.16]
Olerud[a] *et al*[26]	3	27	3	28	37.1%	1.04 [0.23, 4.70]
Olerud[b] *et al*[27]	2	30	2	30	25.2%	1.00 [0.15, 6.64]
Stableforth[28]	1	16	1	16	12.6%	1.00 [0.07, 14.64]
Total (95%CI)		123		124	100.0%	1.14 [0.45, 2.86]
Total events	8		7			

Heterogeneity: $\chi^2 = 1.57$, df = 4 ($P = 0.81$); $I^2 = 0\%$
Test for overall effect: Z = 0.28 ($P = 0.78$)

B

Study or subgroup	Operative		Non-operative		Weight	Risk ratio M-H, fixed, 95%CI
	Events	Total	Events	Total		
Boons *et al*[24]	0	25	1	25	30.1%	0.33 [0.01, 7.81]
Fjalestad *et al*[9,25]	4	25	1	25	20.1%	4.00 [0.48, 33.33]
Olerud[a] *et al*[26]	3	27	1	28	19.7%	3.11 [0.34, 28.09]
Olerud[b] *et al*[27]	9	30	1	30	20.1%	9.00 [1.21, 66.70]
Stableforth[28]	1	16	0	16	10.0%	3.00 [0.13, 68.57]
Total (95%CI)		123		124	100.0%	3.62 [1.38, 9.49]
Total events	17		4			

Heterogeneity: $\chi^2 = 3.03$, df = 4 ($P = 0.55$); $I^2 = 0\%$
Test for overall effect: Z = 2.62 ($P = 0.009$)

Figure 5 Pooled estimate of mortality rate (A) and re-operation rate (B).

important impact on our confidence in the estimate of effect and is likely to change the estimate.

Sensitivity analyses

Two of the included trials used older implants that are no longer commonly used in clinical practice[28,29]. To ensure the stability of our pooled results, we conducted a sensitivity analysis that excluded data from these two studies, but found that there was no change in our meta-analysis conclusions as described above.

DISCUSSION

This systematic review and meta-analysis compared operative treatment *vs* non-operative treatment of three- and four-part proximal humeral fractures in elderly patients. According to the GRADE system, the evaluation of physical function constituted moderate quality evidence. We did not find a significant difference in physical function between the operative and non-operative treatment for both the short term and long

Table 2 Complications chart

Ref.	Operative					Non-operative				
	Infection	Avascular necrosis	Nonunion	Nerve injury	Post-traumatic osteoarthritis	Infection	Avascular necrosis	Nonunion	Nerve injury	Post-traumatic osteoarthritis
Boons *et al*[24]	0	0	0	NR	NR	0	2	3	NR	NR
Fjalestad *et al*[9,25]	0	8	0	7	NR	0	13	2	6	NR
Olerud *et al*[26]	0	0	0	0	0	0	3	1	0	5
Olerud *et al*[27]	2	3	1	0	3	0	2	1	1	2
Stableforth[28]	1	NR	NR	NR	NR	0	NR	NR	NR	NR
Zyto *et al*[29]	2	1	1	NR	2	0	0	0	NR	2
Total	5	12	2	7	5	0	20	7	7	9

NR: Not reported.

Table 3 Grading of Recommendations Assessment, Development, and Evaluation summary findings: Operative *vs* non-operative treatment in proximal humeral fractures

