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Shortening Subtrochanteric Osteotomy and Cup Placement at True Acetabulum in Total Hip Arthroplasty of Crowe III– IV Developmental Dysplasia: Results of Midterm Follow-up

Alireza Manafi Rasi[1], Gholamhossein Kazemian[1], Mohammad Khak[1], Reza Zarei[2]

Abstract

Introduction: The anatomic abnormalities in developmental dysplasia of hip (DDH) often make total hip replacement (THR) inevitable at a younger age. However, there is no universal gold standard technique of THR for high dislocated dysplastic hips.

Materials and Methods: Here we present the outcomes of midterm follow-up after THR in patients diagnosed with DDH Crowe type III and IV hospitalized in a tertiary center in Iran for whom placement of a cup in true acetabulum and selective transverse subtrochanteric osteotomy was performed. Pre- and postoperative Harris Hip Score, leg length discrepancy and postoperative complications were evaluated.

Results: A total of 48 patients with DDH Crowe type III and IV (uni- or bilateral which made 52 hips) were studied. Mean age of patients was 41 years with minimum follow-up ranging from 12 months to 3 years. Mean Harris Hip Score significantly improved from 41.70 preoperatively to 88.1 at last follow-up postoperatively. Leg length discrepancy of less than 2 cm was observed which was well tolerated using shoe lifts. Regarding postoperative complications, two patients had transient peroneal nerve palsy in early postoperative period which recovered within 2 months. No other major complication was encountered.

Conclusion: THR in patients with DDH (Crowe III and IV) with a cup positioned in true acetabulum and transverse subtrochanteric osteotomy is a safe successful procedure.

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Keywords Developmental dysplasia of hip, Total hip replacement, True acetabulum, Subtrochanteric osteotomy, Cotyloplasty

Introduction

Developmental dysplasia of hip (DDH) is labeled as one of the utmost widespread developmental illnesses diagnosed among children leading to secondary osteoarthritis of the hip joint [1, 2]. This states a spectrum of developmental abnormalities which hamper the growing hip and leads to altered anatomy of the acetabulum and proximal femur [3]. Dysplastic hips have one single pathophysiological feature in common; i.e., the anatomic abnormalities raise the contact stress leading to osteoarthritis [4]. Hence, this severe osteoarthritis secondary to DDH often makes total hip replacement (THR) inevitable at a younger age [5, 6]. Although the pathology at the acetabular side of the joint is more prominent, the femoral head may be deformed and high riding with hypoplastic proximal femur.

However, there is no universal gold standard technique of THR for high dislocated dysplastic hips and treatment of each patient should be individualized. Due to some certain characteristics of these patients such as young age as well as anatomic abnormalities of the hip, the complication rate after THR in DDH patients is higher than normal population [2-6]. The new center of hip rotation after cup placement alters hip biomechanics, leg length and femoral reconstruction. Hence, in order to achieve successful acetabular reconstruction during THR in DDH patients, knowing the position of acetabulum is mandatory. Purpose of acetabulum reconstruction is insertion of acetabular component in the true acetabulum for its biomechanical advantages. Crowe classification is the most frequent way of categorizing hip dysplasia [7] (Table 1).

Once we are set to select one appropriate treatment model for reconstruction of acetabulum, we are required to bring pros and cons as well as the rate of bone deformity involved to a meticulous consideration. Pros of biomechanical and practical reconstruction of acetabulum and cons of the urgent need for sufficient coverage of implant in acetabulum must be balanced out. Shallow socket with bone deficiency at anterior, lateral and superior aspects of acetabulum is considered as one of vital changes in dysplastic hips. In dislocated hips, the femoral head articulates with iliac bone and results in false acetabulum formation. Force vector direction of abductor muscles that is usually vertical changes to horizontal, and they become shorten and contracted. Despite the advanced methods and the available implants, THR in Crowe grade III and IV DDH is a challenging surgery. The most important part of the treatment is selection of the right technique. Unfortunately, there is no consensus on surgical planning in these patients. The success of operation hangs on the severity of illness.

However, in this study the outcome of 12- 36-month long follow-up after THR in patients diagnosed with DDH Crowe type III and IV hospitalized in a tertiary center in Iran over 2013–2015 in whom placement of a cup in true acetabulum and selective transverse subtrochanteric osteotomy was performed is presented.

Table 1: Crowe classification of adult developmental dysplasia of the hip according to the extent of the underlying subluxation on AP X-ray of the pelvis [7].

Crowe grade	Dislocation	Description
Grade 1	< 50% subluxation	Femur and acetabulum show minimal abnormal development
Grade 2	50–70% subluxation	The acetabulum shows abnormal development, femoral head articulates with false acetabulum, which partially covers the true acetabulum
Grade 3	70–100% subluxation	The acetabulum is developed without a roof
Grade 4	> 100% subluxation (luxation)	The acetabulum is deficient but remains recognizable

Materials and Methods

Study protocol was in accordance with the Declaration of Helsinki for human research and approved by Shahid Beheshti University of Medical Sciences Ethic committee; informed consent was obtained from the patients. In this study, 48 patients with DDH Crowe type III and IV (uni- or bilateral which made 52 hips) who underwent THR between May 2013 and April 2015 in a tertiary referral center in Iran were studied. THR indications included severe pain or functional impairment with difficulty in performing daily living activity and walking (or both). All patients were evaluated clinically and radiographically before surgery. For each cases, according to Harris Hip Score [8] pain and grade of disability were assessed in terms of limitation of hip range of motion, limb length discrepancy and restriction on walking and in doing daily activities. Preoperative shortening was radiographically measured between tear drop on pelvis and lesser trochanter on femur. The patients were followed up clinically and radiographically at 2 weeks, 3, 6 and 12 months after surgery and yearly thereafter.

All the surgeries were conducted by a single surgeon (AMR) in lateral position using Harding approach. Soft tissue dissection is conducted carefully keeping in mind that neurovascular bundle may not be present at normal anatomic place. During the surgery, gluteus minimus is released from the top of anterior tuberosity. The femoral neck is resected at around 1 cm proximal to lesser trochanter. Pushing down toward capsule and by direct palpation, the correct position of the true acetabulum is located. Although the precise position of acetabular component is well determined in preoperative radiographs, the whole process of finding the true acetabulum is monitored by image intensifier (Fig. 1). After sufficient soft tissue dissection, the acetabulum is deepened and enlarged gradually with serial reaming. The first ream is done in a posterior-directed fashion with reamer size 36. Cotyloplasty (medialization of the anatomic joint) is also carried out. Then, we keep reaming at the desired angle of abduction and anteversion till anterior and posterior wall appear in order to fix a cementless component with two to three screws. It is reamed to size 39–40,

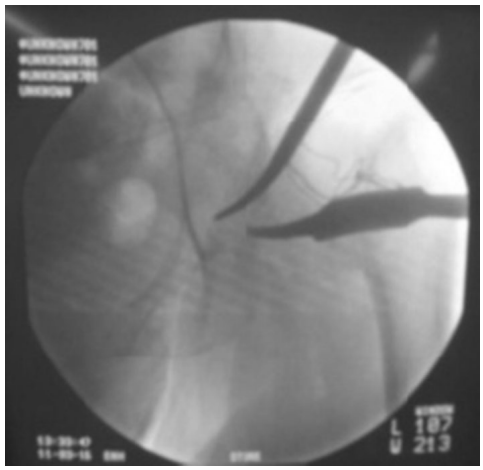

Fig. 1: Localizing true acetabulum with the help of image intensifier.

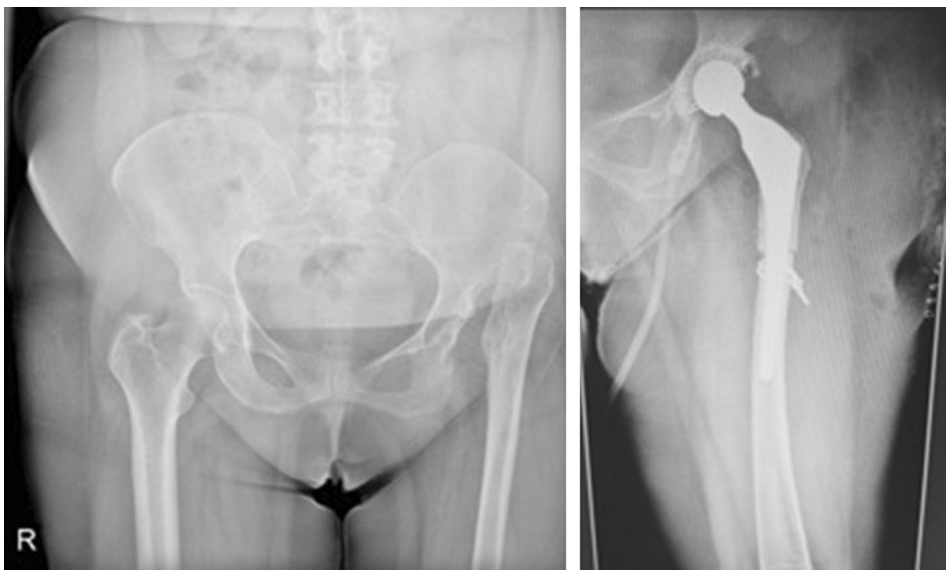

Fig. 2: In two cases, we used cemented cup for THR. Distal fitting stem was also used.

and the cup (size 40–44) is applied. However, a cemented cup was applied for two patients (Fig. 2). After capturing a proportional press fit, the cup is tightened with long screws (at least one screw per dome) (Fig. 3).

If the acetabular roof is deficient with more than 30% of the cup uncovered, we would reinforce the superior section with placement of cortico-cancellous structural bone graft from femoral head. This was done in 5 acetabula (Fig. 4a, b). The acetabular component is then impacted and fixed with screws. In some cases, the acetabulum was very small and reconstruction was possible only with smaller cups (Fig. 5).

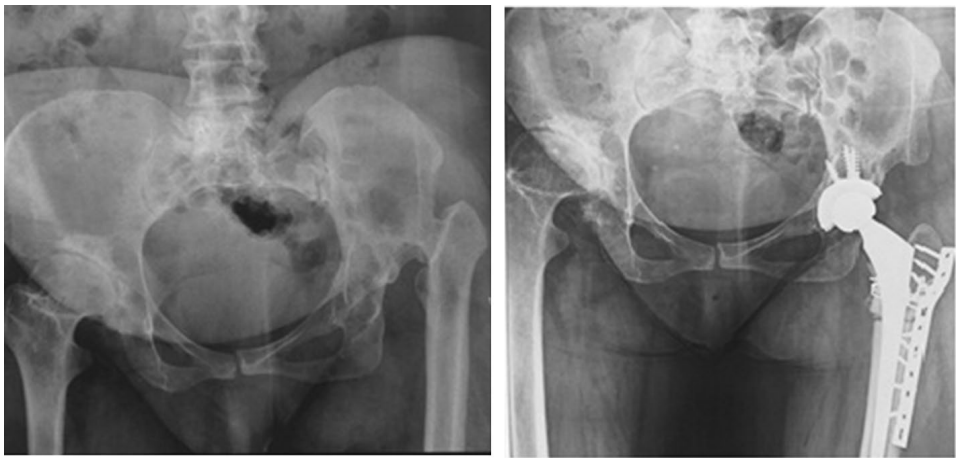

Fig. 3: High-riding DDH which underwent THR with cup placement in true acetabulum using multiple screws; transverse subtrochanteric osteotomy was performed and fixed with a plate.

