PRINCIPLES OF HIP ARTHROSCOPY

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PRINCIPLES OF HIP ARTHROSCOPY

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The field of arthroscopy, originating from Denmark in 1912, has rapidly evolved to diagnose and treat a wide range of musculoskeletal pathologies. Although around for sometime, arthroscopy in the field of orthopedics has traditionally focused on the knee, shoulder, or elbow, as arthroscopy of the hip is technically challenging; the deep structures of the hip, including neurovascular bundles, require specialized training and equipment to access. However, with advances in surgical techniques, hip arthroscopy has become increasingly popular given its ability to treat pathologies with previously poor prognoses such as labral tears, hip arthritis and femoroacetabular impingement (FAI).

When indicated, hip arthroscopy results in shorter recovery times, low complication rates, and excellent outcomes in quality of life and pain regardless of age, gender or activity level. The purpose of this e-book is to shed light on this expanding field by delving into the common hip pathology femoroacetabular impingement, its clinical relevance, and to explore various surgical techniques and postoperative rehabilitation. It is our hope that this textbook provides valuable knowledge to advance the field of hip arthroscopy, enhance surgical techniques, and ultimately increase the quality of patient care.

Enjoy!

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EDITORIAL
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Editorial: Hip Arthroscopy

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Keywords: hip arthroscopy, capsular management, femoroacetabular impingement, hip preservation surgery, cam deformity, pincer deformity, labral repair and reconstruction

The Editorial on the Research Topic

Hip Arthroscopy

Hip arthroscopy is a minimally invasive surgical procedure employed in the management of several hip pathologies. It is relatively novel procedure that has gained acceptance for the diagnosis and treatment of hip pathologies (Lee et al.; Kuhns et al.). Due to less morbidity, relatively shorter recovery time, and excellent outcomes, hip arthroscopy has become one of the fastest growing procedures performed in the field of orthopedic surgery (Lee et al.; Kuhns et al.).

The focus of this research topic is on the management of hip and pelvis pathologies. Femoroacetabular impingement (FAI) has only recently been described by Kuhns and colleagues as a clinical syndrome that results from abnormal osseous morphology of the proximal femur and acetabulum (Kuhns et al.). Numerous studies have cited that hip arthroscopy for the treatment of FAI may result in pain relief, improvement of activities of daily living, and return to sporting activities (Kuhns et al.).

The natural history of FAI is not well understood, but there are some patients that are at-risk of significant chondrolabral injury that may lead to early onset hip joint degeneration. Identification and treatment of hips at-risk may alter the natural progression of disease, but there is insufficient evidence currently in literature to suggest that surgical intervention in symptomatic or asymptomatic patients will prevent subsequent development of osteoarthritis.

Early diagnosis of FAI is dependent on an improved ability to identify abnormal morphology. Plain radiographs are the initial screening tests for FAI, but there are some patients with subtle pathomorphology. Levy and colleagues affirmed that CAM deformities are more common in males while pincer deformities are predominant in females (Levy et al.). They also reported that the CAM deformities in females may be more subtle than their male counterparts. Kuhn and others described the role of the capsule in hip pathology, but we still do not fully understand the differences in biologic and biomechanical profiles but likely contribute to altered kinematics of the hip (Strosberg et al.). Clinical and basic science studies have demonstrated that the capsule should be either repaired or plicated to prevent iatrogenic instability (Kuhns et al.).

Bittersohl and others described the use of magnetic resonance imaging as the most precise imaging modality in characterizing the extent of chondrolabral damage. The authors asserted that the integrity of the articular cartilage significantly affects the surgical decision to perform hip arthroscopy as well as the outcome of the procedure (Bittersohl et al.).

White and investigators described the labrum as a crucial contributor to hip joint stability by maintaining joint fluid pressurization and providing seal (White and Herzog). While the decision to perform labral debridement, repair, or reconstruction may depend on surgeon preference, the authors advocated that the indications for labral reconstruction include insufficient labral tissue or an irreparable labral tear (White and Herzog).

The relationship between FAI and surrounding neuromuscular dysfunction of the hip and pelvis has not been well defined and often exist together. Strosberg and colleagues explained that alterations

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in hip biomechanics in the setting of FAI lead to excessive strain on core musculature culminating in symptomatic core muscle injury (also known as athletic pubalgia or sports hernia) (Strosberg et al.).

Rehabilitation is a vital component of a successful outcome after hip arthroscopy. Grzybowski and others reported heterogeneity in rehabilitation after hip arthroscopy (Grzybowski et al.). Consequently, the authors believe that the development of evidence based protocols may provide consistency in the rehabilitation after hip arthroscopy.

In some cases, hip arthroscopy may not be able to address the deformity comprehensively, and open hip preservation techniques need to be utilized. Kuhns and colleagues reviewed the open techniques for the treatment of FAI in addition to developmental or acquired deformities of the acetabulum or femur (i.e., varus/valgus, torsion, or version), Legg–Calve–Perthes disease, and chronic slipped capital femoral epiphysis that may be more effectively managed by open procedures (Levy et al.).

The editors of the Hip Arthroscopy research topic believe that the content provides the most up to date information in a field that is rapidly evolving. We hope that you enjoy these articles and may stimulate further discussion and understanding of non-arthritic hip pathology.

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REVIEW
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The Natural History of Femoroacetabular Impingement

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Femoroacetabular impingement (FAI) is a clinical syndrome resulting from abnormal hip joint morphology and is a common cause of hip pain in young adults. FAI has been posited as a precursor to hip osteoarthritis (OA); however, conflicting evidence exists and the true natural history of the disease is unclear. The purpose of this article is to review the current understanding of how FAI damages the hip joint by highlighting its pathomechanics and etiology. We then review the current evidence relating FAI to OA. Lastly, we will discuss the potential of hip preservation surgery to alter the natural history of FAI, reduce the risk of developing OA and the need for future arthroplasty.

Keywords: femoroacetabular impingement, hip osteoarthritis, hip preservation surgery, FAI etiology, hip arthroscopy

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INTRODUCTION

The management of femoroacetabular impingement (FAI) is a rapidly developing field in orthopedics. Described by Ganz in 2003, FAI is a pathologic condition resulting from abnormal acetabular and femoral head/neck morphology that has been implicated as a precursor to secondary osteoarthritis (OA) (1–3). However, the relationship between FAI and OA is not straightforward as there exists a large asymptomatic population and without radiographic signs of OA that possesses the morphologic characteristics of FAI (4). While initially managed conservatively, symptomatic FAI is often treated surgically with the goals of relieving pain, increasing range of motion, and preventing or delaying OA and the potential need for total hip arthroplasty (THA). As FAI is increasingly diagnosed in a younger and more active population, the link between high intensity athletic participation during adolescence and the onset of FAI is under investigation (5). The purpose of this article is to review our current understanding of FAI by focusing on the mechanisms of injury, etiology, treatment strategies, and the debate about its predisposition to OA.

HOW DOES FAI DAMAGE THE HIP JOINT?

Femoroacetabular impingement results from femoral and acetabular incongruity that induces labral, and chondral damage, causing pain and restricting mobility. Cam lesions at the femoral head/neck junction as well as pincer lesions signifying acetabular overcoverage comprise the osseous deformities of FAI (**Figure 1A**) (1, 6). Termed "mixed" lesions, commonly FAI is a combination of both with varying degrees, but cam and pincer lesions also occur in isolation. One recent systemic review of 1130 hips found mixed impingement in 45% of cases (7–9). While both lesions are seen in FAI, they result in distinct patterns of articular damage which are markedly different (**Table 1**). Pincer lesions can vary in severity from focal overgrowth of the anterior acetabular rim with acetabular retroversion

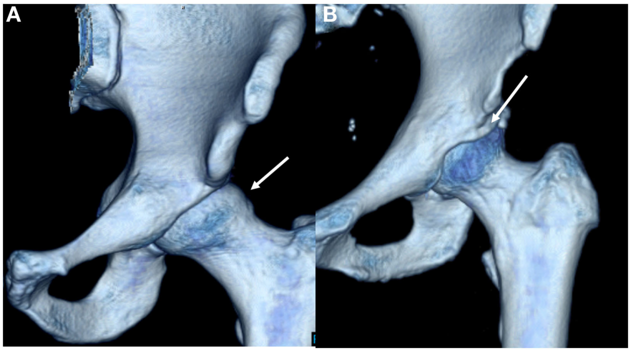

FIGURE 1 | Three-dimensional CT reconstructions demonstrating cam (A) and pincer (B) deformities.

TABLE 1 | General characteristics of cam and pincer deformities in FAI.

	Cam	Pincer
Presentation	Hip/groin pain	Hip/groin pain
Demographic trends	Younger males	Young–middle-aged females
Osseus morphology	Aspherical bump at the femoral head–neck junction, decreased femoral head–neck offset	Focal or global acetabular overcoverage; acetabular retroversion
Injury mechanism	Primarily affects cartilage with repeated flexion. The labrum gets damaged secondarily	Affects labrum primarily; with damage patterns located on the peripheral acetabulum. Associated with contrecoup lesions
Radiographic predictors	Pistol grip deformity; alpha angle >50°	LCEA > 39°; ACEA > 39°, posterior wall sign

to the more global deformities seen with coxa profunda or protrusio acetabuli (**Figure 1B**) (2). The pincer deformity initially damages the labrum when the hip is in flexion, which brings the acetabular overgrowth into apposition with the femoral neck, thereby compressing the anterior labrum (3, 6). With repeated hip flexion, the labrum sustains repetitive microtrauma gradually separating from the acetabular cartilage and eventually failing (2). As the disease progresses, persistent pressure between the posteroinferior acetabulum and the posteromedial aspect of the femoral head initiates acetabular cartilage damage known as the "contrecoup" lesion (10, 11).

Cam deformities present with femoral head asphericity, seen as a flattening of the anterior contour of the head/neck junction or an osseous bump producing a decreased femoral head–neck offset. The bump is often located in the anterolateral or anterosuperior region of the head–neck junction and can be identified as a "pistol grip" deformity on AP and modified Dunn radiographs (3, 11). Similar to the pincer lesion, cam impingement is most symptomatic with the involved leg in flexion (12). However, unlike pincer lesions, the mechanism of impingement is through shear stress generated as the femoral lesion rotates through the anterosuperior acetabulum (11). From a clinical standpoint, the mixed variant of FAI can present with variable degrees of both injury patterns depending on the predominance of the existing lesions (3).

While osseous deformities underlie FAI, symptoms usually result following labral and chondral injury secondary to the impingement itself. In a recent study, Clohisy et al. found that 93% of patients undergoing surgery for FAI had associated labral injury, and 83% had associated cartilage damage (9). Labral and cartilage injuries occur by different mechanisms for cam and pincer lesions. Patients with pincer impingement present primarily with labral damage, consistent with the pathomechanics of acetabular overcoverage (12). Cartilage lesions in patients with pincer deformities are distinct, with acetabular chondral injury occupying a narrow circumferential band that is less severe than those with cam deformities (7, 12). Additionally, repeated microtrauma to the labrum in pincer abnormalities initiates bone growth at the acetabular rim and promotes eventual labral ossification.

For cam deformities, as the eccentric aspect of the lesion passes through the anterosuperior acetabulum during flexion, the transition zone between the labrum and acetabular cartilage is subjected to compressive and shear stresses (11). This causes the labrum to translate away from the joint while the cartilage is pushed in the opposite direction, preserving the labrum until later in the disease process (7, 12). Consequently, cam lesions initially damage the acetabular cartilage, causing delamination of the cartilage from the labrum, compared to pincer lesions which affect the labrum primarily (3, 11). As the mixed variant of FAI is common, patients frequently present with evidence of both chondral and labral damage resulting from cam and pincer deformities, respectively (3). Notably, poor preoperative cartilage status in symptomatic FAI patients is associated with delayed time till surgery and is a harbinger of potentially worse outcomes (13–15). Overall, the bony lesions of FAI induce variable damage to the hip joint, with cam lesions preferentially affecting the acetabular cartilage and pincer lesions affecting the labrum and peripheral acetabulum in a more circumferential manner (16).

WHO GETS FAI?

The collective understanding of the etiology, history, and clinical presentation of FAI has evolved dramatically over the past decade. As FAI represents a syndrome with varying degrees of bony, chondral, and labral pathology at the hip joint, its presentation is similarly diverse. FAI is frequently seen in athletes. One recent systematic review of North American patients undergoing surgery for FAI found that the average age at surgery was 28 years and there was a mild female preponderance FAI at 55% of patients (9). Pincer FAI typically presents in middle-aged women; however, pincer lesions occur commonly in males as well (3, 9, 17). Cam lesions, on the other hand, demonstrate a near 3:1 male predominance and are seen more often in the younger population (3, 17). FAI can be present in the acute or chronic setting, and can be associated with prior trauma, such as malunion of a femoral neck fracture. It has also been associated with pediatric hip diseases, such as developmental dysplasia of the hip (DDH), slipped capital femoral epiphysis (SCFE), and Legg–Calve–Perthes disease (LCPD) (18, 19). Despite this, the most common presentation for FAI is idiopathic, atraumatic pain that has been ongoing between 12 and 16 months (9).

The precise etiology of FAI is still unclear; however, several theories exist linking genetic predisposition, pediatric deformity, and trauma, as well as high intensity adolescent athletic activity to the onset of FAI. Genetic factors involved in FAI pathogenesis were proposed by Pollard et al. who reported that siblings of patients with symptomatic FAI possessed an increased predilection for radiographic and clinical impingement signs (20). These findings, coupled with the increased incidence of cam FAI in males, promote the conclusion that there are intrinsic, although as of yet unidentified, genetic factors influencing hip morphology in the development of FAI (19, 21).

Additionally, pediatric hip disorders can predispose to FAI. SCFE deformities have been shown to predispose to the development of cam impingement in adulthood, which is mechanically consistent with the anterosuperior displacement of the femoral metaphysis in the pediatric disease (5, 19, 22, 23). Similarly, the natural history of LCPD can lead to FAI, in this case resulting from aspherical enlargement of the femoral head (coxa magna) representing the healed osteonecrotic epiphysis (23–25). Unlike SCFE, however, LCPD promotes both intra- and extra-articular impingement, complicating the nature of pain generation (19, 26, 27). Cam lesions have been found in the patients with prior femoral neck fractures, with Mathew et al. finding radiographic FAI in 84% of this cohort (28, 29). Furthermore, FAI can arise as a postsurgical consequence of the Bernese Peri-Acetabular Osteotomy, as the procedure can induce an iatrogenic pincer type acetabular conformation (30, 31). In general, any condition or procedure that alters the native bony anatomy of the hip joint can lead to clinical and radiological signs of impingement and secondary FAI.