Outcomes	No. of Participants (studies) Follow up	Quality of the evidence (GRADE)	Relative effect (95%CI)	Anticipated absolute effects	
					Risk difference between non-operative and operative[1] (95%CI)
Physical Function by Constant score - long term	229 (5 studies)	Moderate due to risk of bias			The mean physical function by constant score-long term in the intervention group was 1.63 higher (2.84 lower to 6.11 higher)
Health Related Quality of Life - long term	154 (3 studies)	Moderate due to risk of bias			The mean health related quality of life - long term in the intervention group was 0.23 standard deviations higher (0.09 lower to 0.54 higher)
Constant pain - long term	229 (5 studies)	Low due to risk of bias, inconsistency			The mean Constant pain - long term in the intervention group was 0.28 higher (1.01 lower to 1.57 higher)
Mortality rate	247 (5 studies)	Moderate due to risk of bias	RR 1.14 (0.45 to 2.86)	Study population 56 per 1000	8 more per 1000 (from 31 fewer to 105 more)
				Moderate 63 per 1000	9 more per 1000 (from 35 fewer to 117 more)
Re-operation Rate	247 (5 studies)	Low due to risk of bias, imprecision	RR 3.62 (1.38 to 9.49)	Study population 32 per 1000	85 more per 1000 (from 12 more to 274 more)
				Moderate 36 per 1000	94 more per 1000 (from 14 more to 306 more)

[1]The basis for the assumed risk (*e.g.* the median control group risk across studies) is provided in footnotes. The corresponding risk (and its 95% confidence interval) is based on the assumed risk in the comparison group and the relative effect of the intervention (and its 95%CI). RR: Risk ratio; GRADE Working Group grades of evidence: High quality: Further research is very unlikely to change our confidence in the estimate of effect; Moderate quality: Further research is likely to have an important impact on our confidence in the estimate of effect and may change the estimate; Low quality: Further research is very likely to have an important impact on our confidence in the estimate of effect and is likely to change the estimate; Very low quality: We are very uncertain about the estimate.

term follow-up periods. The outcome of pain was limited by low quality of evidence, although we found a significant difference in the long term period in favor of the operative group. Health related quality of life was ranked as moderate quality of evidence and there was no statistically significant difference in the short and long term health related quality of life between the two treatment groups. Mortality comparison was of moderate quality evidence and showed no statistically significant difference. Re-operation rate was limited by low quality of evidence and we found a statistically significant difference in the re-operation rate in favour of the non-operative group.

Strengths and limitations
Overall, the results of this study must be interpreted in the context of the primary studies' design. This meta-analysis included randomized controlled trials with methodological limitations and consequently a high risk of bias. These limitations include small

sample sizes, inadequate blinding, and poor reporting of randomization technique. Blinding is not always possible in trials comparing surgical *vs* non-operative management. Strategies to mitigate this limitation could have been implemented including blinded adjudication of outcomes and a blinded analysis and interpretation of the data. In an attempt to further minimize bias, we did not include observational studies in this review. Their inclusion may have increased the overall sample size, but may have also introduced a higher level of bias due to their non-randomized designs.

The six trials included in this review did not report on all relevant outcomes. For example, the trials did not report on the cost-effectiveness of operative *vs* non-operative management, which is an important consideration. Pain was also poorly reported, with only one study reporting pain as an individual outcome measure as opposed to a component of the Constant score.

The trials were conducted in four different countries within Europe which may limit the generalizability of the findings beyond this region. It is also important to recognize that differences in surgical practice, technique, and management exist across the trials which may skew the overall results due to expertise bias. In addition, two of the included trials used older implants that are no longer commonly used in clinical practice[28,29]; however, our sensitivity analyses showed that the results remained robust with the inclusion of these two trials.

Despite these limitations, our meta-analysis is strengthened by its systematic approach, pre-defined and broad eligibility criteria, our duplicated data abstraction methods, and the use of the GRADE quality assessment system. The GRADE system was developed by a widely representative group of international guideline developers to offer a comprehensive grading system that can separate decisions regarding the quality of evidence from the strength of recommendations; where high quality evidence does not always result in strong recommendations. Additional advantages of GRADE over other systems include explicit evaluation of the importance of outcomes of alternative management strategies; explicit, comprehensive criteria for downgrading and upgrading quality of evidence ratings; a transparent process of moving from evidence to recommendations; the acknowledgement of values and preferences of the population under study and/or for which guidelines are being developed; clear, pragmatic interpretations of strong *vs* weak recommendations for clinicians, patients, and policy makers; and is useful for systematic reviews, health technology, and guideline assessments.