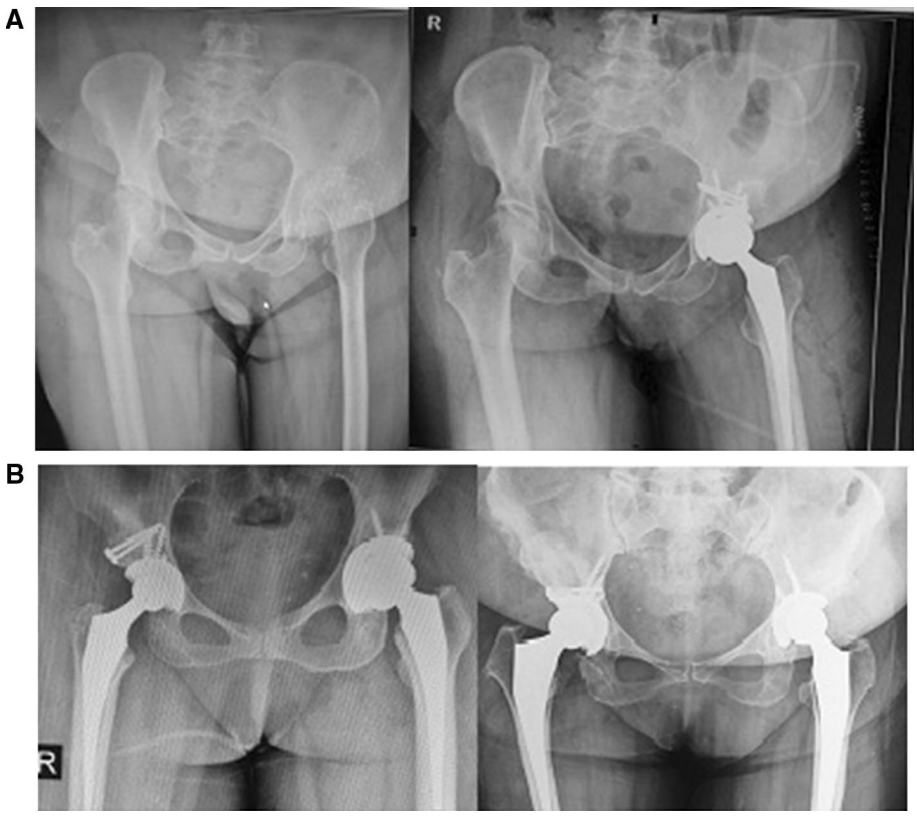

Fig. 4: Use of autograft in cases with over than 30% of cup uncovered (**a**). Postoperative radiographs of two other patients after graft union (**b**).

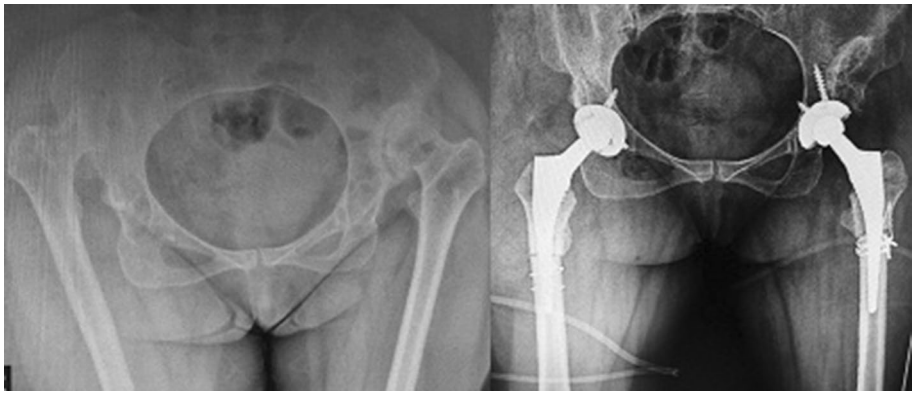

Fig. 5: Bilateral DDH undergone THR with small cup placed in true acetabulum and transverse subtrochanteric osteotomy.

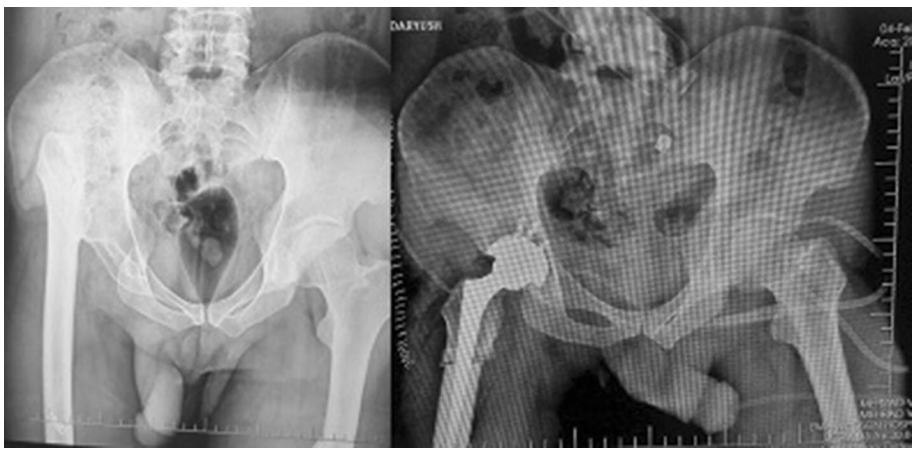

Fig. 6: High-riding DDH undergone THR with cup placement in true acetabulum, fixed with three screws and transverse subtrochanteric osteotomy.

For femoral components, a primary reaming is done at first. Bringing down of femoral head to the level of the true acetabulum is impossible in some hips after proximal dislocation because of soft tissue contracture. In such cases, a transverse subtrochanteric osteotomy is performed (Fig. 6). Measurement of subtrochanteric osteotomy is done intraoperatively. After reduction in the hip joint, we stretch the leg (with moderate tension) at a conventional length and mark the proximal and distal overlap and have it transversely excised. The medullary canal is reamed progressively. Finally, we lay the femur trial over the proximal part and measure the reduction. Then, the main stem (distal fitting type with normal size) is utilized. After reduction, stability of the hip joint is assessed and limb length discrepancy is checked.

Physiotherapy was started the day after surgery. All patients were followed up for at least 12 months, and Harris Hip Score questionnaire was applied to study the outcome; the patients

were asked to fill in the questionnaire before surgery. During the follow-up visits, it was filled in once more after 12 months post-surgery.

Result

A total of 42 patients with unilateral and 5 with bilateral DDH were studied (52 hips). Mean age of patients was 41 years (range 19–55 years). The minimum follow-up ranged from 12 months to 3 years. Two patients were lost to follow-up between 9 and 12 months. Uncoverage of > 30% was observed in 10 hips for which structural bone grafting was performed. Transverse subtrochanteric osteotomy was also performed in 24 hips.

Mean Harris Hip Score preoperatively was 41.70 (range 32–46) and postoperatively at last follow-up was 88.1 (range 74–94). According to Harris Hip Score, postoperative pain and limping were reported to be absent or slight among the patients. Support was not needed in any cases, and the distance patients walked, use of public transportation, going up from stairs, sitting and putting on shoes and socks were near normal. Flexion contracture under 30°, fixed abduction under 10° and fixed internal rotation in extension under 10° were not observed in any cases. We observed leg length discrepancy of less than 2 cm; three cases had limb length discrepancy of about 2 cm that was well tolerated using shoe lifts. All the patients reported to have proper range of motion and were satisfied with the outcome of surgeries. Clinical improvement in all patients was observed; all patients had the ability to walk normally without any help at 3 months after surgery (Video 1).

Considering the postoperative complications, two patients had transient peroneal nerve palsy in early postoperative period which recovered within 2 months. No early or late wound dehiscence of infection occurred. No patient had iatrogenic vascular injury to femoral artery. We also did not encounter any iatrogenic fracture at the proximal femur. One case reported to suffer from falling 15 months after surgery who successfully underwent revision. No nonunion or heterotopic bone formation was seen in osteotomy site (Fig. 7). The mean leg length discrepancy was 5 cm preoperatively (range 2–7 cm) and 1 cm postoperatively (range 0–2 cm). We did not observe any septic or aseptic loosening of the components.

Discussion

THR in Crowe type III and IV DDH is a challenging surgery. The most important goals are restoration of near-normal biomechanics and achieving sufficient cup coverage. Dysplastic hips have one single pathophysiological feature in common in which anatomic abnormalities intensify contact stress leading to degenerative arthritis [4]. Biomechanics and anatomy are altered with hypoplastic true acetabulum, excessive femoral anteversion, narrow medullary canal, proximal migration of femoral head and defective abductor mechanism [1-6].