While FAI is associated with prior hip pathology, it is most often idiopathic, and particularly common in the athletic population (3). This finding has led to multiple efforts investigating the relationship between sports participation and FAI development (19, 30, 32–37). One recent systematic review of 208 competitive male athletes (300 hips) concluded that athletes participating in high-impact sports (basketball, hockey, and soccer) were significantly more likely to develop cam lesions than non-athletes (odds ratio 1.9–8.0) (35). Furthermore, it has been proposed that the cam lesions develop in response to high intensity activity during development (5, 32, 38). In a study of 77 elite adolescent hockey players, Siebenrock et al. report higher alpha angles in athletes with closed physes as well as higher alpha angles in athletes reporting hip pain (39). In a recent prospective study of pre-professional adolescent soccer players, Agricola et al. measured proximal femur morphology at baseline and 2 years, finding significantly increased radiologic evidence of cam lesions at the 2-year time point (40). While there is evidence that suggests cam lesions can develop in high-intensity adolescent athletes, these studies primarily investigated a western European population. The prevalence of cam deformities in East Asian populations, however, is markedly reduced (41, 42). Thus, the role of genetics likely predisposes certain populations to FAI deformity under given repetitive and supra-physiologic loading conditions (21).

DOES FAI PREDISPOSE TO ARTHRITIS?

Based on multiple *in situ* observations of the impingement and damage patterns associated with FAI through open surgical dislocation of the femoral head, Ganz et al. proposed FAI as a precursor to the development of OA (1, 2). Their group highlighted the specific labral and chondral injuries affiliated with cam and pincer lesions and argued that prolonged contact between the deformed acetabulum and proximal femur promote further cartilage damage and eventual joint deterioration. Cam lesions, in particular, have demonstrated an increased risk for the development of OA (16, 43–46). One retrospective study analyzed the radiographs of patients with unilateral hip OA and found that the presence of a non-spherical femoral head as seen in cam lesions has a significant association with OA (45). Furthermore, one prospective study of Dutch patients demonstrated that moderate (alpha angle >60°) and severe cam deformities (alpha angle >83°) demonstrated a respective 3.7 and 10 times greater likelihood of developing OA over a 5-year time span when compared to controls (47). This study also identified a positive predictive value of 53% for the future development of OA in patients with cam deformities on X-ray and a positive impingement sign (47). Similarly, in a study investigating the prevalence of FAI deformities in patients undergoing THA for OA, found patients younger than 65 undergoing THA were more likely to have evidence of cam, but not pincer lesions (48). Thus, while cam lesions are linked to the development of OA, the relevance of pincer lesions in OA are less clear (44, 49). However, as isolated pincer lesions are rare, seen in only 7% of FAI cases, the cam lesion present in the other 93% of FAI cases may be the primary driver of OA in FAI (9).

In addition to the epidemiologic and radiographic studies correlating OA development to characteristic FAI lesions, biomarkers seen in OA are being investigated to identify correlations to patients with FAI [**Table 2** (72–80)]. While there are over 70 biomarkers that have been studied in OA, validation has proved challenging (50). One recent systematic review identified six biomarkers that were correlated to OA progression: cartilage oligomeric protein (COMP), 25-OH vitamin D, N-terminal telopeptide (NTX), type II collagen C telopeptide (CTX-II), TIMP metalloproteinase inhibitor (TIMP), and vascular cell adhesion molecule 1 (VCAM-1) (50). In support of COMP as a biomarker, Dragomir et al. found that COMP levels were higher in patients with clinical signs of hip dysfunction and Bedi et al. reported COMP levels to be significantly increased in male athletes with FAI compared to a control group (50–52). However, the relevance of COMP has been questioned by several studies that have not found associations between COMP and hip OA (50, 53, 54). One study suggests that deamidated COMP (DCOMP) may be a more useful biomarker as they found a strong association with DCOMP levels and radiographic OA, as well as higher DCOMP concentrations in regions in proximity with OA lesions (54). Additionally, Bedi et al. also found a 276% increase in circulating CRP levels in patients with FAI compared to controls, indicating that there may

TABLE 2 | Molecular biomarkers associated with the onset and/or progression of hip osteoarthritis and their relation to FAI.

Biomarker	Relation to hip OA	Relation to FAI
Cartilage oligomeric protein (COMP) (52, 74)	Higher levels may be associated with hip OA progression	Elevated in male athletes with FAI (1 study)
25-OH vitamin D (75)	Lower levels may be associated with worsening Hip OA	
N-terminal telopeptide (NTX) (76)	Higher levels may be associated with hip OA progression	
Urine type II collagen C telopeptide (CTX-II) (77)	Higher levels associated with hip OA progression	
Tissue inhibitor of metalloproteinase-1 (TIMP) (78)	Higher levels may be associated with hip OA progression	
Vascular cell adhesion molecule 1 (VCAM-1) (79)	Higher levels may be associated with hip OA progression	
C-reactive protein (CRP) (52)		Higher in FAI patients compared to non-FAI patients (1 study)
Synovial fibronectin-aggrecan complex (sf-FAC) (80)		Higher in patients undergoing surgery for hip replacement compared to hip arthroscopy (1 study)

be an inflammatory component to FAI (52). This observation was supported by a recent histologic study which found significantly increased macrophage and mast cell expression in labrums from patients with FAI compared to labrums from patients with OA (55). While there are currently no validated biomarkers for FAI, studies have shown promising associations that must be confirmed by future research (50).

While cam or pincer deformities are a necessary condition for FAI, they are not pathognomonic and are frequently encountered in the asymptomatic population. One recent systematic review of 26 studies with 2114 total asymptomatic hips found an average cam and pincer lesion prevalence of 37 and 63%, respectively (4). Previously reported percentages of cam lesions ranged between 10 and 24%, and the authors attribute their reported increase to the high percentage of athletes in the review population (56–58). Cam lesions, measured on MRI as well as AP and modified Dunn radiographs, are variably defined by alpha angle and standardized cutoff values for normal and abnormal alpha angles are lacking (59–61). Pincer lesion prevalence may also be over-reported as radiographic findings, such as the cross over and posterior wall signs have proven unreliable markers (4, 62). Despite this, it is clear that the radiographic findings of FAI are common in the asymptomatic population, which has brought the correlation between cam and pincer deformities and OA into question (63). One putative explanation for this discrepancy lies in status patient's articular cartilage. Hogervorst et al. introduced the term "cartilotype" to assess the susceptibility of cartilage to degradation in response to mechanical stress (21). Thus, patients with radiographic FAI may remain asymptomatic if their articular cartilage is able to withstand the impingement produced by the osseous deformities (64). Taken together, the surgeon should relate the patient's clinical history and findings on physical exam to the radiographic evidence when preparing for the surgical correction of FAI.

DOES SURGICAL TREATMENT ALTER THE NATURAL HISTORY?

A number of studies have demonstrated that surgery for FAI is a safe and effective means to improve function and decrease pain levels in the short- and mid-term (65–67). Generally, open and arthroscopic treatment modalities appear to provide comparable outcomes in the mid-term aside from general health-related quality of life, which is significantly higher in the arthroscopic group (68). Intuitively, it makes sense that surgical intervention to remove the osseous mechanical blocks to motion will prevent further damage to the soft tissue structures (cartilage and labrum) of the hip. Studies have corroborated that the severity of cartilaginous and labral degenerative changes are directly associated with the duration of the underlying pathology (69–71). However, the available literature to date cannot assure that surgical intervention either in the asymptomatic or symptomatic patient will prevent the progression to OA and the risk of eventually requiring a THA. Prognostic indicators of early OA following treatment of FAI have yet to be elucidated, thus it is difficult at this time to associate treatment of FAI and the progression of OA.

Research strategies to further investigate the natural history of FAI and the association with OA are currently underway. Such efforts focus on prospective evaluations of younger patients with an early diagnosis of FAI. This study design enables researchers to focus on early interventions that may change the disease course over a long period of time. This study design, ideally in a randomized fashion, will aid in answering long-term questions regarding surgical intervention (both arthroscopic and open) and the ability of these interventions to delay or prevent OA and the need for THA.

CONCLUSION

The purpose of this article is to review our current understanding of FAI by focusing on the natural history of the disease process. Surgical correction of the underlying osseous pathology in the symptomatic patient will improve function and decrease pain. Although an association between FAI and the development of OA is logical, long-term longitudinal studies have not yet been completed to substantiate cause and effect. Therefore, there currently is insufficient evidence to recommend prophylactic surgery in asymptomatic patients with radiographic evidence of FAI. Future studies targeting the early diagnosis and treatment of FAI will assist in elucidating the etiology of FAI, the natural history of the disease process, and ultimately the association between FAI and the progression to hip OA.

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REVIEW
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Fifty most cited articles for femoroacetabular impingement and hip arthroscopy

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Growing awareness of femoroacetabular impingement (FAI) and recent innovations in management have resulted in hip arthroscopy becoming one of the fastest-growing orthopedic subspecialties. The purpose of this study was to identify the 50 most cited articles related to the topic of FAI and hip arthroscopy and to analyze their characteristics. The overall number of citations within these articles ranged from 99 to 820. Citation density ranged from 4.41 to 74.55. Seven countries produced these articles with the majority attributed to the United States ($n = 26$) and Switzerland ($n = 18$). Clinical studies made up more than half of the top articles ($n = 27$). The Journal of Bone and Joint Surgery level of evidence most commonly encountered was level IV ($n = 24$), while the remaining articles were level III ($n = 3$). No randomized controlled trials or non-randomized controlled trials were encountered in this search. The level of evidence was not significantly correlated with the overall number of citations, publication year, or citation density. The current top 50 list provides orthopedic surgeons interested in hip arthroscopy with an up-to-date core list of the most cited articles in the scientific literature and represents a foundation to use to develop their knowledge regarding hip arthroscopy and FAI.

Keywords: hip arthroscopy, femoroacetabular impingement, top 50, sports surgery, citation review

Introduction

Analyses of "most cited articles" have been performed in the field of orthopedics as a specialty in general (1, 2), as well as in various orthopedic subspecialties, including pediatrics, hand, shoulder, arthroscopy, and total joint arthroplasty (3–7). However, no such study has been published on "hip arthroscopy" or "femoroacetabular impingement (FAI)." In the current literature, a study identifying the top 25 cited articles in orthopedic arthroscopy in 2012 by Gheiti et al. (5) included only one article related to hip joint.

While Smith-Peterson first described FAI in 1935 as the "impingement of the femoral neck on the anterior acetabular margin" in a 55-year-old male patient, the concept of FAI has only relatively recently become widely accepted as a source of hip pain and dysfunction. This is due, in large part, to the extensive work by Ganz and colleagues (8–10). Similarly, the first clinical report of hip arthroscopy was published by Takagi in 1939 (11), but it was not until the 1980s that hip arthroscopy became more widely utilized in the diagnosis and treatment of hip pathology (12). The understanding of FAI as well as the surgical technique and clinical outcomes following hip arthroscopic procedures has grown exponentially.

The purpose of this study was to identify the 50 most cited articles related to the topic of FAI and hip arthroscopy and to analyze their characteristics. By this method, we sought to create an up-to-date list of the most important articles in this emerging field.

Methods

This study did not require approval from institutional review board as it involved publicly available data. Following previously described methods (2, 4, 6), we used the "cited reference search" through the ISI Web of Knowledge (Thompson Reuters, New York, NY, USA) to identify the top 50 cited articles in FAI and hip arthroscopy. The search was performed in October 2014. Articles published in any of the 67 journals categorized under the topic heading of "orthopedics" in the ISI Web of Science, which include general and subspecialty-specific, clinical, and basic science orthopedic journals, as well as physical therapy journals, were considered. The following search terms were used: "Hip Arthroscopy," "Femoroacetabular Impingement," and "Hip Labral Tears." Although our primary aim was to include articles that arthroscopic hip surgeons would find relevant to their practice, we also chose to include articles describing open management of FAI as we felt that the history and evolution as well as alternative treatments of FAI would be of interest to an arthroscopic hip surgeon. Moreover, studies pertaining to diagnostic, perioperative, and postoperative management of FAI were included. Articles that were considered to be relevant to FAI and hip arthroscopy were reviewed by two authors and the decision to include or exclude was made through consensus. The articles were then ranked according to the number of highest citations to generate a list of 50 articles. When the articles had identical number of citations, the paper with higher citation density (defined as numbers of citations per year since publication) was ranked higher.

While reviewing the identified articles, the following information was recorded: article title, source journal of the article, first author, corresponding author, year of publication, country of origin (in accordance with the corresponding author's address), and article type (basic science, clinical research article, and diagnostic studies). Clinical studies were further subtyped as randomized controlled trial, cohort study, case series, review article, case report, or expert opinion and assigned a level of evidence based on the Journal of Bone and Joint Surgery (JBJS) criteria (13).

All statistical analyses were calculated using SPSS statistical software (SPSS Inc., Chicago, IL, USA).

Results

There were 50 total publications included in this top FAI and hip arthroscopy articles list (**Table 1**). The overall number of citations within these articles ranged from 99 to 820, with an average of 182.70 ± 133.50 citations per article. Citation density for these articles ranged from 4.41 to 74.55, with an average density of 18.55 ± 13.33. The total amount of citations attributed to these articles was calculated to be 9135. These articles were published between 1987 and 2009, with 2004 producing the greatest number of top articles ($n = 8$) (**Figure 1**). The average number of years since publication of these articles was 11.34 ± 4.88. The selected articles were published in 10 of the 67 examined orthopedic journals, with Clinical Orthopaedics and Related Research containing the greatest amount of publications ($n = 18$) followed by Arthroscopy: The Journal of Arthroscopic and Related Surgery ($n = 11$) (**Table 2**). When analyzed by total citation, Clinical Orthopaedics and Related Research represented the highest citation count ($n = 3611$) followed by the JBJS-British Volume ($n = 1600$). Every article was published in the English language.

Seven countries produced these top articles with the vast majority being attributes to the United States ($n = 26$) and Switzerland ($n = 18$). Canada ($n = 2$), Brazil ($n = 1$), Italy ($n = 1$), Japan ($n = 1$), and the United Kingdom ($n = 1$) did not produce more than two articles each. While the United States represented the highest amount of articles in the top 50, the articles originating from Switzerland contained a greater amount of total citations (US: 3684, Switzerland: 4664), a higher citation average per article (US: 141.69, Switzerland: 259.11), higher total citation density (US: 382.19, Switzerland: 480.00), and a greater average citation density (US: 14.70, Switzerland: 26.67).