There is a lack of high quality evidence to determine the effects of operative *vs* non-operative treatment on patient-important outcomes among elderly patients with three- or four-part proximal humeral fractures. There is moderate quality evidence to suggest that there is no difference in functional outcomes between the two treatments. Further high quality trials are warranted to determine if operative treatment in elderly patients with three- and four-part fractures is the optimal method of managing these complex fractures.

COMMENTS

Background
Proximal humerus fractures are associated with a substantial burden of disability and impaired quality of life. Most proximal humeral fractures are nondisplaced or minimally displaced and are usually treated successfully non-operatively, but the optimum treatment becomes less clear in more complex, displaced fracture patterns.

Research frontiers
Optimal treatment of displaced proximal humerus fractures in elderly patients remains controversial, and an evidence-based approach is critical to improve patient outcomes and allocate limited health care resources.

Innovations and breakthroughs
In the present study, the authors investigated the outcomes of operative *vs* non-operative treatment of displaced proximal humerus fractures in elderly patient by pooling results from six randomized controlled trials. This is the first report of a meta-analysis comparing the effects of operative *vs* non-operative treatment on patient-important outcomes among elderly patients with three- or four-part proximal humeral fractures.

Applications
There is moderate quality evidence to suggest that there is no difference in functional outcomes between operative *vs* non-operative treatment of displaced proximal humerus fractures in elderly patients.

Peer-review
Very well put together paper and review.

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CASE REPORT

"Push back" technique: A simple method to remove broken drill bit from the proximal femur

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Institutional review board statement: This study was approved by the Orthopedics Departmental Review Board, Postgraduate Institute of Medical Education and Research.

Informed consent statement: The patient gave their informed consent to take part in the study.

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Abstract

Broken drill bits can be difficult to remove from the proximal femur and may necessitate additional surgical exploration or special instrumentation. We present a simple technique to remove a broken drill bit that does not require any special instrumentation and can be accomplished through the existing incision. This technique is useful for those cases where the length of the broken drill bit is greater than the diameter of the bone.

Key words: Broken drill bit; Interlocking nail; Femoral fracture; Surgical technique

Core tip: Drill bits can break during locking in femoral intramedullary nailing. In this article, the authors describe an innovative yet simple technique to remove a broken drill bit from the proximal femur.
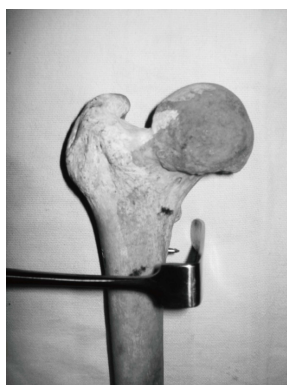
INTRODUCTION

Locked intramedullary nailing of the femur is widely used to treat fractures of the shaft of femur. Drill bit breakage is one of the most commonly encountered hardware breakage problems[1] and may occur during proximal or distal locking. The presence of muscle bulk and the femoral neurovascular bundle make drill bit retrieval from the proximal femur difficult. We present a simple method to remove a broken drill bit from the proximal locking hole.

CASE REPORT

The stab incision for the proximal locking hole is

Figure 1 Langenbeck retractor is inserted with its blade tip facing proximally and advanced well beyond the medial cortex of femur (in this example a 15 mm × 45 mm retractor is shown, in clinical practice a 10 mm x 30 mm or smaller retractor is preferable).
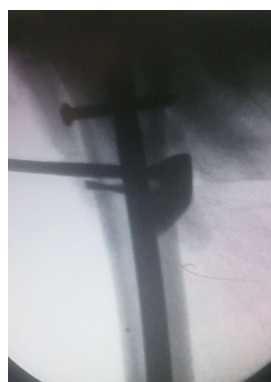

Figure 2 Retractor blade is rotated by 90°.