Even though there are varieties of alternatives to non-arthroplasty treatment of DDH, there are a remarkable number of patients reported to have received total hip replacement as the treatment. Due to some certain characteristics of patients such as young age as well as

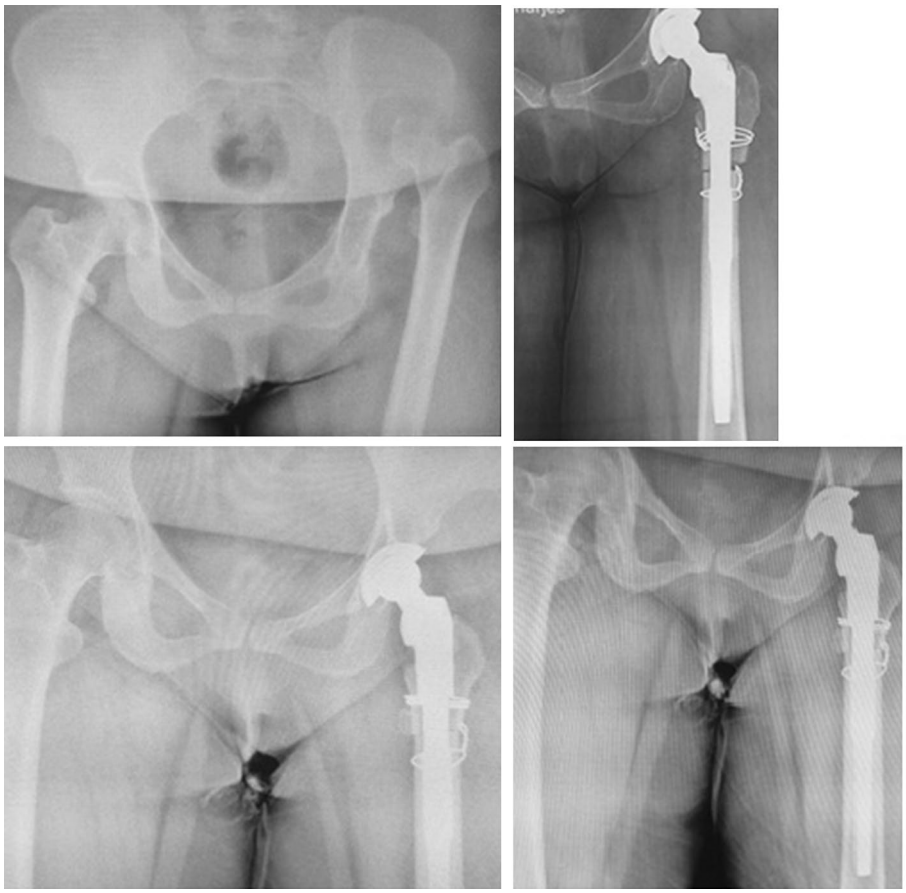

Fig. 7: High-riding DDH undergone THR with cup placement in true acetabulum and transverse subtrochanteric osteotomy. Follow-up radiographs at 12th and 18th months reveal union of osteotomy site.

anatomic abnormalities of hip, THR failure rate and complications in DDH patients are higher than normal population [9, 10]. Shallow socket with bone deficiency at anterior, lateral and superior areas of acetabulum is considered as one of the vital changes. THR, particularly determination of implant spot for acetabular component, causes new center of hip rotation which consequentially affects hip biomechanics, leg length and femoral reconstruction. Due to anatomic abnormalities, the use of standard-sized cup in dysplastic acetabulum leaves parts of component to be uncovered from native bone. A wide range of prostheses should be available, to choose the appropriate one for such hips. Absence of support intensifies the stress in the bone–implant or bone–cement interface which eventually leads to mechanical failure. The native bone should cover 70% of component surface as to generate the sufficient sustainability which allows for the bone ingrowth [11].

Once the sufficient coverage of the main bone is not attained by an implant, an alternative method needs to be applied. Two most important issues to be considered in these patients are the site of acetabular cup placement and fixation method. High rate of mechanical failure with cemented acetabular components without structural augmentation has been reported. A failure rate of 16–25% over a follow-up period of 10–20 years has also been reported. Younger ages during surgery, intense dysplasia with displacement of femoral head toward proximal and unanatomic acetabular component all result in weaker prognosis [11-13]. This demonstrates that when cemented acetabular component is used and cup coverage is required, no cup cement augmentation should be done. Over 10–12 years, about 40% of autograft-supported cemented acetabular component revealed signs of loosening of which 10–20% underwent revision [11, 14].

Lee *et al.* [15] stated that failure rate of 36 cases of cemented cup varied from 6% over 5 years to 39% in 10 years. Results came out to be far superior when hip center repositioned to its anatomic position with graft supporting less than 30–40% favored with superior and posterior wall. Kobayashi and colleagues [16] reported that there was no evidence of clinical failure when it came to cemented cups for 19 years. Results are much better once the graft supports less than 30–40% of component and a good job of superior support as posterior support is done. Huge bone grafts which interact with cement sockets do not typically have optimal longevity. Yet if reconstruction fails, bone graft takes much of bone stock and facilitates revision surgery.

There are plenty of techniques when it comes to non-augmented cemented acetabular component. Anderson and Harris [17] reported 20 cases of dysplastic hip reconstructed with non-cemented hemispheric cup followed up for about 6.9 years. Native bone covered 7–100% of the socket with component settled up to 28 mm proximal from inter-teardrop (5–66 spectrum) (some were high hip centers). None of sockets underwent revision surgery with no sign of loosening, migration or complete radiolucent line. This all attests to the vitality of non-cemented reconstruction in dysplastic hips.

Positioning acetabular component higher in proximal section for patients whose acetabular component in true acetabulum requires graft for provision of component support is recommended by Russoti and Harris [18]. Embedding of acetabular component in proximal section suits the elderly patients where anatomic position of acetabulum leaves more than 40–50% of socket surface uncovered and requires bone graft. Pagnano *et al.* [19] on the contrary found high rate of loosening of components with proximal position. Russoti and Harris [18] and some other authors favored more proximal but not lateral placement of acetabular component. Doehring *et al.* [20] found that superior only placement may be mechanically acceptable.

According to the available articles, there are no documented data on the prevalence of neglected DDH in Iran. However, many cases of infantile DDH were unfortunately neglected in the very past in the rural area of Iran with low socioeconomic living conditions; as a result, adult-type high-grade DDH is not uncommon in such areas. As a tertiary referral center, we are having 3–5 new patients with neglected DDH visited at our clinic mostly from western areas of Iran every 2 weeks. Here in this article, we present our experience with DDH patients who underwent reconstruction of acetabulum at true acetabulum level (Figs. 8, 9). Placement of acetabular component in true acetabulum level restores a near-normal biomechanics while providing the best

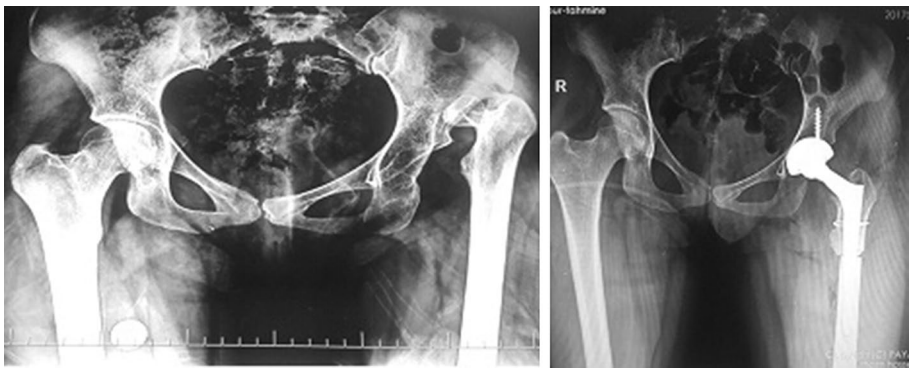

Fig. 8: Another case of high-riding DDH undergone THR with cup placement in true acetabulum and transverse subtrochanteric osteotomy.

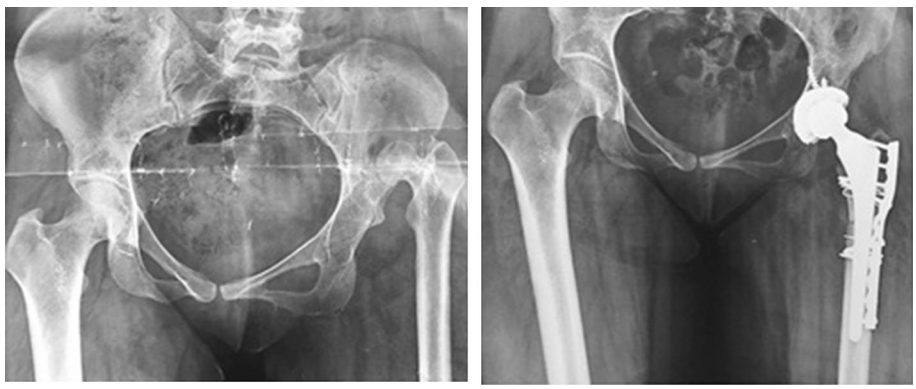

Fig. 9: A high-riding DDH undergone THR with cup placement in true acetabulum and cotyloplasty; transverse subtrochanteric osteotomy was done and fixed with a plate.

available bone stock for cup placement [3, 21] making it the ideal place for acetabular cup placement [22, 23]. When femoral head is proximally dislocated, the iliac bone stock becomes very deficient and securing the cup at or near true acetabulum becomes a challenge. For enhancement of the cup coverage, we used medialization of the acetabulum with small-sized cup and structural bone grafting. Most authors accept that if coverage is between 60 and 80%, augmentation should be used and coverage with graft should not be more than 30–40%. In our study, 10 hips had an uncoverage of > 30% for which structural bone grafting was performed. By use of a smaller component, good resection of medial osteophyte and adequate medialization at cotyloid fossa, we were able to place acetabular cup at true acetabulum.

In our study, transverse subtrochanteric osteotomy was done in 24 hips. Many authors reported good result with low rate of nonunion of osteotomy site [24-27]. We favor to use uncemented

press-fit distally fixed stems. Many authors reported excellent survival with modular uncemented stem [9, 10, 23, 24].

Conclusion

Performing THR in patients with DDH (Crowe III and IV) with a cup positioned in true acetabulum and transverse subtrochanteric osteotomy is a safe successful procedure. Small-sized cup with medialization of acetabulum produces good results. We favor uncemented press-fit acetabular cup and modular uncemented stem with transverse subtrochanteric osteotomy. However, there is no universally accepted standard treatment for Crowe III and IV dysplastic hip and each case needs individualized treatment.

Compliance with ethical standards

Conflict of interest The authors declare that they have no competing interests.

Ethical standards: Study protocol was in accordance with the Declaration of Helsinki for human research and approved by Shahid Beheshti University of Medical Sciences Ethic committee.

Informed consent: Informed consent was obtained from the patients.

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Mobility of the Rotating Platform in Low Contact Stress Knee Arthroplasty is Durable

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Abstract

Purpose: The mobile bearing or rotating platform (RP) in total knee arthroplasty (TKA) is originally part of a low contact stress (LCS) concept, with bearing undersurface mobility compensating higher bearing upper-surface congruency. The in vivo range of axial femorotibial rotation in RP knees has been the subject of many studies, but always involving the performance of relatively low demanding task conditions. Hardly any study has addressed the maintenance of this rotation over time.

Methods: Two consecutive series of patients with LCS RP knees were studied in a cross-sectional study of 1- and 5-year follow-up. They were assessed using optoelectronic movement analysis during gait and the performance of a sit-to-walk (STW) task with and without turning steps.

Results: A mean range of rotation (SD) was found in the 1-year group of 13.4° (3.7) during gait, 17.8° (6.8) during STW straight, and 17.9° (6.9) during STW with turning. The range in the 5-year group was 11.2° (6.0) during gait, 18.5° (8.7) during STW straight, and 18.3° (8.3) during STW with turning. A so-called paradoxical axial rotation pattern during gait and STW straight occurred in both groups in a normal prevalence.

Conclusion: The amount and pattern of rotation in a LCS RP knee does not become impaired between 1 and 5 years postoperatively. The theoretical benefit of RP TKA has not been proven in any clinical study so far, and studies with suitable long-term follow-up need to prove whether this mobility also leads to improved prosthesis survival. However, our findings support the functioning of the rotating platform at a basal science level and illustrate the need for the use of more complex tasks in kinematic studies.