Ganz had the highest cited article with his 2003 publication "Femoroacetabular impingement – a cause for osteoarthritis of the hip." JWT Byrd held the most first-authored articles with 4 of the top 50, closely followed by Ganz, McCarthy, and Philippon with 3 first-authored articles each. However, when this list was analyzed by corresponding authors, Leunig was listed as the corresponding author for the most with 5, followed by Ganz and Byrd with 4, and Philippon and McCarthy with 3.

Stratifying the top 50 articles by citation density, Ganz again continued to represent the top article (74.55 citations per year), while Beck had the second densest article (58.78 citations per year). Dr. Ganz had the third most densely cited article as well (44.17). In fact, Dr. Ganz published three of the most densely cited articles within the top 10 and Beck had two of the most densely cited articles in the same list.

Clinical studies made up more than half of the top articles ($n = 27$), while the remaining articles comprised review type articles ($n = 12$), radiographic and/or diagnostic based articles ($n = 7$), and basic science articles ($n = 4$). Among the clinically based articles, the JBJS level of evidence most commonly encountered was level IV ($n = 24$), while the remaining articles were level III ($n = 3$). No randomized controlled trials or non-randomized controlled trials were encountered in this search. The level of evidence was not significantly correlated with the overall number of citations ($R = 0.043$, $P = 0.767$), publication year ($R = 0.211$, $P = 0.142$), or citation density ($R = -0.014$, $P = 0.924$).

The most recently published article on the top 50 list was published in 2009 by Leunig et al., and while it ranks 33rd in total citations (124 total citations), this article ranked 11th in terms of citation density. The earliest article was published in 1987 by Glick, ranking 41st in terms of total citations (119 total citations); however, it was the least densely cited article among the top 50 papers (4.41). Interestingly, while the year of publication does not significantly correlate with total citations, it does so with citation density ($R = 0.023$, $P = 0.002$). There were no significant differences when comparing clinical basic science type studies in relation to total citations or citation density ($P > 0.05$).

TABLE 1 | List of the top 50 cited articles in femoroacetabular impingement and hip arthroscopy with total citations and citation density.

Rank	Article	Total citations	Citation density
1	Ganz et al. (2003). Femoroacetabular impingement: a cause for osteoarthritis of the hip (9)	820	74.55
2	Beck et al. (2005). Hip morphology influences the pattern of damage to the acetabular cartilage: femoroacetabular impingement as a cause of early osteoarthritis of the hip (14)	529	58.78
3	Ganz et al. (2001). Surgical dislocation of the adult hip a technique with full access to the femoral head and acetabulum without the risk of avascular necrosis (8)	435	33.46
4	Ito et al. (2001). Femoroacetabular impingement and the cam-effect. A MRI-based quantitative anatomical study of the femoral head-neck offset (15)	376	28.92
5	Beck et al. (2004). Anterior femoroacetabular impingement: part II. Midterm results of surgical treatment (16)	346	34.60
6	Siebenrockwt al. (2003). Anterior femoroacetabular impingement due to acetabular retroversion. Treatment with periacetabular osteotomy (17)	286	26.00
7	Ganz et al. (2008). The etiology of osteoarthritis of the hip: an integrated mechanical concept (10)	265	44.17
8	Lavigne et al. (2004). Anterior femoroacetabular impingement: part I. Techniques of joint preserving surgery (18)	239	23.90
9	McCarthy et al. (2001). The Otto E. Aufranc Award: The role of labral lesions to development of early degenerative hip disease (19)	237	18.23
10	Byrd and Jones (2000). Prospective analysis of hip arthroscopy with 2-year follow-up (20)	203	14.50
11	Espinosa et al. (2007). Treatment of femoroacetabular impingement: preliminary results of labral refixation. Surgical technique (21)	200	25.00
12	Philippon et al. (2009). Outcomes following hip arthroscopy for femoroacetabular impingement with associated chondrolabral dysfunction: minimum two-year follow-up (22)	196	39.20
13	Fitzgerald (1995). Acetabular labrum tears. Diagnosis and treatment (23)	195	10.26
14	Murphy et al. (2004). Debridement of the adult hip for femoroacetabular impingement: indications and preliminary clinical results (24)	178	17.80
15	Tanzer and Noiseux. (2004). Osseous abnormalities and early osteoarthritis: the role of hip impingement (25)	177	17.70
16	Meyer et al. (2006). Comparison of six radiographic projections to assess femoral head/neck asphericity (26)	166	20.75
17	Wenger et al. (2004). Acetabular labral tears rarely occur in the absence of bony abnormalities (27)	165	16.50
18	Siebenrock et al. (2004). Abnormal extension of the femoral head epiphysis as a cause of cam impingement (28)	154	15.40
19	Seldes et al. (2001). Anatomy, histologic features, and vascularity of the adult acetabular labrum (29)	151	11.62
20	Farjo et al. (1999). Hip arthroscopy for acetabular labral tears (30)	150	10.00
21	Myers et al. (1999). Anterior femoroacetabular impingement after periacetabular osteotomy (31)	149	9.93
22	Ikeda et al. (1988). Torn acetabular labrum in young patients. Arthroscopic diagnosis and management (32)	148	5.69
23	Philippon et al. (2007). Femoroacetabular impingement in 45 professional athletes: associated pathologies and return to sport following arthroscopic decompression (33)	143	20.43
24	Larson and Giveans (2008). Arthroscopic management of femoroacetabular impingement: early outcomes measures (34)	135	22.50
25	Peters and Erickson. (2006). Treatment of femoroacetabular impingement with surgical dislocation and débridement in young adults (35)	135	16.88
26	Kelly et al. (2005). Arthroscopic labral repair in the hip: surgical technique and review of the literature (36)	132	14.67
27	Byrd (1994). Hip arthroscopy utilizing the supine position (37)	132	6.60
28	Philippon et al. (2007). Arthroscopic management of femoroacetabular impingement: osteoplasty technique and literature review (38)	127	18.14
29	Beaulé et al. (2005). Three-dimensional computed tomography of the hip in the assessment of femoroacetabular impingement (39)	127	14.11
30	Leunig et al. (2004). Magnetic resonance arthrography of labral disorders in hips with dysplasia and impingement (40)	127	12.70
31	Wagner et al. (2003). Early osteoarthritic changes of human femoral head cartilage subsequent to femoroacetabular impingement (41)	125	11.36
32	Anderson et al. (2001). Hip and groin injuries in athletes (42)	125	9.62
33	Leunig et al. (2009). The concept of femoroacetabular impingement: current status and future perspectives (43)	124	24.80
34	Byrd and Jones (2004). Diagnostic accuracy of clinical assessment, magnetic resonance imaging, magnetic resonance arthrography, and intra-articular injection in hip arthroscopy patients (44)	124	12.40
35	Larson and Giveans (2009). Arthroscopic debridement versus refixation of the acetabular labrum associated with femoroacetabular impingement (45)	123	24.60

(Continued)

TABLE 1 | Continued

Rank	Article	Total citations	Citation density
36	Clohisy et al. (2008). A systematic approach to the plain radiographic evaluation of the young adult hip (46)	122	20.33
37	Kelly et al. (2003). Hip arthroscopy: current indications, treatment options, and management issues (47)	122	11.09
38	Beaulé et al. (2007). Quality of life following femoral head-neck osteochondroplasty for femoroacetabular impingement (48)	121	17.29
39	Mintz et al. (2005). Magnetic resonance imaging of the hip: detection of labral and chondral abnormalities using non-contrast imaging (49)	120	13.33
40	Lage et al. (1996). The acetabular labral tear: an arthroscopic classification (50)	120	6.67
41	Glick et al. (1987). Hip arthroscopy by the lateral approach (51)	119	4.41
42	Burnett et al. (2006). Clinical presentation of patients with tears of the acetabular labrum (52)	116	14.50
43	Clarke et al. (2003). Hip arthroscopy: complications in 1054 cases (53)	115	10.45
44	Jamali et al. (2007). Anteroposterior pelvic radiographs to assess acetabular retroversion: high validity of the "cross-over-sign" (54)	113	16.14
45	Eijer et al. (2001). Anterior femoroacetabular impingement after femoral neck fractures (55)	111	8.54
46	Santori and Villar (2000). Acetabular labral tears: result of arthroscopic partial limbectomy (56)	106	7.57
47	McCarthy et al. (2003). Anatomy, pathologic features, and treatment of acetabular labral tears (57)	105	9.55
48	Byrd (1996). Labral lesions: an elusive source of hip pain case reports and literature review (58)	102	5.67
49	McCarthy and Busconi (1995). The role of hip arthroscopy in the diagnosis and treatment of hip disease (59)	100	5.26
50	Tannast et al. (2005). Tilt and rotation correction of acetabular version on pelvic radiographs (60)	99	11.00

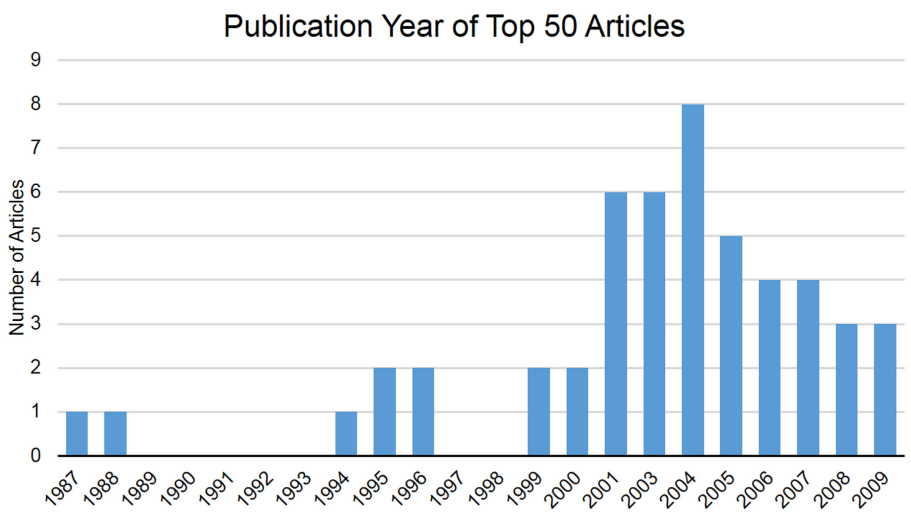

FIGURE 1 | Publication year of top 50 articles.

Discussion

Femoroacetabular impingement is a relatively new concept when compared to other classically described pathologies in the field of orthopedic surgery. However, growing awareness of this condition and its management as well as recent technical advancements have resulted in arthroscopic hip surgery becoming one of the fastest-growing orthopedic subspecialties. The rapid development of this field has been closely correlated with increasing interest in the subspecialty as well as the amount of new hip arthroscopists entering practice. Therefore, we believe that it is important to identify and analyze the most important articles in the field of hip arthroscopy in order to provide the orthopedic community with a list of essential publications critical to this emerging field. This list represents a basis of fundamental knowledge for hip arthroscopy and can act as a starting point for residency and fellowship programs aiming to train future hip arthroscopists. Although the presented articles are relatively contemporary as compared to other classic orthopedic publications, these articles were written during the development of the essential knowledge of FAI and the field of hip arthroscopy. Therefore, they represent the field's scientific foundation and are valuable for clinicians who are developing their own management techniques.

TABLE 2 | List of the journals of the top 50 articles are published within along and the total amount of citations each journal accounts for.

Journal	No. of top 50 articles	% of top 50 articles	Total citations
Clinical Orthopedics and Related Research	18	36.0	3812
Arthroscopy	11	22.0	1442
Journal of Bone and Joint Surgery-American Volume	6	12.0	980
Journal of Bone and Joint Surgery-British Volume	5	10.0	1684
American Journal of Sports Medicine	4	8.0	498
Journal of Orthopedic Research	2	4.0	240
Journal of Orthopedic Trauma	1	2.0	111
Knee Surgery Sports Traumatology Arthroscopy	1	2.0	143
Orthopedics	1	2.0	100
Osteoarthritis and Cartilage	1	2.0	125

We analyzed the characteristics of these articles to determine what qualities make an orthopedic article important to authors writing about FAI and hip arthroscopy. We found that the majority of articles where either published from the United States or Switzerland. Other reviews of classic articles in general surgery, plastic surgery, anesthesia, emergency medicine, and orthopedic surgery have similarly found a predominance of American authors within classic literature (1, 2, 61–64). However, this current review found that the number of articles originating from the United States when compared to other countries is proportionally lower as compared to the previously referenced specialties. Switzerland in particular represents a high proportion of top articles within the classic FAI and hip arthroscopy literature. This is not surprising as several of the clinicians who initially and extensively studied FAI in hip arthroscopy originate from Switzerland.

We found that the majority of published articles were clinical studies; however, these papers were primarily limited to level IV and level III evidence. Given the relative infancy of the field, such level of evidence is not unexpected. However, we do not believe that this lower level of evidence detracts from the value or importance of these articles. We expect that as the quantity of practitioners and patients continues to grow with time, additional studies with increasing patient cohort sizes and possibly higher levels of evidence will be conducted and published. The recent emphasis placed on "evidence-based medicine" in clinical practice encourages high-quality research to provide a basis for clinical management paradigm, and current and future studies will draw from classic literature presented in this list to accomplish this goal.

In addition to the clinical studies, we also found that a significant number of the top 50 articles were categorized as basic science studies. Many of these articles were biomechanical studies utilizing cadaveric tissue to elucidate the potential pathophysiology of symptomatic hip pain related to FAI or to develop novel surgical techniques. The remaining articles were imaging-based in nature and sought to improve the ability of clinicians to appropriately diagnose and evaluate pathological FAI lesions, as well as allow increased precision in preoperative planning. As we develop new surgical techniques, improve preoperative planning, and optimize postoperative rehabilitation, these articles provide the basis of knowledge necessary to advance these areas. Additionally, a minority of the articles found in this list were review type publications. As the current scientific literature for FAI and hip arthroscopy is still developing, the process of understanding this disease process and surgical technique is ongoing. As the scientific literature continues to mature in volume as well as quality, more comprehensive reviews will be possible, providing valuable summaries for the aspiring clinician.

Although the total amount of citations attributed to articles listed in the current top 50 list is lower as compared to the top 100 articles in orthopedic surgery and even when compared to the top 50 articles in shoulder surgery, we found that the citation density of top FAI and hip arthroscopy articles was generally greater. For example, Lefaivre et al. identified "Traumatic arthritis of the hip after dislocation and acetabular fractures: treatment by mold arthroplasty. An end-result study using a new method of result evaluation" by Harris as the top-cited article in orthopedic surgery with 1748 total citations; however, the citation density of this article was only 41.62 (2). Similarly, Namdari et al. identified "A clinical method of functional assessment of the shoulder" by Constant et al. as the top-cited article in shoulder-specific orthopedic surgery with 1211 total citations, but this paper only had a citation density of 50 (4). The top-cited article in the current study by Ganz had a total of 820 citations, significantly lower than the top orthopedic surgery or shoulder specific articles, but its citation density was higher at 74.55. We found this to be a trend within the current top 50 articles list when compared to other top-cited article publications in the scientific literature. As citation density may be used as a proxy of current interest in any particular field or article, the current study demonstrates that FAI and hip arthroscopy are emerging and impactful topics in the current orthopedic scientific community. Therefore, while the articles identified within this analysis are significantly more contemporary as compared to other "classic" orthopedic concepts, the high level of activity within the subspecialty may benefit from this list.