Figure 3 Drill bit is pushed back by the blade of the retractor.

Figure 4 Image intensifier view of the technique.

extended by 2 cm both proximally and distally. Dissection proceeds down to the proximal femur after splitting the vastus lateralis muscle and the drill hole is identified. Maintaining a strictly sub-periosteal plane, the vastus intermedius and medialis origin is lifted subperiosteally and two curved Hohmann retractors are introduced to aid in retraction. Next, a right angled narrow blade Langenbeck retractor (10 mm blade width, 30 mm blade length) is inserted through the incision with its blade tip facing proximally. A retractor with a smaller blade (6 mm blade width, 20 mm blade length) may be used if the surgeon encounters difficulty in introducing the 10 mm × 30 mm blade retractor. Care is taken to ensure that the shaft of the retractor is flush with the anterior cortex of femur. The blade is advanced well beyond the medial cortex of femur and this is confirmed on the image intensifier in the antero-posterior view (Figure 1). Next, the blade is rotated by 90 degrees so that its blade tip faces posteriorly and the broken drill bit lies in the center of the retractor's blade (Figure 2). Once the correct position has been verified on the image intensifier, the blade of the retractor is pushed towards the medial cortex of femur and on to the penetrating drill bit. This "pushes back" the drill bit into the drill hole and out through the lateral entry hole from where it can be retrieved under direct vision

(Figure 3).

A 34-year-old male with mid - diaphyseal, comm-inuted shaft femur fracture was taken up for locked intramedullary nailing (Simplified Universal Nail, Synthes, Paoli). The drill bit broke while statically locking the screw hole. On image intensifier examination, it was found the broken end of the drill bit was protruding from the medial cortex of the femur. The drill bit was removed using the "push back" technique (Figure 4).

DISCUSSION

Broken drill bits protruding through the far cortex of a drill hole can be difficult to retrieve from the proximal femur. The usual method in other locations is to make an incision on the far side, dissect the soft tissues and retrieve the drill bit under direct vision or to push the bit out through the opposite side by inserting K wires[2] or new screws[3]. However, this method may be difficult to perform in the proximal femur as the large bulk of the adductor compartment necessitates a longer skin incision and a lot of soft tissue dissection. Also of concern is the femoral neurovascular bundle that courses within the adductor canal and may be inadvertently injured during dissection.

We believe that our method is a safe alternative to retrieve broken drill bits in such situations. It can be easily adapted for the distal femur as well. Also, it is

important to use a narrow blade Langenbeck retractor since the iliopsoas tendon and the periosteum may make placements of larger retractors difficult. The only time this method would not work is when the length of the broken drill bit is quite small and it is retained entirely within the medullary canal of the proximal femur. In such cases, the surgeon may need to fish out the drill bit through a small cortical window in the lateral or the medial cortex. Alternatively, the technique described by Matthews *et al*[4] may be useful.

Fortunately, such occurrences are rare and in the authors' experience, the broken drill bit is invariably longer than the diameter of the medullary canal.

To conclude, we believe that the "push back" technique may be an effective and safe alternative to retrieve broken drill bits from the proximal femur if the length of the drill bit is greater than the diameter of the femur and the method may be adapted to other sites as well.

COMMENTS

Case characteristics
A 34-year-old male presented with injury to right thigh after road traffic accident.

Clinical diagnosis
Fracture shaft of femur.

Imaging diagnosis
Comminuted mid-diaphyseal fracture of the femoral shaft.

Treatment
Statically locked femoral intramedullary nailing (Simplified Universal Nail, Synthes).

Experiences and lessons
Drill bit breakage is a frequent occurrence in orthopedic surgery and the surgeon must be prepared to handle it; the push-back technique can be a valuable alternative in some cases.

Peer-review
This case report paper presents an alternative technique for removing broken drill bits from the proximal (or distal) femur.

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