Level of evidence: Therapeutic study, Level III.

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Keywords Mobile bearing, Rotating platform, Low contact stress, TKA, Rotation, Sit-to-walk

Introduction

The rotating platform (RP) in total knee arthroplasty (TKA) is originally part of a low contact stress (LCS) concept, in which a bearing with higher upper-surface congruency is compensated by undersurface mobility. This is assumed to reduce articular contact stress without increasing bone–implant interface stress [2], which in turn would theoretically increase prosthesis survival thanks to reduced polyethylene wear and aseptic loosening. Wear is less of a problem with the ongoing improvement of polyethylene quality [21, 33], but loosening is still a point of concern in current TKA [5]. Some surgeons also hope to benefit from a natural accommodation of patellofemoral alignment, while others might have to overstep a fear of possible dislocation of a mobile bearing. Although the original LCS RP knee or its derivatives are recognized as a successful prosthesis [1–3, 16, 20, 25, 30, 32], the clinical results appear not to be better than those for conventional fixed-bearing knees [4, 28, 29, 36]. There is even one study, using national joint replacement registries, which concluded that mobile-bearing non-posterior-stabilized variants presented a greater risk of failure than fixed-bearing (FB) non-posterior-stabilized variants [23]. These findings raise questions regarding the actual functioning of the concept: Does the RP provide sufficient mobility, and if so, is this mobility maintained over time?

Some in vivo kinematic studies found significant differences in axial femorotibial rotation between RP and FB TKA variants [6, 26, 27], while others did not [8, 18, 38]. Apart from magnitudes of rotation, there is also the concern about a so-called reverse or paradoxical axial rotation pattern in both RP and FB TKA variants [2, 8]. All these studies had a certain limitation in that they used relatively low demanding task conditions (mostly knee bends during stance). In an earlier study, it was found that the range of axial knee rotation after RP knee replacement was as large as in healthy knees when moving from sit to walk, with or without turning steps [39]. We figured that such a more demanding task could be helpful in exploring the geometric constraints of TKA variants.

At the time we conducted the current study, only one study had addressed to the maintenance of mobility over the years: a decrease in axial femorotibial rotation was found in RP NexGen knees by Wolterbeek *et al.* [37]. Since the design principles in RP designs vary in femoral congruency and position of the rotational axis, we hypothesized that in case of the originally designed LCS RP knee there would be no decrease in rotation over time. Furthermore, we expected that the proportion of reverse rotation would remain the same. In order to test these hypotheses, we used more demanding task conditions than commonly used in in vivo kinematic studies, to actually provoke turning and the explore ranges of axial knee rotation.

Materials and Methods

Two consecutive series of TKA patients, including 12 one-year (1y) postoperative patients (15 knees) and 14 five-year (5y) postoperative patients (17 knees), underwent non-invasive movement analysis. All patients had been operated on in the Slotervaart Hospital or VU University Medical Center (Amsterdam, The Netherlands) in the periods of November 2004 to May 2007 or February 2002 and December 2003. Some of the patients in the 5y group also participated in a prior study [39]. All patients were given a non-cemented LCS® Rotating Platform knee (DePuy Inc, Warsaw, IN) by the same surgeon (RGP), except for one patient in each group. The posterior cruciate ligament was sacrificed, and a standard balanced gap surgical technique was used for bone cuts and ligament balancing.

Included were patients successfully operated for osteoarthritis or rheumatoid arthritis, with a postoperative Knee Society Knee Score of 80 points or more. Range of motion was comparable for both groups, with a mean flexion of 115° (median 110) in the 5y group and 120° (median 120) in the 1y group. Exclusion criteria were revision surgery, neurological disorders that interfered with walking, and a body mass index (BMI) of 35 or more. The patient characteristics are shown in Table 1. There were no statistically significant differences between both groups regarding gender, age at surgery or BMI. The 5y group consisted of both osteoarthritis and rheumatoid arthritis patients, whereas all patients in the 1y group had rheumatoid arthritis.

Movement analysis took place in a laboratory for human movement analysis (Department of Rehabilitation Medicine, VU University Medical Center, Amsterdam, The Netherlands). An OptoTrak motion analysis system (model 3020, Northern Digital Inc, Waterloo, Ontario, Canada) was used to record the 3D position of active surface markers at a sampling rate of 50 Hz. For the tibia, a cluster of three markers was strapped over the middle lateral shank. For the femur, a cluster of three markers was rigidly attached to an epicondylar frame. The Femoral Epicondylar Frame is a validated tool for non-invasive tracking of femoral axial rotation, with an error of 3.3° up to 40° of knee flexion [41]. For higher flexion, the error increases, but the majority of peak rotation took place within this range [15, 40]. The error for tibial rotation using surface markers is 2° [19].

Table 1: Patient characteristics.

Parameters	1y	5y
Diagnosis (OA/RA)	0/15	11/6
Gender (female/male)	14/1	13/4
Side (right/left)	8/7	8/9
Mean BMI (SD)	29.8 (2.5)	28.3 (3.5)
Mean age at surgery (years, SD)	66.4 (7.4)	57.4 (4.2)
Mean interval from surgery to analysis (months, SD)	16.3 (4.3)	64.2 (3.6)

OA osteoarthritis, *RA* rheumatoid arthritis, *BMI* body mass index, *SD* standard deviation

For the calculation of three-dimensional knee kinematics and definition of anatomical points and coordinates, we refer to prior publications [39, 40].

The subjects performed four tasks: gait, move from sit-to-walk (STW) straight ahead, STW crossover step turning and STW sidestep turning. Chair height was adjusted to 90 % of the lower leg length. Only the prosthetic knee in the weight-bearing leg was measured, the contralateral side acting as the swing leg. The subjects practiced each task until they could perform it smoothly at a natural pace. Three measurements per task were recorded and used for analysis. Videos are available in the online version of this article (Videos 1–3). The tasks were highly standardized and have been described previously in a study with healthy subjects [40]. Also, in that particular study, good results of within-test reliability for the range of axial knee rotation by means of intraclass correlation coefficients (95 % confidence interval) were found: 0.76 (0.42–0.92) for STW straight, 0.89 (0.73–0.96) for STW crossover stepping and 0.96 (0.90–0.98) for STW sidestepping.

Ranges of rotation during the various tasks were compared between the 1y and 5y groups. The difference between peak internal and peak external femorotibial rotation was used to define range of rotation. The difference between internal rotation during crossover stepping and external rotation during sidestepping was used to define overall range of rotation for STW turning. Reverse rotation was defined in terms of timing of peak rotation as a percentage of stance phase and/or the proportion of knees showing a higher peak external than peak internal rotation.

Informed consent was obtained from all subjects, and permission for the study was given by the local medical ethics committee (Medische Ethische Toetsingscommissie voor het Slotervaartziekenhuis, Jan van Breemeninstituut en BovenIJ Ziekenhuis, reference number 0303).

Statistical Analysis

The original sample size calculation with power set at 0.80 had revealed that 16 patients per group were needed to find a difference of 5° between groups with 5° of variance. An independent samples test was used to compare variables (ranges of rotation during gait, STW straight and STW turning) as well as patient characteristics between the groups (1y and 5y). Level of significance was set at $p = 0.05$.

Results

Results for the individual magnitudes of rotation and mean range of rotation for gait, STW straight ahead and STW with turning are shown in Table 2. The normal values were retrieved from a prior study [40]. The table shows that there was no significant difference between the values 1y and 5y postoperatively in any of the movements. It also shows that STW implies a higher range of rotation than gait. During normal gait, the 1y group had an average range of rotation of 13.4° (SD 3.7), versus 11.2° (SD 6.0) in the 5y group.

During STW straight, the average peak internal tibial rotation in the 1y group was 16.7° (9.4) and peak external tibial rotation 1.1° (SD 3.9), accounting for a range of rotation of 17.8° (SD 6.8).

Table 2: Mean ranges of axial knee rotation (SD) for both postoperative groups and healthy subjects.

	1y	5y	Normal	*p* value
Gait	13.4° (3.7)	11.2° (6.0)		n.s.
STW straight	17.8° (6.8)	18.5° (8.7)	13.5° (3.9)	n.s.
STW turning	17.9° (6.9)	18.3° (8.3)	20.9° (7.9)	n.s.

n.s. not significant (between 1y and 5y postoperative groups, independent samples test)

Table 3: Mean timing of peak rotation as percentage of stance phase (±SD).

	Normal	1y	5y
Gait			
Peak int	96 ± 5	93 ± 8	89 ± 9
Peak ext	12 ± 8	15 ± 8	19 ± 13
Reverse pattern	33 %	13 %	35 %
STW straight			
Peak int	96 ± 15	88 ± 25	89 ± 17
Peak ext	28 ± 23	13 ± 18	18 ± 19
Reverse pattern	7 %	7 %	12 %
STW crossover stepping			
Peak int	98 ± 4	87 ± 25	86 ± 16
Reverse pattern	0 %	7 %	12 %
STW sidestepping			
Peak ext	75 ± 32	23 ± 31	27 ± 31
Reverse pattern	67 %	27 %	18 %

Reverse pattern represents the proportion of subjects with a higher peak external knee rotation than internal rotation magnitude

This did not differ significantly from the range of rotation in the 5y group, which was 18.5° (8.6), with an average peak internal tibial rotation of 16.1 (SD 9.4) and external rotation of 2.5° (SD 2.8).

STW turning resulted in an average peak internal tibial rotation for the 1y group of 15.9° (SD 9.7) during crossover stepping and 2.0° (SD 3.7) during sidestepping. This accounted for an overall range of rotation during turning of 17.9° (SD 6.9). In the 5y group crossover stepping resulted in an average peak internal tibial rotation of 16.3° (SD 8.9) and an external rotation of 2.1° (SD 2.3), accounting for a range of rotation of 18.3° (SD 8.3).

The results concerning timing and pattern of rotation are depicted in Table 3. During gait and STW straight, peaks of rotation 1 and 5 years postoperatively occurred in the same half of stance phase. The normal values were retrieved from the same prior study [40]. Overall, the proportion of patients with a reverse pattern of rotation did not alter significantly between both postoperative groups.

Discussion

The most important finding of this present is that axial knee rotation in a RP knee did not decrease from 1 to 5 years postoperatively. Although the focus of the study was range of rotation, both magnitude and pattern of rotation were comparable to normal values from a prior study on healthy subjects.