Limitations

This study has limitations. All previously established methods of analyzing and ranking the top articles within the specific medical field contain limitations in their evaluation processes, including those directed toward orthopedic surgery. Similar to previously described methods, our analysis did not account for self-citations, oral or poster presentations, textbooks citations, as well as the intrinsic bias of citing articles from the Journal of which they intend to publish. Self-citation in particular may be particularly important as high-volume authors may have a tendency to cite their own previous articles in their newly submitted work. An additional limitation of our methodology is that the categorization of journals and citations in web of science may lead to the omission of influential articles about FAI and hip arthroscopy from known-orthopedic journals. However, our aim was to provide orthopedic surgeons list of the top 50 most impactful articles on a specific subspecialty as opposed to orthopedic surgery in general, so therefore we believe that the vast majority of articles on FAI and hip arthroscopy will be found within these 61 analyzed orthopedic journals and that these publications truly reflect the most important works in this subspecialty. An additional weakness attributed to this methodology is that work published prior to 1945 could not be included within the initial search as the citation database was non-existent at that time. The impact of this, however, was probably minimal within our research for articles about FAI and hip arthroscopy, since these concepts are relatively recent and have only been established in the scientific literature within the past three decades. In fact, while the initial article that we encountered within the top 50 list was published in 1987, the vast majority of the remaining articles were produced in the 2000s.

Finally, as this analysis is a cross-sectional study at one point in time, we can only develop conclusions based on the citation counts of these articles at that particular time. As new developments and scientific knowledge and techniques continue to evolve within the subspecialty, major paradigm shifts in management based on more relevant articles may significantly altered this list in the future. In this situation, it would be prudent to establish the validity of this list at a later time as the field continues to mature.

Conclusion

We rank the top 50 articles in the subspecialty of arthroscopic hip surgery and FAI. We found that these articles written in English, most commonly published in *Clinical Orthopaedics and Related Research,* were primarily level III and level IV observational clinical studies, but with a significant amount of basic science research as well. The current top 50 list provides orthopedic surgeons interested in hip arthroscopy with a list of the most important articles in the scientific literature currently and represents a foundation that young clinicians can use to develop their knowledge regarding hip arthroscopy and FAI.

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REVIEW
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The Role of Femoroacetabular Impingement in Core Muscle Injury/ Athletic Pubalgia: Diagnosis and Management

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Chronic groin pain in athletes represents a major diagnostic and therapeutic challenge in sports medicine. Two recognized causes of inguinal pain in the young adult athlete are core muscle injury/athletic pubalgia (CMI/AP) and femoroacetabular impingement (FAI). CMI/AP and FAI were previously considered to be two distinct entities; however, recent studies have suggested both entities to frequently coincide in the athlete with groin pain. This article briefly discusses the role of FAI in CMI/AP and the diagnosis and management of this complex disease.

Keywords: core muscle injury, athletic pubalgia, femoroacetabular impingement, sports hernia

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INTRODUCTION

Chronic groin pain in athletes represents a major diagnostic and therapeutic challenge in sports medicine. Athletic injuries to the hip and groin occur less frequently than injuries to the lower extremities (1); however, the complexity of the anatomy and biomechanics of the groin makes these injuries more difficult to identify and manage. Patients may find themselves evaluated by multiple physicians and receive numerous diagnostic studies over a period of months. Early and accurate diagnosis is essential for return to play and improved quality of life (2).

Two recognized causes of an insidious onset of groin pain in the young adult athlete are core muscle injury/athletic pubalgia (CMI/AP) and femoroacetabular impingement (FAI). CMI/AP, or "sports hernia," is a syndrome of disabling exertional inguinal and adductor pain commonly seen in high-performance athletes, possibly due to a disruption of the musculature of the posterior inguinal wall (2, 3). FAI or hip impingement syndrome may also cause inguinal pain in the athlete, whereby abnormal contact between the femoral head and acetabular junction results in chondral and labral injury (4).

While CMI/AP and FAI were previously considered to be two distinct entities, recent studies have suggested both entities to frequently coincide in the athlete with groin pain. Our primary objectives are to discuss the role of FAI in CMI/AP, and to discuss the diagnosis and management of this complex disease.

CORE MUSCLE INJURY/ATHLETIC PUBALGIA AND FEMOROACETABULAR IMPINGEMENT

A comprehensive understanding of normal inguinal anatomy is critical to the diagnosis and management of groin pain. The anterior abdominal wall consists of the external oblique muscle and aponeurosis, internal oblique muscle and aponeurosis, transversus abdominis muscle and aponeurosis, and transversalis fascia. Medially, the rectus abdominis muscle fibers insert on the pubic tubercle. The inguinal canal extends between the deep inguinal and superficial inguinal rings, or defects in the aforementioned aponeuroses and fascia, and contains the spermatic cord in men and round ligament in women. Clinical hernias develop with a protrusion of omentum, fat, or bowel through the inguinal canal (indirect hernias), through the floor of a weakened abdominal wall musculature medial to the epigastric vessels (direct hernias), or below the inguinal ligament (femoral hernias). There are multiple notable nerves in the inguinal region, including the iliohypogastric nerve, the ilioinguinal nerve, and the genital branch of the genitofemoral nerve. The iliohypogastric nerve travels on the anterior surface of the internal oblique muscle and aponeurosis just medial and cranial to the deep ring. The ilioinguinal nerve runs anterior to the spermatic cord in the inguinal canal, and the genital branch of the genitofemoral nerve travels through the inguinal canal with the spermatic cord. A laparoscopic view of the inguinal anterior abdominal wall is shown with the presence of a direct inguinal hernia passing medially to the epigastric vessels (**Figure 1**).

Core muscle injury/athletic pubalgia is also known as a sports or sportsman's hernia, however, the term "hernia" may be a misnomer as there is no true protrusion through a defect in the anterior abdominal wall. There is no consensus for the etiology of CMI/AP, although most theories support an overuse syndrome. Repetitive pelvic motion against a fixed extremity may produce a shearing force across the pubic symphysis, leading to attenuation, avulsion, or tearing of the musculature or fascia of the posterior inguinal wall (1). It has been suggested that CMI/AP may result in disruption of the origin of the rectus abdominis muscle from the pubic tubercle, avulsion of the internal oblique muscle fibers at the pubic tubercle, or an abnormality in the external oblique aponeurosis (2, 3). Another theory postulates a laxity in the posterior inguinal wall that stretches under force, entrapping the nerves along the inguinal floor, including the genital branch of the genitofemoral nerve, ilioinguinal, lateral femoral cutaneous, or obturator nerves (5).

Femoroacetabular impingement represents abnormal contact between the femoral head and acetabular junction in the young active adult population, ultimately causing patterns of chondral and labral injury. There are two main variations: pincer and cam lesions (**Figure 2**). Pincer impingement involves over coverage of the femoral head by the acetabulum due to focal rim lesions or cephalad retroversion (4, 6). The labrum is frequently injured with the abnormal contact of the femoral neck and acetabular rim. A cam lesion is an osteochondral prominence at the femoral head–neck junction leading to loss of the normal femoral head–neck offset. Cam lesions are most commonly anterolateral, and affect the anterosuperior chondrolabral junction. This results in chondrolabral separation and frequently delamination of the adjacent acetabular chondral surface (4, 6). The alpha angle, or the angle between the femoral neck axis and a line through a point where the contour of the femoral head–neck junction exceeds the radius of the femoral head, is considered diagnostic of cam impingement when greater than 50–55° (7).

The relationship between CMI/AP and FAI has been a recent area of interest. Loss of clearance between the femoral neck and acetabular rim with FAI may restrict terminal motion of the hip in multiple planes. This restriction in the high-performance athlete may lead to compensatory stresses on the lumbar spine, pubic symphysis, sacroiliac joint, and posterior acetabulum

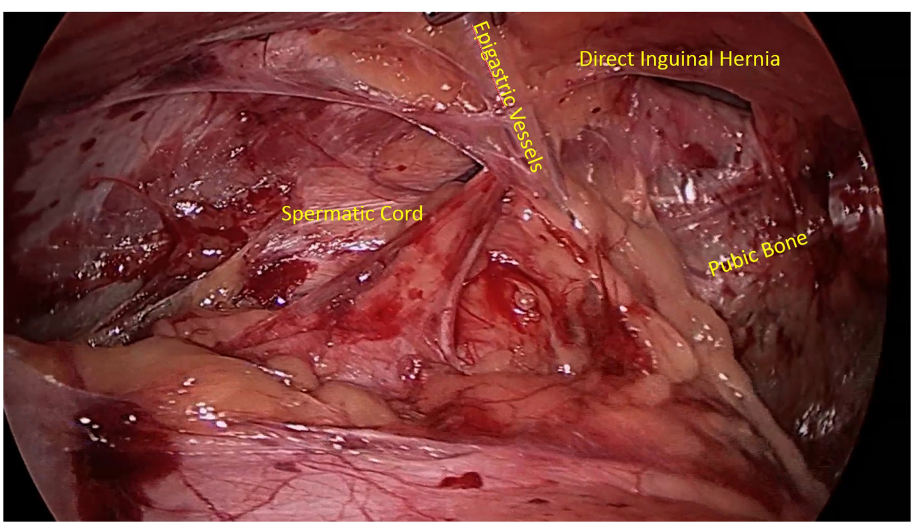

FIGURE 1 | **Laparoscopic view of the inguinal abdominal wall musculature with the presence of a direct inguinal hernia**.

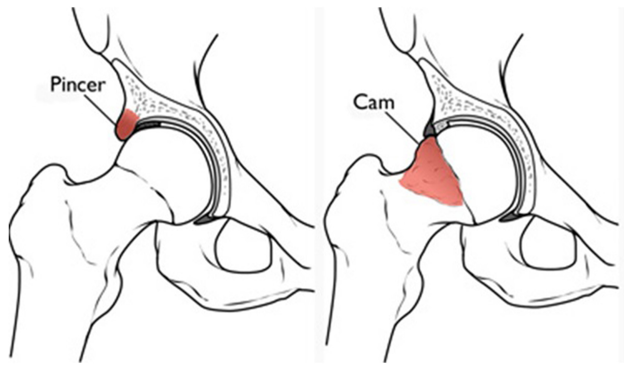

FIGURE 2 | **Pincer and cam impingement in femoroacetabular impingement (Reproduced with permission from the American Academy of Orthopedic Surgeons)**.

(3, 4). Excessive biomechanical stress on the groin may lead to secondary injury to the abdominal wall musculature, including the posterior inguinal wall, resulting in symptomatic CMI/AP; however, the biomechanical relationship has yet to be elucidated in this theorem. The muscles typically affected by FAI include the adductor longus, proximal hamstrings, abductors, iliopsoas, and hip flexors (4).

Recent studies have demonstrated an association between CMI/AP and FAI. Hammoud et al. described a consecutive series of 38 professional athletes who had been treated for symptomatic FAI, with 12 (32%) of those patients identified as having previous surgical intervention for CMI/AP. After additional treatment for FAI, all 12 patients were subsequently able to return to play. Additionally, of the 26 remaining patients, 15 had symptoms of CMI/AP that resolved with isolated treatment of their hip pathology. In this study, 39% (15/39) of athletes with both CMI/AP and FAI symptoms had complete resolution of pain and return to field with FAI surgery alone (4).

Another retrospective review by Economopoulos et al. investigated radiographic evidence of FAI in patients who had been treated for CMI/AP. Athletes who underwent surgical intervention for CMI/AP were found to have concomitant radiographic evidence of FAI in at least 1 hip in 37 of 43 patients (86%) (6). Cam lesions were identified by measurement of the alpha angle on frog-leg lateral radiographs, with an alpha angle of 55° or greater considered positive for FAI. Cam lesions were identified in 84% and pincer lesions in 28% of hip radiographs (6).

DIAGNOSIS

The diagnosis of CMI/AP is difficult to make given its insidious onset and variable physical exam findings (8). Many patients cannot recall when the specific injury occurred, and nearly all patients will completely stop their competitive level of activity by the time of evaluation (9). Pain is typically located in the inguinal canal near the insertion of the rectus abdominis on the pubis, and worsens with activity and alleviated with rest. Pain will often extend down the internal thigh/lateral portion of the scrotum/perineum during activity. Sneezing, coughing, or Valsalva maneuvers may worsen the pain in up to 10% of patients, despite the lack of a palpable bulge on examination (2, 9). Physical examination may also reveal pubic tubercle tenderness, with point tenderness over the medial aspect of the inguinal ligament before its insertion into the pubic tubercle (10). The examiner will elicit tenderness in 88% of patients with resisted adduction of the hip, and pain with a resisted sit-up is common (1, 9).

The examiner should also evaluate the hip joint for clinical signs and symptoms of FAI in this patient population. Patients with FAI will exhibit hip and groin pain with flexion and internal rotation of the hip, and some patients may experience limited hip internal rotation, flexion, and abduction (8, 10). The anterior impingement test, or pain with hip flexion, adduction, and internal rotation, may also suggest hip pathology (8).

If suspecting underlying FAI in a patient with CMI/AP, plain radiographs of the anteroposterior pelvis of both hips and lateral view of the proximal femur should be performed to evaluate pathology and the femoral head–neck junction and acetabulum. Magnetic resonance imaging (MRI) is the only imaging modality useful in the diagnosis of CMI/AP, as radiographs are often negative (10). Disruption or cleft sign at the rectus abdominis or adductor aponeurosis at the anterior pelvis is suggestive of CMI/AP (8). In the literature, 9 to 65% of MRIs will identify a tear of the rectus abdominis muscle at the insertion on the pubis in patients with symptoms of CMI/AP. However, there is a higher incidence of non-specific radiographic signs, including small avulsion fractures, unexplained edema, and musculotendinous asymmetry (9, 11). Compared with findings at surgery, MRI is 68% sensitive and 100% specific for rectus abdominis disruptions, and 86% sensitive and 89% specific for adductor pathology (11).