The LCS RP knee arthroplasty concept allows for free bearing rotation on a central axis, while muscle activity, capsule and ligaments restrict rotation to ensure knee stability. The results of our study suggest that these soft tissue restrictions do not change in the years following TKA. This finding is in disagreement with the study by Wolterbeek *et al.* [37]. They studied a group of seven patients with NexGen RP knees during the performance of a step-up using fluoroscopy, finding a decrease from 11° to 6° in femorotibial rotation from 8 months to 3 years postoperatively. The authors suggested that the formation of fibrous tissue was possibly restricting of bearing mobility, although this explanation was not based on their own findings at retrieval or revision surgery [10]. They also proposed that there might be a lack of bearing upper-surface congruency and a non-centrally placed axis of bearing rotation, which might be suboptimal in terms of facilitating bearing undersurface mobility. High articular congruency and a central axis of rotation in the LCS knee could explain the different outcome in our study with respect to maintenance of rotation. LaCour *et al.* [17] also fluoroscopically analysed RP knees during the performance of a deep knee bend. From 3 months to 10 years postoperatively, the bearing in eight patients with a PFC Sigma posterior-stabilized knee continued to rotate with respect to the tibial component and no decrease in overall femorotibial rotation was found. The Sigma and LCS knee derive from the same company and share the same tibial component; however, they are not comparable at the femoral side of the articulation: the LCS has more bearing upper-surface congruency, while the cam-post mechanism adds congruency to the PFC bearing.

A possible limitation in the former studies is that the fluoroscopic set-up could prohibit freedom of movement. As a result, the task loads are relatively simple (mainly knee bends), which may explain the limited ranges of rotation in these studies. Also, bearing mobility during deep flexion becomes irrelevant because of loss of weight-bearing and articular congruency [9]. In the present study, a movement analysis system was chosen, using optical cameras, which provided space for our subjects to perform a transitional task (sit-to-walk) to provoke rotation and imitate daily life activity. The relevance of adding turns lies in the fact that turning steps make up a considerable portion of steps taken during daily life walking [11] and many patients after TKA have difficulty in performing them [24].

Our findings on reverse rotation patterns are somewhat different from the literature, but this may partly be attributed to defining reverse or paradoxical rotation. The timing of peaks of rotation in the current study was not very different from normal, except for a shift in peak external rotation to the first half of stance during the sidestepping task. Dennis *et al.* [8] found a proportion of 33 % reverse rotation in a group of 76 posterior-cruciate-sacrificing mobile-bearing knees during a deep knee bend and 49 % during gait; we found 12 % during STW straight and 35 % during gait 5 years postoperatively. Other studies also report that the actual mobility of the RP was

reversed as opposed to normal knee rotation [31, 35]. In our opinion, however, the importance of reverse rotation should not be over esteemed. Rotating platforms were originally designed as part of a concept to achieve less wear and loosening stresses, rather than as the solution to the so-called 'kinematic conflict'. This means that the attempt to create of a clinically successful TKA design is not necessarily the same as the restoration of natural knee kinematics [34].

Although the original LCS concept has a good track record of more than 30 years, it still remains a debate whether RP variants of TKA have a potential to be superior to FB variants. In a recent meta-analysis by Moskal *et al.* [22] and a Cochrane review by Hofstede *et al.* [12], no difference regarding clinical performance and prosthesis survival was found between RP and FB knees. Mean follow-up in systematic reviews is usually short, but also an original study with 17-year follow-up showed no differences between the LCS and a FB knee within the same patient [14]. National joint registries make analysis on a larger scale possible: Namba *et al.* [23] compared mobile- and fixed-bearing variants of non-posterior-stabilized knees in 319.616 patients. Their results in terms of risk of failure were in favour of FB, although the interpretation could be troubled by the heterogeneity in the mobile-bearing group. Hopley *et al.* [13] combined data from a systematic literature search with national joint registry data of LCS RP and non-LCS knees. Their results on survivorship were in favour of the LCS RP knee. Future studies may need to differentiate highly congruent designed RP knees, with a central axis of rotation, from non-LCS-related designs. As long as there is no proof of any clinical benefit, it is worthwhile to study whether a RP is functioning according to its original concept at all. The current study focused on the maintenance of rotation over time with a focus on advanced task complexity.

The present study had some limitations. One drawback is that an optical motion analysis system cannot differentiate between bearing rotation and overall femorotibial rotation. It is not possible to visually track the bearing using external markers. However, previous data from studies using fluoroscopic analysis and tantalum-beats-inserted bearings have showed that most of the rotation of a RP was due to bearing undersurface mobility [6, 7]. Another shortcoming was that not the same series of patients were measured 1 and 5 year postoperatively, which means that the patient groups differed in terms of relevant known and unknown variables. In the 5-year postoperative group, six out of 17 patients had rheumatoid arthritis, while in the 1-year postoperative group, none of the 15 patients had rheumatoid arthritis. This may have influenced the results.

Our findings may support the functioning of the rotating platform at a basal science level. Future studies with suitable long-term follow-up need to prove whether this sustained mobility leads to improved prosthesis survival. The present study also illustrates the use of complex tasks in evaluating replaced knee performance. Simple tasks such as normal walking or knee bending may not be sensitive enough to differentiate potential kinematic differences.

Conclusion

The original concept of the mobile-bearing TKA depends on free rotation of a highly congruent polyethylene bearing around a central axis. This study showed that under demanding task conditions the amount and pattern of axial rotation in the LCS RP knee does not become impaired from

1 and 5 years postoperatively. Although this concept has a theoretical advantage, rotating platforms have not provided better clinical outcomes than fixed bearings nor do they have restored natural knee kinematics.

Compliance with ethical standards

Conflict of interest: This study was financially supported by an unrestricted Grant from DePuy (Johnson & Johnson Medical) and Biomet. All the authors declare that they have no other conflict of interest.

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Total Knee Arthroplasty Technique: ROSA® Knee

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Conventional wisdom from decades of scrutiny regarding the mechanisms of failure in total knee arthroplasty (TKA) has been that precise bone resections within 2 or 3 degrees of variability from a neutral mechanical axis are of paramount importance to ensure implant durability and limit mechanical failures. Twenty years ago, component malalignment, malposition, and instability were common reasons for failure [1]. Despite a better understanding of the importance of achieving acceptable component alignment and soft tissue balancing during TKA, as well as improvements in instrumentation, implant materials, and designs that make them more durable and accommodating of even subtle "errors," the incidence of failures related to instability, malalignment, or malposition is between 2.9% and 20.7% [2-4]. Some now suggest that a narrow range of component or limb alignment is less important than soft tissue balancing for success and durability in TKA [5, 6]. Still others have argued that positioning the limb and components in alignment with the native anatomy may better restore kinematics and soft tissue balance [7]. To be clear, however, despite the newer tolerances of "imprecision" or "malalignment," positioning the components or limb beyond some acceptable range, particularly when coupled with soft tissue imbalance, can lead to failure and thus must be mitigated [8].

Robotic tools were developed explicitly to optimize bone preparation and enhance limb and component alignment and position. Furthermore, semiautonomous robotic systems provide the additional and important vehicle for quantifying soft tissue balance in TKA, with the expectation that these elements, in concert, will improve kinematics, stability, functional outcomes, and dura-

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bility [9]. At this time, the preponderance of data shows that compared to conventional manual methods of bone preparation, robotics shows greater precision and less variability in component alignment, with fewer outliers [10-14]. Additionally, robotic assistance can effectively quantify resection orientation in kinematic alignment methods for TKA, with commensurate alterations in the need for, or extent of, soft tissue releases [15] while minimizing the misjudgments and the frequency of errors of tibial and femoral coronal plane resections and femoral rotational resections in the so-called "kinematic" approach to TKA [16]. Notwithstanding the above-mentioned controversies on optimal alignment in TKA, robotic assistance should be able to deliver on a particular surgeon's preferences regarding targeted alignment [8]. Ongoing study is paramount to track functional outcomes and durability with newer robotic systems that combine precision of bone preparation and quantified soft tissue balancing. This chapter will review the early experience with the ROSA Knee robotic system (Zimmer Biomet, Warsaw, IN) for TKA.

ROSA Knee Robot System Description

First used in Australia in 2018, ROSA Knee robot (Fig. 1) received 510K clearance for use for TKA by the US Food and Drug Administration in January 2019. While some orthopedic robotic systems require the integration of additional advanced preoperative imaging studies, such as CT scans, for planning and integration for bone preparation [9, 10], ROSA Knee does not. ROSA Knee is unique in that it has two options for case creation and plan development. One option is the morphing of a three-dimensional virtual model derived from the synthesis of data from preoperative plain radiographs with discrete surface bone and cartilage landmarks registered by

Fig. 1: The ROSA Knee Robot system.

the surgeon intraoperatively, serving as a check and balances approach to minimize inaccuracies from use of erroneous data. Compared to CT scans, the use of plain radiographs is less costly, requires less radiation exposure, and is less inconvenient to the patient, as no additional visits are required. The second option, which appears to be equally accurate, does not require any preoperative imaging and uses exclusively intraoperative bony and cartilage landmark acquisition as the guiding data input for three-dimensional modeling, intraoperative decision-making, and resection plans.

ROSA Knee is a robotically assisted semiautonomous surgical system that provides a continuum of data analysis derived from integration of the 3D model, intraoperative bone surface mapping and landmark registration, and soft tissue laxity measurements to augment the ability of surgeons to position surgical instruments, perform bone resections, and assess the balance of the soft tissue envelope in TKA surgery. It uses a captured resection model to precisely execute the preoperatively and intraoperatively determined patient specific plan. There is no constraint of the saw blade, in order to allow the surgeon to maintain the tactile "feel" of cutting the bone, although the resection guides are robotically constrained.

The ROSA Knee robot system has two main components which are positioned on opposite sides of the operating table. A robotic unit which consists of a robotic unit (robotic arm and touch screen) and an optical unit (the camera, positioning arm and touchscreen). The robotic arm contains three unique robotic modes to facilitate ease of use and provide safety during the procedure. In the automatic mode (orange color screen frame), the robotic arm will move to a predetermined position as directed by the computer system. In the collaborative mode (green color screen frame), the robotic arm will move if the surgeon applies a gentle force to the arm so the surgeon can manually move the arm to a desired position. In the stationary mode (gray color screen frame), the robotic arm will lock in place, other than allowing translation of the block tangential to the planned resections, as it is otherwise robotically constrained.

At the end of the robotic arm is the ROSA Knee TKA cut guide, which can be used with any of the Zimmer Biomet TKA implants (Persona®, NexGen®, and Vanguard ®). The robot unit, optical unit, instruments, and patient are linked by optical reference frames.

ROSA Preoperative Planning

While preoperative modeling is unnecessary, some surgeons will prefer the option of using preoperative radiographs to begin planning the surgery. In those circumstances, preoperative X-rays using conventional radiographic equipment are taken. X-ray technologists, trained on the technique, secure a re-usable calibrated X-ray marker to the patient's thigh and calf via a Velcro strap. Standing long leg AP and lateral radiographs are performed from the hip to the ankle. Most conventional radiographic systems can perform this procedure. The two-dimensional radiographic data is then uploaded to as secure portal, and a three-dimensional virtual model of the patient's bony structure and articular surfaces is created. If the surgeon prefers entirely image-free planning, without supplemental radiographs, then the surgeon can also effectively model, plan, and carry out surgery with ROSA Knee with precision.

ROSA Knee Procedure

OR Setup

The patient is placed supine on the operating table. The surgeon and the robot are positioned on the same side of the patient, and the optical system is positioned on the other (Fig. 2). The ROSA Knee system will allow the surgeon to stand on either side of the patient as per their standard surgical technique. The robot is positioned at the level of the patient's hip and is angled approximately 45° relative to the table. A leg holder is not required to perform a ROSA Knee robotic procedure but can be helpful in stabilizing the leg.

Draping and calibrating the robot are performed by the surgical technologist and operating room staff either prior to or during the surgical exposure. This is guided on screen in a step-by-step fashion.

Tracker Placement

The trackers should be installed prior to, or after, arthrotomy and surgical exposure. The femoral tracker is placed approximately 4 fingerbreadths proximal to the skin incision parallel to the long axis of the bone. Pins can be inserted percutaneously or through a small incision. It may be helpful to flex the knee during tracker insertion to avoid tethering the quadriceps. Two self-drilling and self-tapping fixed fluted pins (3.2 × 150 mm) are inserted on power in the center of the femur achieving bicortical fixation. The femoral reference tracker is secured to the pins, as close to the bone as possible without impinging on the skin, roughly 1–2 cm from the skin.

The tibial tracker is placed roughly 4 cm distal to the skin incision. The tibial pins must be placed distal enough not to interfere with the keel preparation of the tibial component but at the same time trying to insert the pins in metaphyseal bone to minimize risk of pin site fracture. Two self-drilling and self-tapping fixed fluted pins (3.2 × 150 mm) are inserted bicortically along the

Fig. 2: View of the setup of robot within the operating room.

long axis of the tibia angled toward the optical camera. The tibial reference tracker is placed as close to the bone as possible without compressing the skin. The stability of the pins and reference trackers should be confirmed, as movement during the procedure could result in errors in cuts or positioning. These tracker positions will ensure visualization by the optical camera during the surgical procedure through a full range of knee motion without interfering with, or being interfered by, the robotic arm (Fig. 3).

Landmark Registration

Once the trackers are placed, it is necessary to map, register, and digitize a series of bony and surface cartilage landmarks of the knee and limb. Again, this information can be morphed with the preoperative radiographs at the surgeon's discretion. The femoral head center is established by capturing 14 distinct positions of the hip during circumduction. The distal femoral canal entry point is obtained next, and the mechanical axis of the femur is thus determined. Further landmark registration points of the distal femur includes the posterior condyles, anterior trochlear groove, posterior trochlear groove, medial and lateral distal condyles, the medial and lateral epicondyles, and the anterior cortex. The posterior condyles are used to determine the posterior condylar axis, and the anterior and posterior trochlear groove is used to determine the A/P axis. The anterior cortex is used for femoral sizing and A/P translational positioning and to determine if notching will occur. When landmarking articular surfaces, the ROSA Knee registration Pointer tip should not pierce the cartilage.

Landmarking of the tibia includes capturing the medial and lateral malleoli distally, the medial third of the tibial tubercle, the tibial canal entry point, the PCL insertion, and the medial and lateral plateau resection references. The system then determines the mechanical and rotational axes of the tibia.

Knee Evaluation

Once the landmarks are registered, the surgeon has the option to perform a Knee Evaluation. This is performed at three time periods during the procedure: initial, intraoperative, and postoperative after the implants are inserted. The knee is moved through a range of motion and ROSA Knee

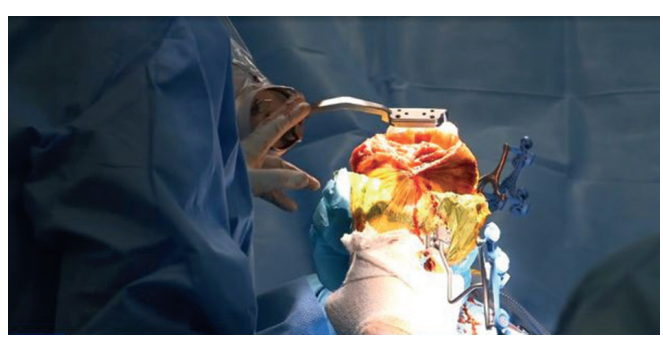

Fig. 3: Position of tracking arrays to avoid interference with the robotic arm.

will quantify and save the following characteristics of the knee: range of motion, alignment, and medial, and lateral compartment gaps (Fig. 4). The values obtained can then be used to guide implant position, size, orientation, and soft tissue balancing.

The Laxity test is performed by either continuously moving the knee through a range of motion while applying varus and valgus stresses or bringing the knee to a series of discrete angles while applying a varus or valgus stress. The system defaults to recording values at 0° and 90°; however, an option exists to also record gap laxities at 30, 45, 60, and 120°, based on the surgeon's preferences.

The *Initial* state is the status of the knee prior to significant soft tissue releases and osteophyte removal. At this time, flexion contractures and coronal deformities can be quantified. The *Intra-Op* state is the same evaluation procedure after the knee has been balanced and prepared, including soft tissue balancing and osteophyte resection. This can be repeated multiple times to evaluate the effect soft tissue releases will have on the balance of the knee. The *Final* state is assessed after resections have been made and trials or final implants are inserted. Based on stability and positioning parameters at this point, further releases or adjustments in bone resections can be made to improve flexion or extension, coronal compartmental balance, sizing, etc. In addition, this test can be done at any time to see if specific surgical changes will influence the results.

Planning Panel

The planning panel is used intraoperatively to set the femoral and tibial component sizes and positions and orientations of bone resections (Fig. 5a, b). All parameters of the bone cuts and implant

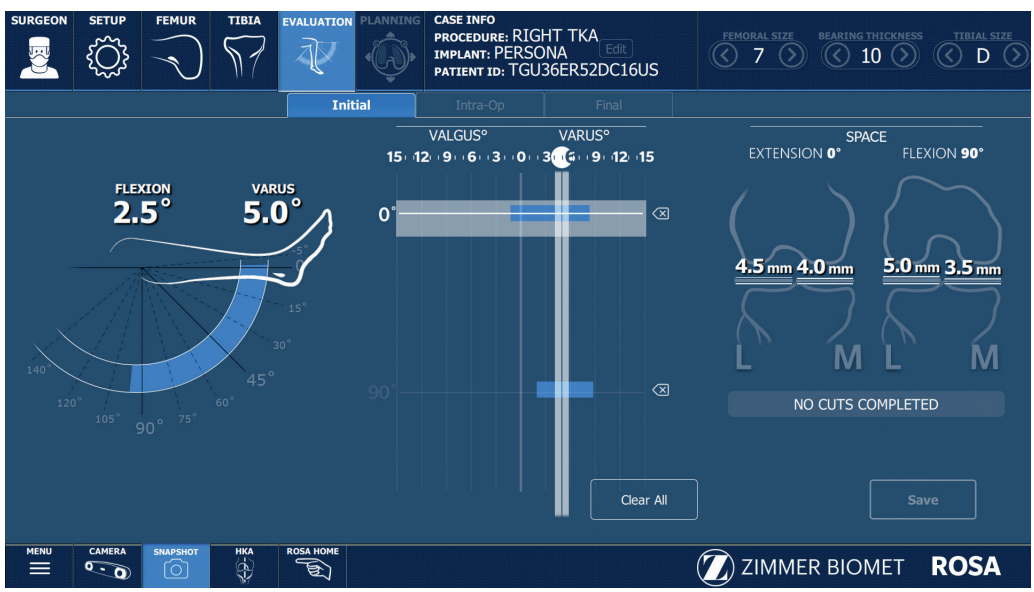

Fig. 4: The knee is brought through a range of motion without stressing the ligaments and then with varus and valgus stress to determine range of motion, as well as medial and lateral gap laxity or tightness.

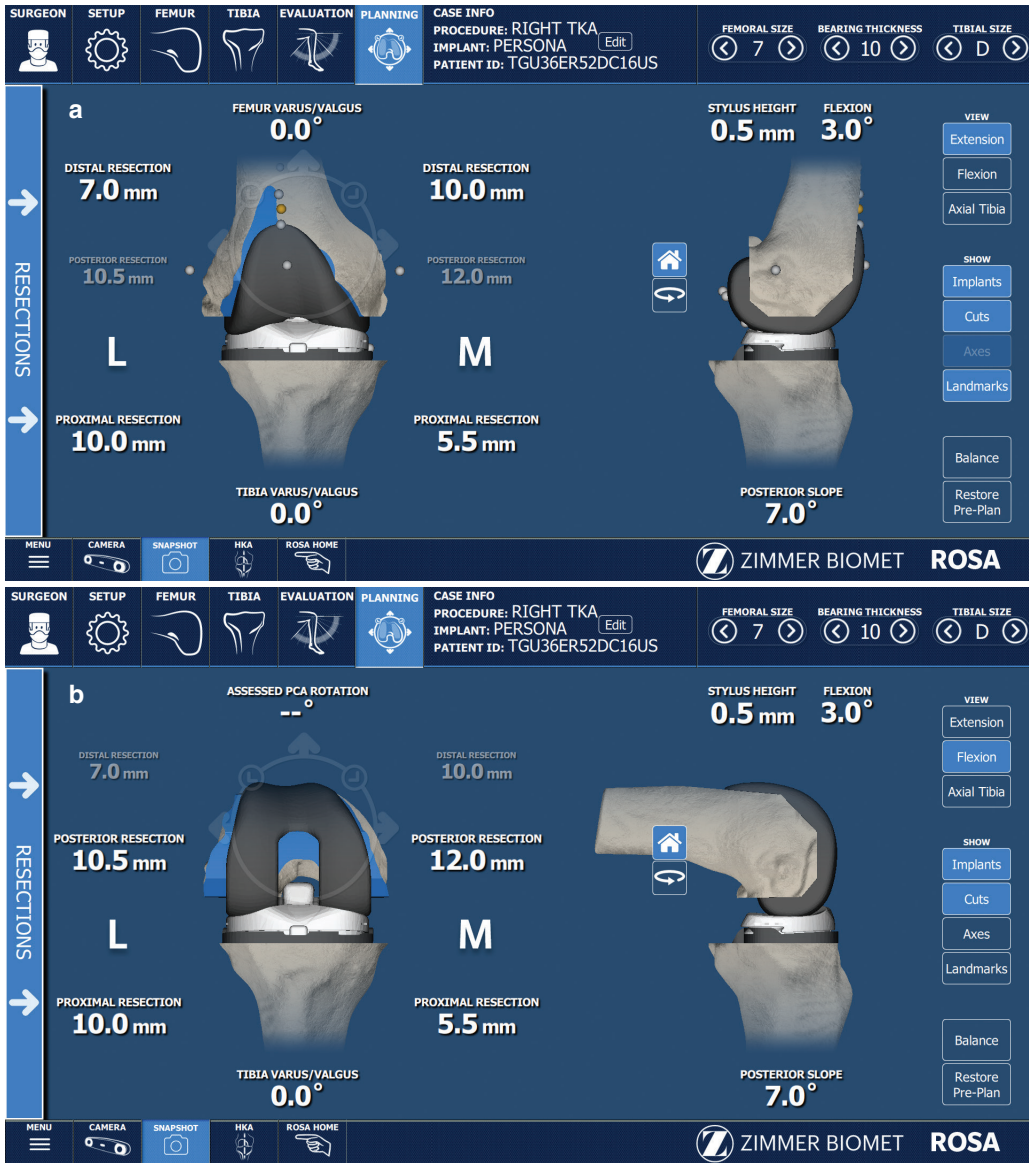

Fig. 5: After registering points on the knee surfaces and limb, planning of implant sizing, position, orientation of resections, and gap balancing are performed (in both extension (**a**) and flexion (**b**).

sizing and positions can be manipulated on screen to give a "virtual" understanding of the balance of the knee based on the planned implant positions. Manipulation of the implants will give "live" feedback on alignment and gaps (Fig. 6). Ultimately ROSA Knee will assist the surgeon in carrying out the cuts, precisely following the plan of resection.