The authors routinely use plain radiographs and dedicated hip CTs to determine amount of bony deformity and whether the FAI is due to an isolated cam deformity, isolated pincer deformity, or components of both. They also look at the femoral version and the prominence of the anterior inferior iliac spine (AIIS), as the presence of those in combination with pain with straight hip flexion is suggestive of impingement of the anterior facet of the trochanter on the AIIS, known as extra-articular impingement. For patients who have failed core and gluteal strengthening programs, MRI is useful to evaluate the hip and pubic symphysis as an adjunct diagnostic tool.

MANAGEMENT

As with many disease processes, non-surgical options should be considered prior to surgical intervention of CMI/AP or FAI. Non-narcotic analgesics during game play can be considered if the athlete is willing to participate with high levels of pain for the short term. Intra-articular corticosteroid injections may be considered in the professional athlete with CMI/AP to help complete a season; however, there is little literature on its efficacy (8). Platelet-rich plasma (PRP) intra-articular injection has been shown to decrease immediate postoperative pain following arthroscopic hip surgery for FAI in a randomized control trial; however, the long-term advantage is uncertain (12). The senior author of this paper has abandoned the use of corticosteroids for

CMI/AP due to the lack of lasting relief, and routinely injects PRP for chronic adductor pain.

Physical therapy has shown a 27% success rate for return to sports activities after 3 months of therapy in CMI/AP (13), and should be attempted if symptoms began <2 months at presentation. Physical therapy should be aimed at strengthening of the muscles that stabilize the pelvis, hip joints, lower abdominal musculature, and adductor muscles. Most athletes who have failed conservative management will elect surgical intervention. Surgical intervention should be considered if physical therapy fails after 2 months in the professional athlete, and 4–6 months in non-professional athlete patients (13).

Conservative treatment for FAI should be aimed at core strengthening, non-steroidal anti-inflammatory medications (NSAIDs), and physical therapy. Therapy should optimize the alignment and range of motion of the hip joint, while avoiding passive stretches that may exacerbate symptoms (7).

Nearly all studies have demonstrated surgical correction for CMI/AP to be more effective for relief of pain and earlier return to field (5, 9, 13–15). Described techniques for the general surgeon include open tissue repair, tension-free repair with mesh, and laparoscopic total extra pre-peritoneal inguinal hernia repair (TEP) (2). Open inguinal hernia repair for CMI/AP aims to reinforce areas of laxity along the inguinal floor and to restore the rectus abdominis muscle to its origin at the pubic tubercle, rather than re-approximate or recreate the internal ring (9). Alternatively, TEP allows for visualization of the posterior inguinal wall musculature and placement of a large mesh to distribute forces over a greater surface area (**Figure 3**). Implementing hernia repair techniques in CMI/AP has a high success rate, as athletes who underwent open tissue or tension-free repair with mesh returned to sports 80–95% of the time, and those who underwent laparoscopic repair with mesh had a 93–100% return rate (8). Patients with CMI/AP who underwent laparoscopic repair returned to sports at mean 3 weeks, compared to 5 weeks postoperatively for open tissue or mesh repairs (16).

Adductor release is a newer option in the treatment of CMI/AP. Given the opposing force of the adductor on the pelvis, this technique involves cutting the insertion of the adductor longus muscles from its insertion on the pubic bone (9). The tendon is released from its insertion approximately 1 cm from the pubis.

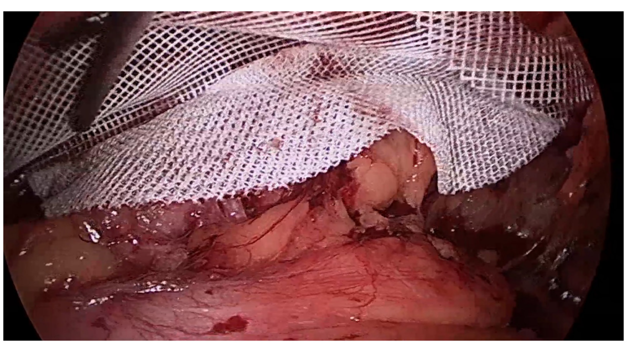

FIGURE 3 | **Laparoscopic view of the inguinal abdominal wall musculature following mesh placement**.

A retrospective study by Rossidis et al. investigated 54 patients with CMI/AP symptoms who underwent combined laparoscopic TEP inguinal hernia repair and ipsilateral adductor longus tenotomy. All were able to return to full sports activity in a mean of 24 days (range 21–28 days) (14).

In patients with FAI, treatment of the impingement lesion may restore the femoral head–neck junction offset to a more physiologic state, and relieve stress on nearby muscle groups (4). Surgical techniques include open femoroacetabular osteoplasty, hip arthroscopy, or combined arthroscopy with limited open osteoplasty. FAI is confirmed visually, labral and chondral injuries are identified, debrided, or repaired. Normal bony anatomy is restored through resection of the cam lesion or with acetabular rim trimming (**Figures 4** and **5**). A burr is used to resect the pincer deformity, and if extra-articular impingement is present, the distal portion of the AIIS is resected. The cam

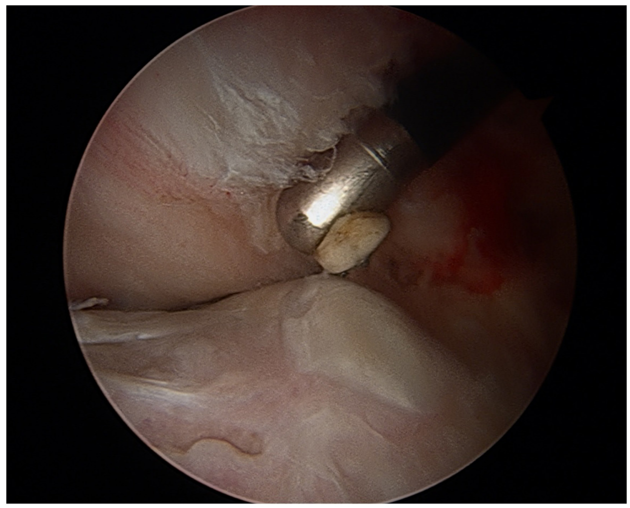

FIGURE 4 | **Arthroscopic view of a cam lesion, right hip**.

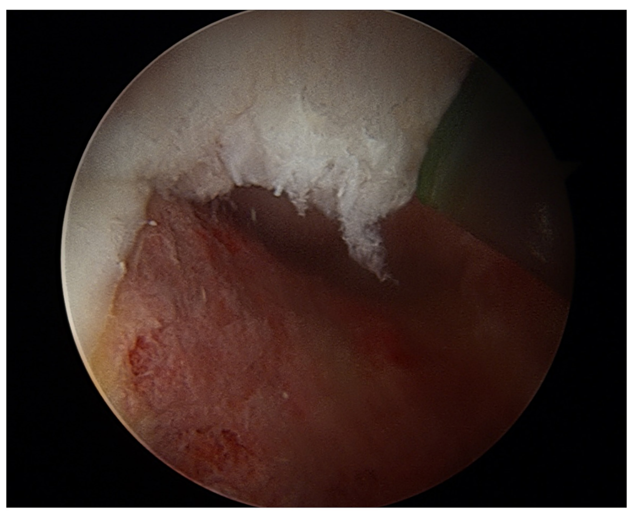

FIGURE 5 | **Arthroscopic view of the hip following cam resection**.

lesion is then addressed with a burr. As the cam lesion can also be focal or more global anteriorly, a three-dimensional computed tomography scan is used to help assess the margins and the lesion. Intraoperatively, the use of fluoroscopy is helpful to confirm that the resection is complete. The ultimate goal is to preserve the hip joint and increase range of motion to 120° of flexion and 40° of rotation (7).

There is some evidence that surgical therapy for both CMI/AP and FAI has shown optimal results than either alone. A case series by Larson et al. demonstrated improved postoperative outcome scores and unrestricted return to sports in 89% of patients who underwent concurrent or eventual surgical treatment of both CMI/AP and FAI (17). However, to the best of our knowledge, there is no literature comparing simultaneous and staged surgical therapy. The authors of this paper previously treated all patients with both hip arthroscopy and laparoscopic inguinal hernia repair simultaneously; however, they now decide which entity is more symptomatic and address that first based on history, physical examination, and advanced imaging. If symptoms persist after the more symptomatic lesion is addressed, the authors address the other lesion.

A multidisciplinary approach between family and sports medicine, and orthopedic surgery and general surgery is essential for improved outcomes in CMI/AP. As FAI and CMI/AP are often linked, awareness of CMI/AP symptoms by orthopedists and FAI symptoms by general surgeons is critical, and the initial evaluator may be one of these many specialists.

CONCLUSION

In conclusion, chronic groin pain is often difficult to diagnose and treat in the young athletic population. FAI may lead to compensatory stresses in the biomechanics of the groin. Excessive strains may lead to secondary injury to the posterior inguinal wall, resulting in symptomatic CMI/AP. It is reasonable to consider both overlapping disease processes before surgical intervention is performed.

AUTHOR CONTRIBUTIONS

All authors have contributed in writing and editing the manuscript.

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CrossMark

Prevalence of Cam Morphology in Females with Femoroacetabular Impingement

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Cam and pincer are two common morphologies responsible for femoroacetabular impingement (FAI). Previous literature has reported that cam deformity is predominantly a male morphology, while being significantly less common in females. Cam morphology is commonly assessed with the alpha angle, measured on radiographs. The purpose of this study is to determine the prevalence of cam morphology utilizing the alpha angle in female subjects diagnosed with symptomatic FAI. All females presenting to the senior author's clinic diagnosed with symptomatic FAI between December 2006 and January 2013 were retrospectively reviewed. Alpha (α) angles were measured on anteroposterior and lateral (Dunn 90°, cross-table lateral, and/or frog-leg lateral) plain radiographs by two blinded physicians, and the largest measured angle was used. Using Gosvig et al.'s classification, alpha angle was characterized as (pathologic > 57°), borderline (51–56°), subtle (46–50°), very subtle (43–45°), or normal ($\leq$42°). Three hundred and ninety-one patients (438 hips) were analyzed (age 36.2 ± 12.3 years). Among the hips included, 35.6% were normal, 14.6% pathologic, 15.1% borderline, 14.6% subtle, and 20.1% very subtle. There was no correlation between alpha angle and patient age ($R = 0.17$) or body mass index ($R = 0.05$). The intraclass correlation coefficient for α-angle measurements was 0.84. Sixty-four percent of females in this cohort had an alpha angle >42°. Subtle cam deformity plays a significant role in the pathoanatomy of female patients with symptomatic FAI. As the majority of revision hip arthroscopies are performed due to incomplete cam correction, hip arthroscopists need to be cognizant of and potentially surgically address these subtle lesions.

Keywords: femoroacetabular impingement, cam, female, alpha angle, head–neck offset

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INTRODUCTION

Femoroacetabular impingement (FAI) is a pathologic condition described by Ganz et al. (1) in which there is abnormal contact between the femoral head and acetabulum leading to hip pain, labral tears, chondral injuries, and early osteoarthritis (1–8). The two most common types of FAI are cam and pincer. Pincer-type FAI results from increased acetabular depth or overcoverage, while cam-type FAI is a consequence of decreased femoral head–neck offset. The most common location of the cam deformity (asphericity) is at the anterolateral femoral head–neck junction, which increases shear at the chondrolabral junction of the anterosuperior acetabulum during deep flexion and rotational maneuvers. The magnitude of a cam deformity may be measured by a number of imaging parameters. Initially described by Notzli et al. (9) on axial oblique magnetic resonance imaging (MRI) parallel to the plane of the femoral neck, the alpha (α) angle describes where the head–neck junction loses sphericity. The alpha angle has been extrapolated to plain radiographs and computed tomography (CT). In a healthy population, the average α angle is estimated at 42°(9); larger α angles may indicate the presence of a cam.

Cam and pincer morphologies are thought to predominate in men and women, respectively (10–14). The physiologic development of the hip joint differs between males and females, and there are different hypotheses to explain the association (15). Females have earlier closure of the pelvic and proximal femoral physes vs. males (16). In males, the formation and size progression of the cam morphology is around the time of rapid longitudinal growth (ages 12–16) and is associated with impact sports (e.g., hockey, football, basketball, and soccer) (17–19).

The prevalence and characterization of cam morphology is increasingly recognized in males. However, it is underrepresented and potentially unrecognized in females. The purpose of this study is to determine the prevalence of cam morphology in non-arthritic females with symptomatic intra-articular hip pain. The study hypothesis is that the prevalence of female cam impingement is higher than typically reported in the orthopedic literature.

MATERIALS AND METHODS

New female patients presenting to the senior author's office with a chief complaint of "hip pain" between December 2006 and January 2013 were considered. Inclusion criteria included age under 65 years, Tönnis arthritis grade (20) of 0 or 1, adequate anteroposterior (AP) pelvis and lateral (Dunn 90°, cross-table lateral, and/or frog-leg lateral) hip radiographs, and a clinical history and exam consistent with intra-articular hip pathology. Adequacy of AP radiographs was determined by symmetry of obturator foramina, and distance of pubic symphysis and coccygeal tip (separated by 1.5–2 cm). Subjective clinical evaluation consistent with intra-articular pathology demonstrated deep groin pain, worse with deep flexion and rotational maneuvers, worse with sitting rather than standing, pain with putting on socks and shoes, and worse with activity and better with rest. Objective physical examination demonstrated positive impingement testing and decreased hip flexion and internal rotation. Subjects with hip dysplasia (lateral center edge angle <20°, anterior center edge angle <20°, Tönnis angle >10°, or femoral head extrusion index >25%) or prior hip surgery were excluded.

Radiographs were reviewed retrospectively. Tönnis grades were documented and α angles measured on all AP-pelvis and lateral radiographs as described by Notzli et al. (**Figure 1**) (9). The center of the femoral head, the central axis of the femoral neck, and the resultant α angle were determined using measurement tools available in the MedVIEW Picture Archive Communication System (PACS) software (Aspyra, West Lake Village, CA, USA). Lateral views included frog-leg lateral, cross-table lateral, and/or 90°-Dunn lateral positioning. The largest α angle was used. For each subject, demographic data, including age, ethnicity, and body mass index (BMI), was collected. In order to evaluate the prevalence of cam-type deformity, all patients were classified according to the criteria defined by Gosvig et al. (pathologic > 57° and borderline 51–56°) (21). Additionally, patients were classified as having subtle (46–50°) or very subtle (43–45°) cam morphologies. Normal α angles were defined as ≤42°(9).

Pearson's correlation was used between α-angle measurements, age, and BMI. Student's *t*-test was performed to compare α-angle and ethnicity and to compare measurements between different radiographic views. Measurements were performed by two senior resident physicians. An intraclass correlation coefficient (ICC) was found between the two sets of measurements. *p*-Values of <0.05 were considered significant. All statistical tests were performed using SPSS software for Windows, version 13.0 (SPSS, Chicago, IL, USA).

RESULTS

A total of 969 females were presented to the senior author's clinic between December 2006 and January 2013 with a chief complaint

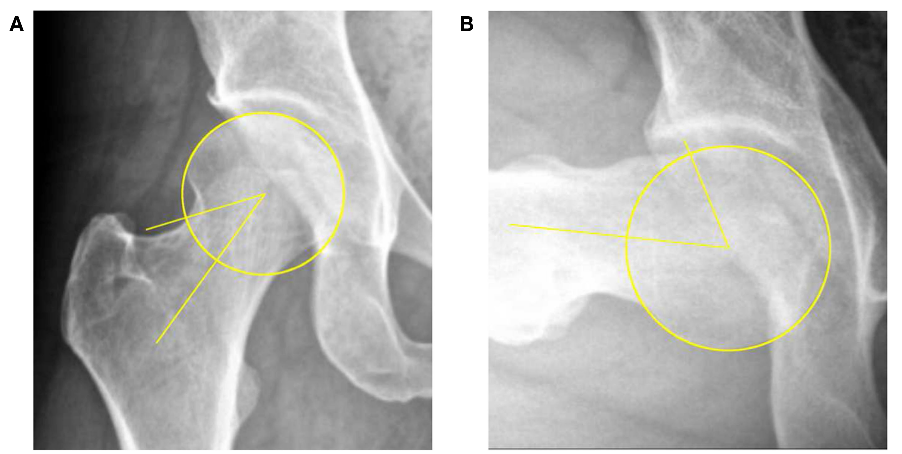

FIGURE 1 | Determination of head–neck offset by measurement of the α angle on AP (A) and 90°-Dunn lateral (B) radiographs.

of "hip pain." Three hundred and ninety-one patients (438 hips) were eventually diagnosed with FAI and had adequate radiographs for inclusion. The mean age was 36.2 ± 12.3 years (range, 12–66). The mean height was 65.3 ± 8.7 in, weight 145.9 ± 37.1 lbs, and BMI 24.0 ± 5.0 kg/m^2. Ninety-eight percent were Caucasian. One hundred and ninety-three patients (49.4%) had isolated impingement of the right hip, 151 (38.6%) had isolated left hip impingement, and 47 (12.0%) had bilateral impingement.

Table 1 lists the distribution of the mean largest α angle measured in the study population. The overall mean α angle was 48.2 ± 11.9°. A deformity that was subtle or greater was present in 44.3% of hips, and 64.4% had a deformity very subtle or greater. There was no correlation ($R = 0.17$) between patients' age and size of the cam lesion nor was there a correlation ($R = 0.05$) between patients' BMI and size of the cam lesion. There was no difference between the ethnicity of the patient and size of the cam lesion ($p = 0.10$). Interobserver correlation coefficient for α-angle measurements was 0.84.

Table 2 lists the distribution of mean α angles measured on the respective views. The mean α angle measured on frog-leg lateral views was significantly greater than that measured on AP, cross-table lateral, and 90°-Dunn lateral views ($p < 0.001$, $p = 0.02$, and $p < 0.001$, respectively). The mean angle measured on AP view was less than that of the cross-table lateral ($p = 0.09$) and significantly less than that of the 90°-Dunn lateral view ($p < 0.001$). There was no significant difference between the cross-table lateral and 90°-Dunn lateral views ($p = 0.36$).

DISCUSSION

Cam deformities have traditionally been associated with young male athletes, while pincer impingement has been described as a disease of middle-aged women (10–14). The current investigation's data suggest that there is a significantly higher prevalence of cam deformities found in symptomatic female patients. In this retrospective cohort of 391 women (438 hips) with symptomatic FAI, 29.7% had an α angle >50.5°, compared to just 5.4% of asymptomatic females presented by Hack et al. (12).

TABLE 1 | Distribution of α-angle.

Classification (α-angle)	Number (%)
Pathologic (>57°)	64 (14.6)
Borderline (51–56°)	66 (15.1)
Subtle (46–50°)	64 (14.6)
Very subtle (43–45°)	88 (20.1)
Normal (≤42°)	156 (35.6)

TABLE 2 | Variation of α-angle measurements by radiographic view.

Radiographic view	Mean α angle (°)	Number of hips in which view showed the largest α angle (%)[a]
Anteroposterior (AP)	41.3 ± 11.0	136 (31.1)
Frog-leg lateral	48.1 ± 12.2	114 (26.0)
Cross-table lateral	43.7 ± 10.3	14 (3.2)
90°-Dunn lateral	44.2 ± 8.6	172 (39.3)

[a] *Two patients had identical α angle measurements on AP and frog-leg lateral views.*

The notion that cam lesions occur predominantly in young males is supported by recent literature (12–14, 22). In 2010, Hack et al. evaluated hip MRI in 200 asymptomatic volunteers and 14% of their subjects had cam deformities >50.5°, 79% of whom were male. They reported decreased head–neck offset in just 5.4% of the females enrolled (12). More recently in 2013, Leunig et al. assessed MRIs in 80 asymptomatic females and found 0 cam deformities >57°(13). While these studies suggest that cam deformities are rare in women, they are cross-sectional evaluations of asymptomatic patients and do not represent females who present with symptomatic impingement. Cam lesions can produce significant hip pain and motion restrictions (23, 24), and Miguel et al. have shown that symptomatic patients have significantly higher α angles compared to asymptomatic controls (25). Therefore, the prevalence of cam deformities in asymptomatic females may underestimate the prevalence of such deformities in those with symptoms.

In a recent assessment of FAI morphology in 100 men and women, Nepple et al. found an even greater percentage of cam deformities amongst females symptomatic enough to require surgery (26). Whereas the current cohort included some non-surgical patients successfully treated with physical therapy, Nepple et al. reported that 88% of female patients requiring surgery had an α angle >50°. Of note, they found that, while the majority of both men and women had cam impingement, the mean α angle was greater in men (70.8° vs. 57.6°, $p < 0.001$). Beaule et al. also reported smaller cam lesions in symptomatic females compared to males ($n = 30$, 73.3° vs. 58.7°, $p = 0.009$) (27).

The current study's findings indicate that symptomatic cam FAI may not be restricted to young males. Moreover, we feel that cam impingement should be thoroughly evaluated in all symptomatic females given the consequences of a missed cam deformity, including continued pain and the possibility of additional surgeries. The leading cause of revision FAI surgery is an inadequate cam resection (28, 29). It is, thus, important to scrutinize the head–neck region in an unbiased fashion and consider a femoral osteochondroplasty for both symptomatic men and women even though it is a technically demanding and time-consuming procedure. With adequate cam resection, both arthroscopic and open hip surgeries have shown excellent short- and midterm outcomes for relieving pain and improving function (30–40).

The α-angle cut-off of 42° for normal female morphology is based on the classification by Gosvig et al. and Notzli et al. (9, 21). This is a conservative threshold compared to the non-gender-specific threshold of 50.5° used in other studies (9, 41–43). The clinical relevance of subtle (46–50°) and very subtle (43–45°) lesions has not yet been established. Abnormal α-angle thresholds in females may need to be lowered compared to male patients to reflect gender-specific pathomechanisms, such as mixed impingement patterns, range of motion differences, and differences in hip girdle musculature (44, 45). Further studies are required to assess the extent of intra-articular pathology associated with these types of lesions and how they may correlate with the risk of developing osteoarthritis.

This study also highlights significant differences in the α-angle measurements depending on the radiographic view. The frog-leg lateral view detected significantly larger cam deformities than each of the other three radiographic views.

Clohisy et al. conducted a level II diagnostic study showing that the frog-leg lateral view provides accurate visualization of the femoral head–neck offset when distinguishing symptomatic FAI patients from asymptomatic controls (46). Barton et al. (47) validated both the 90°-Dunn and cross-table lateral views by comparing them to radial oblique reformatted MRI, which has been established as the gold-standard for detecting cam lesions (9, 48, 49). A single AP view is less sensitive at finding cam deformities, which are typically anterosuperior between the 1:30 and 3:00 positions (47–49). The common consensus is that multiple views should be combined to assess multiple planes. In our study, cam lesions were most commonly detected on the most sensitive 90°-Dunn lateral view. The largest respective α angle was found on AP view in 31.1% of hips, but the head–neck offset from these hips was usually classified as normal. It should be noted that these comparisons represent pooled measurements and cannot speak to the accuracy of each radiograph per individual patient; some patients had all four views while others had only two.

To our knowledge, this study represents the largest cohort of symptomatic females evaluated for cam impingement. Radiographs were assessed using a validated system as demonstrated by our high interobserver correlation. Our findings are based on the largest α angles measured from all available radiographs, which minimizes the risk of having missed subtle deformities in different planes. If MRI were available for review, we would have had a greater sensitivity for detecting cam lesions and the prevalence of abnormal α angles may have been even higher than reported.

The limitations of this study are related to its retrospective and cross-sectional design. Therefore, no firm causal inferences can be made. Prospectively collected data from long-term follow-up of cohorts with both genders could clarify the clinical relevance of our findings and whether different degrees of cam deformities are associated with an increased risk of symptomatic hip arthritis. This study also lacks a formal evaluation for pincer lesions, so we cannot make an assessment of the prevalence and clinical relevance of mixed FAI presentations.

CONCLUSION

In conclusion, we have found that female patients with symptomatic FAI have a higher prevalence of cam lesions compared to prior reports of asymptomatic females. This may require lower gender-specific radiographic α-angle thresholds to diagnose cam deformities in females. Future studies are required to assess this prospectively and help establish the clinical relevance of these findings.

AUTHOR CONTRIBUTIONS

DL: lead author on the study, contributed to all stages of study development. MH: second author, contributed to data analysis and manuscript drafting and editing. JH: third author, contributed to idea of study as well as preliminary data generation and editing of the manuscript. BH: fourth author, contributed to data acquisition ad drafting of manuscript. RF: fifth author, contributed to data analysis and editing of manuscript. SN: sixth author, contributed to study generation and drafting and editing of manuscript.

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Advanced imaging in femoroacetabular impingement: current state and future prospects

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Symptomatic femoroacetabular impingement (FAI) is now a known precursor of early osteoarthritis (OA) of the hip. In terms of clinical intervention, the decision between joint preservation and joint replacement hinges on the severity of articular cartilage degeneration. The exact threshold during the course of disease progression when the cartilage damage is irreparable remains elusive. The intention behind radiographic imaging is to accurately identify the morphology of osseous structural abnormalities and to accurately characterize the chondrolabral damage as much as possible. However, both plain radiographs and computed tomography (CT) are insensitive for articular cartilage anatomy and pathology. Advanced magnetic resonance imaging (MRI) techniques include magnetic resonance arthrography and biochemically sensitive techniques of delayed gadolinium-enhanced MRI of cartilage (dGEMRIC), T1rho (T1ρ), T2/T2* mapping, and several others. The diagnostic performance of these techniques to evaluate cartilage degeneration could improve the ability to predict an individual patient-specific outcome with non-surgical and surgical care. This review discusses the facts and current applications of biochemical MRI for hip joint cartilage assessment covering the roles of dGEMRIC, T2/T2*, and T1ρ mapping. The basics of each technique and their specific role in FAI assessment are outlined. Current limitations and potential pitfalls as well as future directions of biochemical imaging are also outlined.

Keywords: hip, femoroacetabular impingement, cartilage, MRI, dGEMRIC, T1rho mapping, T2 mapping, T2* mapping

Introduction

Seemingly, first described by Smith-Peterson in 1936 (1) and then in more detail by Stulberg et al. (2), Harris (3), and Ganz et al. (4), femoroacetabular impingement (FAI) refers to a condition in which structural abnormalities of the proximal femur and/or acetabulum lead to mechanical abutment or conflict during hip motion. Pain, loss of function, and restriction of motion are characteristic symptoms. Moreover, symptomatic FAI has now been recognized as a cause of early osteoarthritis (OA) of the hip (5, 6). The exact pathomechanism and the threshold including the time frame and severity of this abutment that eventually results in irreversible degeneration of the hip joint remain an enigma.

Femoroacetabular impingement is classified as *cam*-type when the abutment is triggered by an aspherical femoral head that generates shearing forces against the anterosuperior acetabular rim structures while entering the joint during hip flexion and internal rotation (4, 5). Labral tears, cartilage abrasion, and cartilage delamination from the labrum and subchondral bone can result from cam impingement (**Figure 1**). Cartilage delamination may occur without the disruption extending through the cartilage surface (referred to as the carpet phenomenon because of its similarity to a carpet on a greasy floor). Disruption extending to the cartilage surface creates a flap tear. Cam-type FAI is common in young men. An osseous asphericity ("bump") located along the anterosuperior aspect of the femoral head–neck junction may appear as "pistol grip" in an anteroposterior (AP) radiograph.

In *pincer*-type FAI, the abutment of the femoral neck against the acetabulum results from over coverage by the acetabulum (4, 5). The extent of femoral head coverage with abutment may be focal (loss of normal cranial acetabular anteversion, i.e., focal relative retroversion; identified radiographically as a "cross-over sign") or global (increased lateral or anterior center-edge angles, posterior wall sign, prominent ischial spine sign). A deep acetabulum (coxa profunda) with or without femoral head medialization (protrusio acetabulae) may variable culminate in pincer-type FAI. Notably, the cross-over sign has recently been challenged as an accurate measure of cranial acetabular version, as the anterior inferior iliac spine is superimposed and may account (falsely elevate) for a large proportion of positive cross-over signs. A hypertrophied and deformed labrum, labrum ossification, and labral tearing with (succeeding) linear cartilage damage are somewhat distinctive observations in pincer-type impingement (**Figure 2**). A chondral contrecoup lesion at the posteroinferior aspect of the hip joint owed to a lever mechanism at the anterior acetabular rim (during flexion the femoral head can be levered against the posterior wall of the acetabulum, causing shear forces on the posterior chondral surfaces) is another common finding. The pattern of chondrolabral damage in pincer FAI, which is common in middle-aged women, may be circumferential. However, most lesions occur at the anterosuperior acetabular rim as flexion is the central movement of the hip. Notably, many patients reveal morphological FAI features on both sides of the hip joint (then referred to as mixed-type impingement). Whether these features are the normal continuum of initial isolated cam or pincer lesions or a unique bilateral morphology in themselves remains largely unknown.