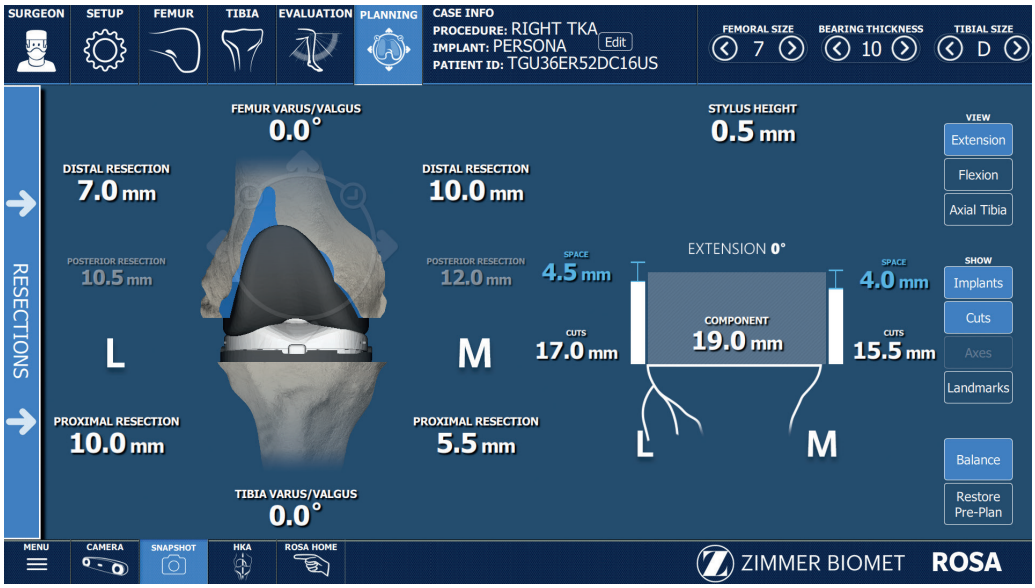

Fig. 6: Virtual assessment of gap balancing can inform the orientation of resections, implant positioning, and sizing, as well as soft tissue releases.

Resection Panel

The Resection panel is where ROSA Knee software will guide the surgeon to perform the distal femoral resection, proximal tibial resection and femoral rotation resections by guiding the robotic arm with the cut guide to the appropriate position to perform the cuts and prepare the bone.

The sequence of bone cuts – either tibia or femur first – can be individualized based on the surgeon's preference. If the surgeon chooses to use the ROSA Knee femoral rotation soft tissue tensioning algorithm, it is necessary to perform the distal femoral and proximal tibial resection prior to making the anterior, posterior, and chamfer femoral cuts with application of the 4-in-1 cutting block. If the surgeon chooses to use standard measured resection protocol, the femoral rotation can be determined by the posterior condylar axis or the A/P axis.

Proximal Tibial Resection

The proximal tibial resection tab is selected. The foot pedal is pressed to bring the robotic arm to the tibial cut plane in automatic mode. This will bring the arm in the appropriate cut plane close to the bone. The ROSA Knee arm will then stop, enter collaborative mode, and the surgeon will need to apply a gentle force to the cut guide to move it to contact the anterior tibial cortex. In collaborative mode, the guide's cut orientation, depth, and slope will be robotically constrained, although the guide remains free to move medially and laterally. With the foot pedal pressed, a pin is placed through the cut guide into bone. On screen, data will show live cut values. If values are acceptable,

the second pin can be placed. A standard manual saw cut through the robotically constrained guide is performed, without any constraint of the saw itself, in order to enhance ergonomics. The pins are removed, and the foot pedal is pressed to move the arm away from the bone. The validation tool is placed on the tibial resection to confirm the cut values correspond with the plan.

Distal Femoral Resection

Once the screen tab for distal femoral resection is selected, the foot pedal is pressed to bring the robotic arm to the femoral cut plane in automatic mode. This will bring the arm in the appropriate cut plane close to the bone. The arm will then stop and ROSA Knee will enter collaborative mode, after which the surgeon will apply a gentle force to the cut guide to move it to the bone. In collaborative mode, the cut plane, slope, volume, and orientation are robotically maintained, but medial and lateral movement will be possible until the guide is pinned. With the foot pedal pressed, a pin is placed through the cut guide into bone. On screen, data will show live cut values. If values are acceptable, the second pin can be placed. Again, a manual saw cut is then made through the robotically constrained guide (Fig. 7 and 8). The pins are removed, and the foot pedal is pressed

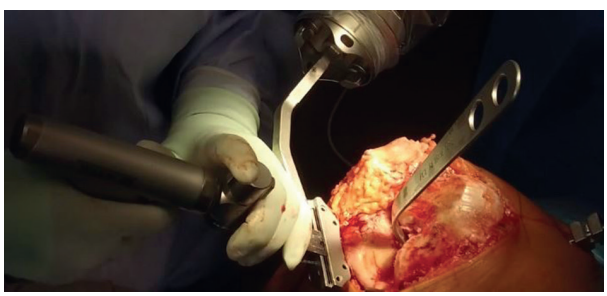

Fig. 7: ROSA Knee robot stabilizing the tibial cutting guide on the anterior tibia for the proximal tibial resection.

Fig. 8: Resection through the distal femoral cutting guide.

to move the arm away from the bone. The validation tool is placed on the distal femur to confirm the cut values correspond with the plan.

Femoral Rotation Using ROSA Knee Rotation Tool

An optional feature of ROSA Knee is the Femoral Rotation Tool, which guides the anterior and posterior rotational cuts of the femur based on a balanced flexion gap. If this option is selected, the ROSA Knee system will provide quantitative information about ligament laxity in flexion and extension after the surgeon performs a "pull" or distraction test. With the knee in approximately 90 degrees of flexion, a manual pull test is performed. Lamina spreaders or a Zimmer FuZion® instrument can be used to equally tension the medial and lateral compartments in flexion. ROSA Knee will record the flexion gap values and assess femoral component rotation. The 4-in-1 femoral resection can now be performed based on the data obtained by the ROSA Rotation tool.

Femoral 4-in-1 Measured Resection Method

The 4-in-1 resection tab is selected, and the foot pedal is depressed to move the robotic arm to the distal femur. The robot enters the collaborative mode, and the guide is placed on bone, aligning it according to the predetermined parameters as described above (referenced from the AP axis of the femur, posterior femoral condyles, or based on ligament tension with the knee in 90 degrees of flexion). The distal femur is drilled through the robotic cut guide. The robotic arm is removed from the field, and the 4-in-1 cut is performed using the cutting block.

Implantation

The trial implants are then manually provisionally implanted, and the postoperative knee state evaluation can be performed to assess the knee balance and range of motion. If the results are approved, proceed with final manual implantation. If alignment, range of motion, or balance is not satisfactory, the surgeon can return to the planning tool to adjust surface preparations or redo component position as desired.

Results

The early data in 30 TKAs performed with the ROSA Knee robot shows a high level of precision of tibial and femoral bone resection orientations and alignment. Compared to historical controls using conventional manual techniques or computer navigation in TKA, ROSA Knee has fewer outliers [17]. When using ROSA Knee robot for TKA, 99.9% of limb hip-knee-angles were within ±3 degrees of the plan, as compared to 87.2% when using conventional computer navigation or 69.9% with manual instrumentation [17]. Additionally, with ROSA Knee, 99% of coronal, sagittal, and rotational alignment parameters were within 3 degrees of the plan when using ROSA Knee, compared to the substantially greater percentage of outliers that have been reported with

Table 1: Percentage of alignment parameters within ±3 degrees of plan.

Alignment Parameters	ROSA Knee	Computer Navigation [17]	Manual Technique [17]
Femur var/val	100	93	83.6
Femur flex/ext	98.9	82.7	65.7
Tibia var/val	100	94.2	87.6
Tibia slope	99.9	84.2	74.6
Femur rotation	99.2	81.2	85.5
Coronal HKA	99.9	87.2	69.9

computer navigation and manual instrumentation (Table 1). Further analysis of quantified soft tissue balance and functional outcomes with ROSA Knee is not yet available.

Summary

Despite recent debate regarding tolerable levels of "imprecision" in TKA, malalignment beyond some acceptable range (particularly when coupled with soft tissue imbalance) can lead to failure and is thus undesirable. Early evidence with ROSA Knee robotic system suggests that not only is the technology effective at restoring or achieving the planned orientation of femoral and tibial bone resections, but also quantifying soft tissue balance, with a rapid learning curve and acceptable surgical efficiencies. Further clinical follow-up will be needed to corroborate our expectation that intraoperative, real-time mapping of a patient's anatomy and motion, coupled with augmented precision of bone resection, implant position and soft tissue balance provided by ROSA Knee will facilitate personalization of TKA procedures and improve functional outcomes and durability.

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Diagnostic Dilemma for the Orthopedic Surgeon

Michael Maher, Cyril Mauffrey

Background

1. Compartment syndrome is associated with serious long-term morbidity.
2. Appropriate treatment is invasive and involves its own risks.
3. The presentation of compartment syndrome is variable.
4. The diagnosis of compartment syndrome relies largely on clinical findings.
5. Pressure monitoring may provide supplemental but imperfect diagnostic guidance.