Femoroacetabular impingement remains a clinical diagnosis that is re-affirmed with imaging. Although cam- and pincer-FAI morphologic features are currently interpreted somewhat variably on imaging modalities (for example, varying threshold values for measuring the aspherity of the femoral head), it is important to note that incidental radiographic findings suggestive of FAI morphology are commonly reported even when individuals are asymptomatic (reported prevalence of an asymptomatic cam deformity of 37 and 67% of an asymptomatic hip with pincer deformity) (7). Having identified the classical physical examination findings, radiographic imaging aims (1) to identify the morphology leading to abutment in the individual case and thus confirm the radiographic diagnosis of FAI, (2) to define the pathological extent of the impingement, (3) to evaluate the extent and severity of chondrolabral damage at the time of presentation, and (4) to differentiate other relevant diagnoses that may occasionally co-exist, including labral tears with hip dysplasia. A variety of AP and lateral plain radiographs and magnetic

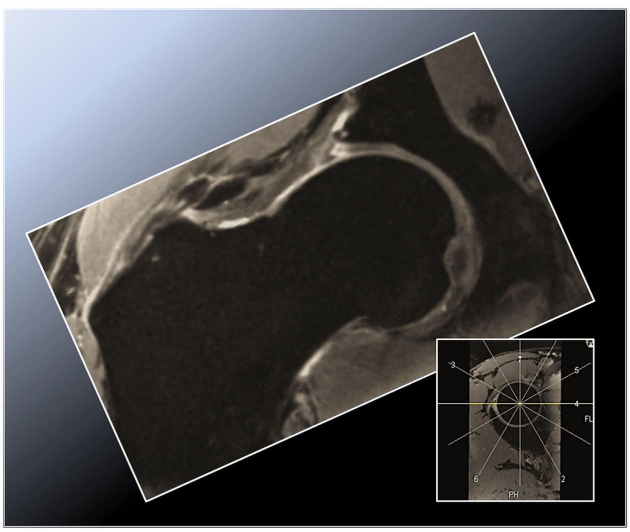

FIGURE 1 | Radial double-echo steady state (DESS) reformat depicting the superior zone (12 o'clock position) in a cam-type FAI hip. Note the aspherical femoral head and the corresponding labral tear with intraosseous and extraosseous extravasation of synovial fluid arising from the torn labrum and peripheral acetabular cartilage abrasion.

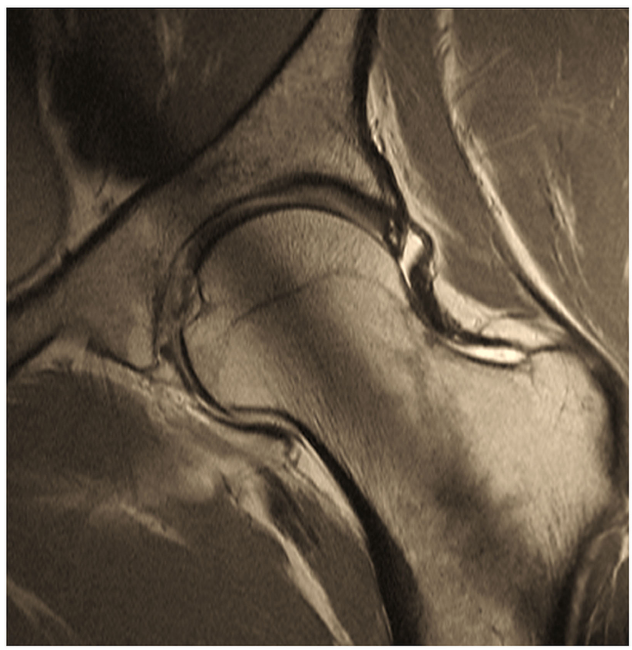

FIGURE 2 | Two-dimensional proton-density (PD) – weighted MR image of a pincer-type FAI patient depicting an increased signal within the center of the labrum that does not extend to the labral margin reflecting intra-labral degeneration. Note that the saturation effect (band of low signal in the center of acetabulum and femoral neck) is constantly present in 2D radial MR imaging.

resonance imaging (MRI) or MR arthrography (MRA) are the primary imaging modalities (8–10). The radiographs provide initial information about the osseous structural abnormalities of the hip and allow a comparison of the affected side with the asymptomatic side for the detection of subtle osseous changes pointing toward morphology of FAI. With superior soft tissue contrast and the capacity for multi-planar image acquisition, MRI and MRA can reveal the degree of chondrolabral damage. In addition, they provide crucial information on the location and extent of hip deformity and other causes of hip pain (such as avascular necrosis of the femoral head, neoplastic synovitis) can be excluded. If surgical treatment is intended, pre-operative MRI or MRA assists in identifying the degree of cartilage damage that may otherwise negatively affect the surgical outcome (11). The utility of contrast agents (MRA) or diagnostic anesthetic into the hip joint (to confirm intra-articular pathology by artificially creating an arthrogram effect) simplifies evaluation by separating the intra-articular structures to delineate the anatomy better (12). Furthermore, the high signal of gadolinium and joint fluid can be visualized clearly in any surface irregularity if present. Computed tomography (CT) and CT arthrography may be used (in patients with contraindications to MRI) because they can offer a three-dimensional (3D) display of the osseous anatomy and sequelae of impingement (13). The 3D assessment helps to define the nature, location, and extent of femoral head over-coverage or femoral head–neck prominence. With a diagnosis on clinical examination, the correct implementation of the various imaging techniques is critical in the evaluation of morphology, deformity evaluation, and planning of management.

The therapeutic goal in symptomatic FAI is to address the abnormal morphology, that is, responsible for the impingement in that individual case, thereby to mitigate the course of progression to arthritis. Pain relief and improvement of motion and function are often realized following the achievement of de-impingement. Recent advances also aim to address and treat chondrolabral lesions in many different ways in order to stop or at least slow the progress of degenerative OA. Depending on the pattern of FAI, the extent of pre-existing chondrolabral damage, the patient's expectations, and the surgeon's training, a number of surgical treatment options are possible (14). These range from hip arthroscopy to mini-open arthrotomy, a combined open arthrotomy – arthroscopic procedure and surgical hip dislocation with appropriate management of intra-articular damage. Depending on the intra-operative observation, debriding or repair of any pre-existing chondrolabral pathology and concomitant femoral head–neck or acetabular osteochondroplasty to improve the femoral head–neck offset is indicated (**Figure 3**). In selected cases, acetabular or femoral correction osteotomies may also be necessary. Recent advances include chondrocyte grafting and chondrocyte transplantation in select cases (15).

A successful outcome following surgical treatment certainly includes the basic requirement of correcting the deformity of abnormal morphology in that individual case. There is no question that the preceding chondrolabral cartilage damage is a strong predictor of the eventual outcome of surgery, often producing poor outcomes in cases with cartilage degeneration in the advanced stages (16). Identification of patients with FAI

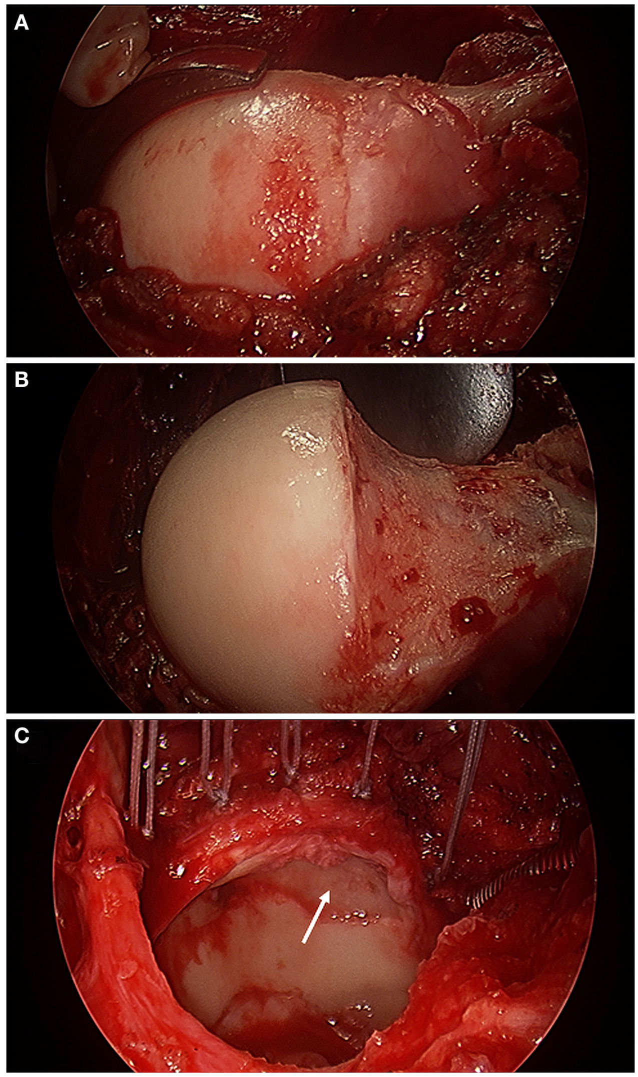

FIGURE 3 | Intra-operative photographs made with an arthroscopic surgery camera after surgical hip dislocation demonstrating a bump deformity at the femoral head–neck junction (A), the femoral head–neck osteochondroplasty to improve the femoral head–neck offset (B), and acetabular evaluation under full direct visualization revealing full-thickness chondral damage at the anterior–superior aspect of the acetabulum (white arrow) and an extended torn labrum that was re-attached to the acetabular rim with five suture anchors (C) in a 56-year-old with impingement.

in the early phases of chondrolabral damage and timely surgical intervention prior to the onset of progressive irreversible chondral damage is critical to the long-term success of FAI treatment. Conversely, despite technical developments that include the use of high-MR field strengths and dedicated cartilage-specific sequences, a comprehensive pre-operative assessment of hip-joint cartilage is still challenging given its location deep within the body, its thinness and its spherical shape, which requires both high-spatial resolution and a high-signal-to-noise (SNR) ratio (17). Also, in FAI cartilage, damage occurs typically as a debonding of the acetabular cartilage from the subchondral bone, leaving the superficial layer intact (5). Therefore, as the contrast medium in MRA will usually not penetrate beneath delaminated cartilage, the extent of the acetabular cartilage damage is probably underestimated in many cases (18). Hence, the accuracy and reliability achieved with MRI and MRA in identifying early chondral damage in FAI remain rather poor (19, 20). However, the accuracy and diagnosis achieved by MRI/MRA are technique dependent (21). Notably, the sensitivity of detection of cartilage delamination, for example, the revealing of fluid under cartilage tissue, has been proved to be at best moderate (sensitivity rates in one recent study range from 35 to 74%) (22).

Biochemically sensitive MRI techniques may help to overcome this limitation as they reproducibly quantify extracellular matrix alterations within cartilage that occur early in the progress of cartilage degeneration prior to advanced changes or gross morphological damage. Biochemically sensitive MRI includes the techniques of delayed gadolinium-enhanced MRI of cartilage (dGEMRIC), T1ρ (T1rho), T2/T2* mapping, and several others (23). The ability of these techniques to evaluate cartilage degeneration accurately and reproducibly could improve the ability to offer fairly reliable and predictable prognostication of whether a patient would benefit from joint preservation surgery for symptomatic FAI.

The present review aims to outline the facts and current applications of biochemical MRI for hip joint cartilage assessment covering the roles of dGEMRIC, T2/T2*, and T1ρ mapping. Therefore, the basics of each technique and potential implications for patient care in FAI are outlined. Furthermore, current limitations and potential pitfalls and the present and future aspects of biochemical MRI in FAI are discussed.

Delayed Gadolinium-Enhanced MRI of Cartilage

Delayed gadolinium-enhanced MRI of cartilage is sensitive to the negative charge of the extracellular glycosaminoglycan (GAG) in which the negatively charged gadolinium-based contrast agent distributes within cartilage inversely to the GAG content (24). Thus, regions with diseased cartilage will demonstrate larger amounts of gadolinium and vice versa. Contrast agent reduces the T1 relaxation time. Thus, higher $T1_{Gd}$ relaxation time values will be measured in healthier cartilage, whereas low $T1_{Gd}$ values will be observed in degenerated, GAG-depleted cartilage.

Most dGEMRIC studies have been performed with the FDA-approved, intravenously injected double negatively charged contrast agent $Gd\text{-}DTPA^{2-}$. Although, more recently, the single negatively charged contrast agent $Gd\text{-}DOTA^{-}$ has been used both after intravenous (25) and after intra-articular administration (26), providing the benefits of both MRA and cartilage mapping. The suggested contrast media dosage for a dGEMRIC measurement is 0.2 mm/kg body weight, twice the recommended clinical dose (27). A definite time frame between the contrast agent administration prior to an exercise protocol and the $T1_{Gd}$ relaxation time measurement, which is based on the route of administration (intravenous or intra-articular) and the thickness of the cartilage tissue (longer uptake times in knee joint cartilage), is required to ensure appropriate penetration of the gadolinium contrast agent into cartilage. For dGEMRIC of hip joint cartilage, a time frame between contrast agent administration and $T1_{Gd}$ relaxation time measurement of 30–90 min after the intravenous application (27) and 15–30 min after the intra-articular injection (28) has been proposed. Notably, diseased cartilage may reveal a faster gadolinium wash-in into cartilage, indicating that $T1_{Gd}$ mapping at earlier time points (after 30–65 min, for instance) may increase sensitivity to cartilage alterations (29).

For generating a T1 relaxation time image ($T1_{Gd}$ after gadolinium contrast application), consecutive images with varying repetition times (TR) and signal levels are required. $T1_{Gd}$ maps were initially obtained with two-dimensional (2D) T1-weighted inversion recovery (IR) sequences that offered the advantages of widespread availability, optimal contrast properties, and relatively low B1 variation, which arise because the radiofrequency (RF) pulse is absorbed differently across the patient, particularly in a high-MRI field (30). Explanatory note: in MRI, there are three types of magnetic fields including the main magnetic field (B0), the RF field that excites the spins (B1), and the gradient fields that offer localization. The main limitations of this 2D-based technique include longer acquisition time and risk of motion artifacts (31). Current techniques, such as gradient-echo (GRE), -based sequences with variable flip angles are capable of generating 3D $T1_{Gd}$ data sets with high-isotropic spatial resolution. These 3D MRI data sets can then be reformatted during post-processing in radial planes of the hip joint (**Figure 4**) instead of just a selected cross-section as with 2D $T1_{Gd}$ mapping (32). Although 3D dGEMRIC is relatively new, recent investigations confirm that it is both highly reproducible and valid in its assessment of hip articular cartilage (33–36). Lattanzi et al. have established a new high resolution, B1-insensitive 2D T1 mapping saturation and recovery pulse sequence with fast spin-echo readout for dGEMRIC of the hip at 3 T including radial imaging (37).