The diagnosis and management of compartment syndrome represents a dilemma for clinicians. A major cause of concern in treating compartment syndrome is the potentially devastating outcome if not treated effectively. Compartment syndrome results in ischemia within a fascial compartment that eventuates into necrosis of the tissues it encompasses. Sequelae of missed compartment syndrome include loss of function, contracture of joints, limb deformity, and painful neuropathies [1, 2]. These complications persist and significantly reduce quality of life. In light of this, the timely diagnosis and treatment of compartment syndrome is a focus of orthopedic surgery training. However, an inconsistency in practice remains. O'Toole *et al*. [3] demonstrated a wide variation between orthopedic surgeons, even within a single practice of orthopedic trauma specialists at a level I trauma center. A diagnostic rate of compartment syndrome for tibia fractures ranged from 2% to 24% depending on the surgeon who was on call. This demonstrates the lack of consensus and clarity with regard to diagnosis.

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The prognosis is grave in cases of missed compartment syndrome, but there are even severe repercussions for a diagnosis delayed by a matter of hours. If the treating surgeon correctly recognizes compartment syndrome, but attempts late release of the fascia over a necrotic compartment, the patient is subject to a high risk of infection and life-threatening complications [4]. Sheridan and Matsen report an infection rate of 46%, and an amputation rate of 21% after fasciotomy was delayed by 12 hours [5]. Only 2% of those patients treated on a delayed basis had a normal functioning extremity at final follow up, compared to 68% in those treated earlier. Reperfusion after severe muscle necrosis may further increase systemic effects. As myonecrosis develops and reperfusion is achieved, myoglobin is released into circulation, further contributing to myoglobinuria, metabolic acidosis, and hyperkalemia. This may lead to renal failure, shock, and cardiac events [6, 7]. Although fascial release is the appropriate treatment of acute compartment syndrome, clinicians must be aware of the dangers of late surgical intervention.

In addition to the serious consequences of missed or delayed treatment of acute compartment syndrome, clinicians and patients may face complications even in the setting of treatment with the correct technique and timing. A retrospective study looking at the long-term outcomes of fasciotomy placement by Fitzgerald *et al*. does not convey a completely benign procedure [8]. Reviewed outcomes of 164 patients over an 8-year period showed pain (10%), altered sensation (77%), dry skin (40%), pruritis (33%), discoloration (30%), swelling (13%), and muscle herniation (23%). Scarring of the extremities caused patients to keep extremity covered (23%), changed hobbies (28%), and even changed occupation (12%). Fasciotomy sites may also require the patient to undergo multiple interventions of attempted wound closure or grafting. In the setting of operative fractures, the placement of fasciotomy incisions may complicate surgical approach and increase risk of infection and non-union of fracture sites.

In addition to the issues relating to the morbidity, complications, and time pressure of compartment syndrome, the diagnosis itself is rarely straightforward. Patients may present following a typical injury and exhibit classic symptoms, but they will likely include a constellation of positive and negative findings. The diagnostic dilemma of acute compartment syndrome is always present because it is a clinical diagnosis. The classic signs and symptoms of acute compartment syndrome are often listed as the 5 or 6 "Ps" including some variation of pain, pressure, pulselessness, paralysis, paresthesia, and pallor [1, 2, 5, 9]. Early descriptions of diagnosis of compartment syndrome begin with those of ischemic contracture in the upper extremity by Volkmann, followed by more recent observations in the lower extremity, such as those described by Seddon [1]. However, while describing the diagnostic "Ps" of compartment syndrome, Seddon noted that they were absent in over half of the cases he reviewed [10]. These diagnostic findings may simply be unavailable in a timely manner. Pain out of proportion or in response to passive stretch may be an early indicator for compartment syndrome, but is unreliable in cases where a patient is obtunded or experiencing a neural deficit. Other signs, such as pallor or paralysis, may be delayed to the point of being useless.

The pressure gradient within the fascial compartment exceeds perfusion pressure in order for compartment syndrome to set in. It is not often possible to specify when this threshold is reached,

but we do know that the clinician only has a limited amount of time by that point. This threshold and the amount of time before irreversible damage is done has been a focus of study. A clear relationship between compartment pressure and blood pressure has been established with the use of animal models and observations of intra-compartmental pressures, tissue histology, oxygenation, and magnetic resonance spectroscopy [11, 12]. A study by Heckman *et al*. documented complete irreversible ischemic infarction of skeletal muscle by inducing elevated intra-compartmental pressures for 8 hours [8]. Variable recovery may be expected with earlier intervention. The threshold at which ischemia begins is difficult to predict. It may coincide with the traumatic event or set in insidiously. McQueen *et al*. [13] reported the average treatment of compartment syndrome 7 hours after manipulation and fixation in 13 cases with continuous monitoring and a delayed onset as late as 24 hours postoperatively. A late-onset variety of compartment syndrome has been reported as late as 4 days after an inciting event [6, 14].

Another factor adding to diagnostic difficulty of compartment syndrome is the myriad of injuries and conditions that may precede its onset. A classic scenario of acute compartment syndrome in the lower extremity is the result of a closed tibial shaft fracture [2, 15, 16]. However, compartment syndrome may develop with a huge variety of situations. Possible etiologies may include open and closed fractures, vascular injury, burns, intravenous access leakage, contusion, coagulopathies, constrictive dressing, patient positioning during surgery, drug overdose or animal bites [17]. Therefore, clinicians cannot rely on specific presentation factors to rule out developing compartment syndrome. The most common causes of acute compartment syndrome, as described in a series presented by McQueen *et al*. [18], was fracture (69%) followed by soft tissue injury without fracture (23.2%). The most common fractures observed were tibial diaphysis (36%) and distal radius (9.8%).

Compartment syndrome is a stressful situation for the patient and clinician. There exists a combination of significant morbidity, risks of invasive intervention, time limitations, and variations in presentation. Unfortunately, there is also the awareness that compartment syndrome and its sequelae are the source of a significant amount of litigation [19-21]. The prospect of undergoing a medical malpractice claim or suit is daunting and can be especially draining for physicians unaccustomed to the medicolegal process. It will likely create a significant cost in time, energy, finances, and emotional burden [22]. Orthopedic surgeons are a medical specialty at relatively higher risk of encountering medicolegal claims [23]. Given the high morbidity to patients, awards for plaintiffs or settlements may be large. One national database review of suits involving compartment syndrome found an average award for settlements out of court to be over 1 million dollars and average verdict awards for plaintiffs to be over 2 million dollars [17]. A review of claims involving compartment syndrome by Bhattacharyya and Vrahas found the average time commitment to resolve a claim to be 5.5 years [17].

Recommendations

The diagnosis of compartment syndrome is largely based on clinical judgment, history, and physical exam. Patient history in regard to mechanism of injury may be helpful in identifying factors

that would increase risk of soft tissue injury such as crushing or high energy trauma. History may also include other medical risk factors such as coagulopathies or infusion injury. Findings on the exam typically focus on the presence of pain, pressure, pulselessness, paralysis, paresthesia, and pallor. These findings are especially instructive if they correspond to a specific compartment in question. The presence of firmness versus compressibility of a compartment is advantageous as it does not require consciousness or cooperation of a patient and may be the earliest manifestation of compartment syndrome. It is important to note that acute compartment syndrome is not a static process and cannot be adequately ruled out in a suspected case based on a single evaluation. Rather, it is advisable to include serial examinations, typically spaced 1–2 hours apart to ensure any changes may be detected and addressed in a timely manner [16].

Measurement of compartment pressures can be a useful tool in situations where the clinical picture is muddled. There are multiple techniques described for pressure monitoring, including slit catheter, wick catheter, infusion, and side port needle devices. Commercially available side-port needle devices have gained popularity with their ability to measure multiple compartments and ease of use [8, 14]. As the development of ischemia is dependent upon a differential between compartment pressure and perfusion pressure, the threshold at which compartment pressures should be considered dangerous is often described in comparison to diastolic pressures. This differential, commonly described as ΔP, was described in canine models with a critical pressure being within 20 mmHg of diastolic pressure, resulting permanent abnormalities noted in muscle tissue. In a prospective study, McQueen and Court-Brown observed 116 patients with tibial diaphyseal fractures who underwent continuous anterior compartment pressure monitoring for 24 hours [24]. They noted absolute pressures reaching as high as 50 mmHg in multiple patients, but only three met a fasciotomy threshold criteria of ΔP less than 30 mmHg. No other patients were noted to develop compartment syndrome, resulting in a ΔP less than 30 mmHg being widely accepted as a threshold for surgical intervention.

Limitations and Pitfalls

Although clinical findings are important in diagnosis of acute compartment syndrome, the predictive value of individual findings is low. One analysis of 4 prospective studies involving 132 cases of compartment syndrome found that the positive predictive value of individual findings such as pain, paresthesia, and paresis was low at 11–15%, but the likelihood of successful diagnosis did increase with multiple clinical findings. However, the negative predictive value was as high as 98% [25]. Therefore, the presence of individual clinical findings was not as useful as noting the absence of such findings, to rule out the presence of compartment syndrome.

The use of local nerve blocks, epidural or regional anesthesia, is not recommended in the setting of possible compartment syndrome. Local anesthetics may mask pain from increasing compartment pressures or neurologic symptoms that would usually alert clinicians [26]. Additionally, the use of epidural anesthesia may increase the risk of developing compartment syndrome as sympathetic blockade will increase local blood flow and possibly exacerbate intracompartmental pressure increases [27, 28].

In situations where clinical findings of compartment syndrome may be unreliable, needle compartment pressure monitoring is often useful to evaluate an impending compartment syndrome. In these cases, a ΔP less than 30 mmHg will indicate the possible need for fasciotomy. However, compartment pressure monitoring is not a panacea for challenging clinical scenarios. As demonstrated by Heckman *et al*., compartment pressures taken from a few centimeters away from fracture site yield unreliable results [15]. One study observing 48 consecutive patients with tibial shaft fractures who were not suspected of developing compartment syndrome underwent pressure measurement of all four lower leg compartments [29]. There was an observed false-positive rate of 35% with the standard threshold of ΔP less than 30 mmHg. Depending upon a single compartment pressure as a sole criteria of surgical intervention would therefore result in unnecessary surgery and morbidity. This reinforces the necessity of clinical observations and judgment that provide context and correct diagnosis compartment syndrome.

Future Directions

The goal of future improvements in the diagnosis of compartment syndrome will obviously focus on increased accuracy, speed, and ease of diagnosis. The current state of practice requires clinical judgment resulting from experience and training. Although the use of pressure monitoring provides a more objective finding, it is a technique that is dependent upon technique and a limited understanding of the threshold of ischemic changes within extremities. Other modalities to better predict and measure intracompartmental pressures will likely improve our ability to diagnose and treat compartment syndrome.

Take-Home Message

The diagnosis and management of suspected compartment syndrome is a troubling situation for any clinician. The risks for long-term morbidity are present even with the most attentive and thorough evaluation. One must be suspicious not only in cases of high-energy trauma and crush injuries but also in unusual circumstances when patients show concerning signs of pressure and pain. The use of compartment pressure monitoring is a useful supplemental tool, but surgeons should be hesitant to base management solely on a single pressure measurement. Clinical judgment and close monitoring are the best tools we have to treat patients presenting with suspected compartment syndrome.

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