Literature Review

Jessel et al. noted a correlation between the $T1_{Gd}$ value and pain (regression coefficient of 0.4; $P < 0.05$) and between the $T1_{Gd}$ value and the alpha angle (coefficient of 0.36; $P < 0.05$), which is a parameter for calculating the asphericity at the femoral head–neck junction (38). Although the amount of radiographic apparent OA was mild (Tönnis grade 0 or 1) in the majority of cases (26 of 37 hips), the drop in $T1_{Gd}$ ($T1_{Gd}$: 464 ± 64 ms) was remarkable. Notably, neither Tönnis grade nor joint space width correlated with patient symptoms.

Bittersohl et al. observed lower $T1_{Gd}$ values in FAI patients in comparison with asymptomatic volunteers (39). Furthermore, the distribution of the $T1_{Gd}$ decrease was in accordance with the FAI damage pattern, which in cam types demonstrated a significant drop of the $T1_{Gd}$ values in the anterior to superior location ($P < 0.05$). In pincer-type FAI, a generalized circumferential decrease was noted. Mamisch et al. reported lower $T1_{Gd}$ values in cam- and pincer-FAI patients than in asymptomatic controls (40). Particularly in the anterior aspect of the joint, the cam-FAI group exposed not only peripheral but also central cartilage $T1_{Gd}$ changes, whereas the pincer-FAI cohort demonstrated a rather global $T1_{Gd}$ decrease for all areas of the hip, with $T1_{Gd}$ values

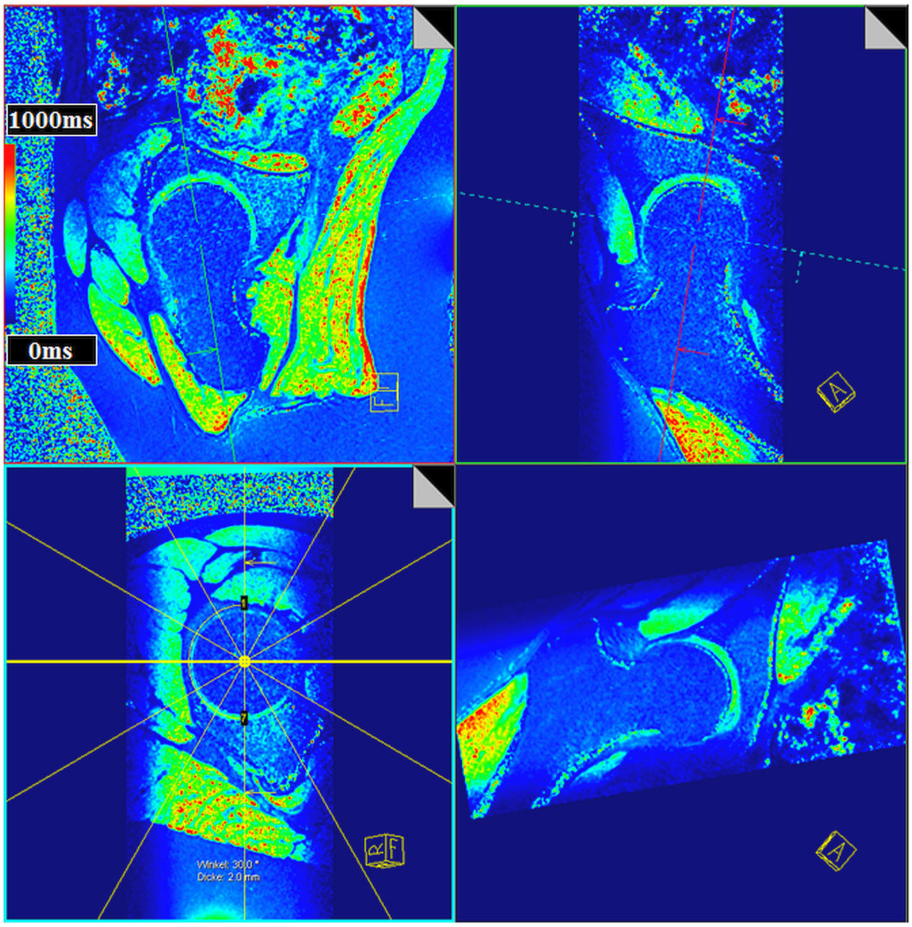

FIGURE 4 | Multi-planar-reconstruction of the three-dimensional (3D) $T1_{Gd}$ data set including plane adjustment through the center of the femoral head and perpendicular to the femoral neck within the sagittal oblique view and the coronal oblique view to create radial $T1_{Gd}$ planes throughout the hip joint. $T1_{Gd}$ values are visualized in a color scale. Note the aspherical nature of the femoral head of this asymptomatic volunteer yet without a decrease in the $T1_{Gd}$ values indicating a normal GAG content within cartilage.

between 69.1 and 79% of the control group (**Figure 5**). The results of these studies are somewhat similar to those of Domayer et al., who studied the $T1_{Gd}$ pattern in symptomatic cases of hip dysplasia and FAI (41). Twenty patients with hip dysplasia and 20 patients with FAI underwent dGEMRIC. The mean $T1_{Gd}$ value was 551 ± 95.7 ms in patients with FAI and 531 ± 92.7 ms in patients with hip dysplasia. In pre-arthritic hip joints (in this study defined by $T1_{Gd}$ values >500 ms), higher $T1_{Gd}$ values were noted in the weight bearing and in the central areas in both study cohorts (P = 0.036 and 0.0001), whereas no such distribution was noted in hips with progressive degeneration ($T1_{Gd}$ values <500 ms). Notably, in view of the high content of GAG in the weight-bearing superior region, the regional distribution of $T1_{Gd}$ in the hip joint with increased values toward the superior and central regions has been noted in asymptomatic adult volunteers (42). These observations regarding the $T1_{Gd}$ pattern both in asymptomatic volunteers and in FAI patients (cam, pincer, and mixed types) may aid in objective stratification and treatment planning.

Pollard et al. spotted lower $T1_{Gd}$ values in asymptomatic hips with cam deformities compared with morphologically normal hips (P = 0.0008) (43). The $T1_{Gd}$ values in the anterosuperior aspect of the acetabular cartilage correlated inversely with the alpha angle ($r = -0.483$; $P = 0.0038$), indicating that the severity of the GAG loss correlates with the magnitude of the cam deformity. Furthermore, cases with a positive impingement test demonstrated lower global (total femoral and acetabular cartilage) $T1_{Gd}$ values than hips with a negative result ($T1_{Gdtotal} = 625$ versus 710 ms; $P = 0.0152$). Somewhat similar observations were made by Jessel et al., who noted a weak correlation ($r = -0.36$) between the alpha angle and femoroacetabular $T1_{Gd}$ value (38). Zilkens et al. noted a correlation between the beta angle (angle between the femoral head–neck junction and acetabular rim) in the superoinferior and superior regions, whereas the alpha angles did not correlate with the $T1_{Gd}$ measures (44). Zilkens et al. explain their results by the fact that the alpha angle only reflects the femoral side, whereas the beta angle accounts for the morphology of both the femur and the acetabulum and

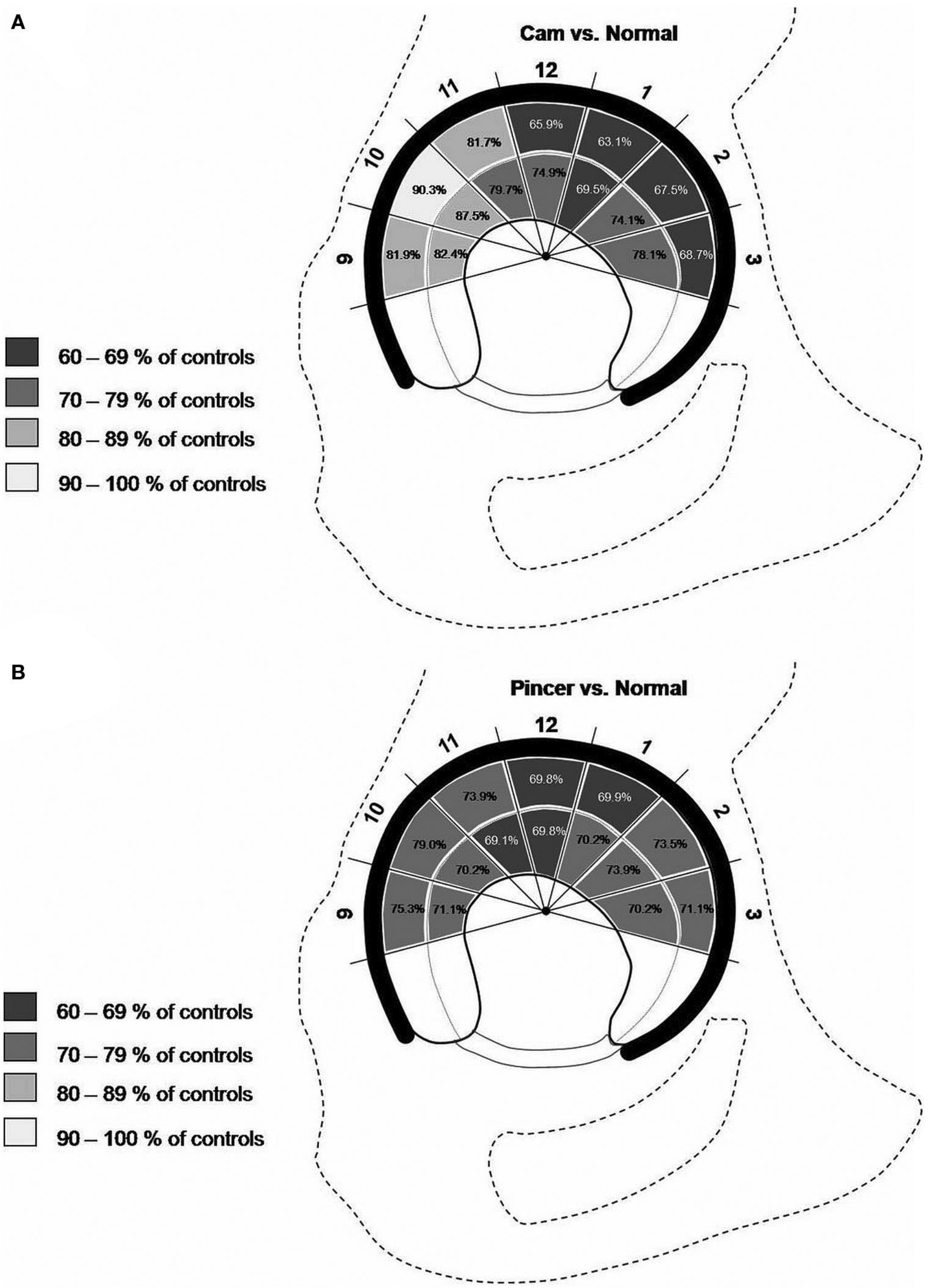

FIGURE 5 | Schematic drawing demonstrating the $T1_{Gd}$ decrease in various regions of hip joint cartilage of cam- (A) and pincer- (B) FAI patients. The percentage values refer to the $T1_{Gd}$ average in corresponding hip joint regions of asymptomatic controls. Note that, particularly in the anterior aspect of the joint, the cam-FAI group exhibited not only a peripheral but also a central cartilage $T1_{Gd}$ decrease **(A)**, whereas the pincer-FAI cohort demonstrated a rather global $T1_{Gd}$ decrease for all areas of the hip **(B)**. Figure reprinted with permission (40).

thus may be the more sensitive surrogate for cartilage damage in FAI.

Despite several technical developments in recent years that have made dGEMRIC a clinically feasible application in the assessment of hip joint cartilage status, one should exercise care during interpretation of dGEMRIC observations prior to implementing any clinical decisions because anatomic, inter-subject, and technically related variations can lead to meaningful misinterpretations and limited comparability. The above-mentioned regional differences in GAG concentration, the effect of the magnetic field strength on the T1 relaxation time and pharmacokinetic-related contrast agent uptake variations owed to patient age, sex, body mass index (BMI), or differences in diffusion and transport rates of gadolinium contrast are just a few examples in this context. Lattanzi et al. therefore proposed a standardized approach to analyze dGEMRIC measurements in FAI (36). This included the transformation of $T1_{Gd}$ values to standard scores (*z*) calculated from the mean and the SD of $T1_{Gd}$ in the (in FAI) assumed healthy weight-bearing femoral head cartilage. Others proposed to normalize regional $T1_{Gd}$ values by dividing them by the average T1 of the total cartilage (acetabular and femoral) to highlight areas of abnormalities (43).

T1ρ Mapping

Similarly to dGEMRIC, T1rho (T1ρ) relaxation time mapping is sensitive to the GAG content of hyaline cartilage (45–49). The main advantage of T1ρ mapping is that it does not require an intravenous injection or an exercise regime or a time frame between contrast agent application and MRI to warrant gadolinium uptake into cartilage. However, a noticeable drawback of this technique is that it involves relatively high- RF energy [measured by the specific absorption rate (SAR)] and this high-RF energy can result in tissue heating during the spin-lock preparation pulse (50). Furthermore, the T1ρ sequence is, yet, not commercially available and still requires post-processing.

In brief (51–53), based on the physics of MRI, a 90° RF pulse is applied on-resonance with Larmor precession frequency to excite nuclei, meaning that spins are tilted in the main magnetic field B_0 into the transverse plane and synchronized to spin (precess) in-phase. The synchronized precession of the spins in the transverse plane is the origin of an RF pulse (signal) that is collected in the MR receiver coil. Nuclei relaxation occurs immediately after the RF pulse because of the exchange of energy between the nuclei and their surroundings (spin–lattice or T1 relaxation) and from nuclei dephasing caused by variations in the precessing frequencies of the nuclei that arise from random interactions between adjacent nuclei (spin–spin or T2 relaxation). In GRE-MRI, which lacks a 180° spin-refocusing pulse, a combination of T2 and "noise" caused by local field inhomogeneities related to differences in the magnetic susceptibility among various tissues, chemical shifts, gradients applied to perform spatial encoding, and main magnetic field heterogeneity is measured. This is referred to as T2* relaxation. A T1ρ pulse sequence applies a long-duration, low-power RF pulse to the transverse component of the magnetization vector. The applied B_1 field attenuates the effect of dipole–dipole coupling, chemical exchange, and background gradients on the magnetization, meaning that the regular signal decay (T2* relaxation) is slowed to a time constant T1ρ that is referred to as spin–lattice relaxation in the rotating frame. In other words, the magnetization is, for the duration of the RF pulse, "spin-locked." Having deteriorated the T2/T2* effects by means of the "spin-locking" pulse, the T1ρ decay results principally from interactions between protons and their surroundings with regard to articular cartilage reflecting interactions between water molecules and extracellular components, such as GAG chains, that restrict the motion of water molecules, which explains the increased T1ρ values in cartilage regions with depleted GAG.

There are some conflicting reports in terms of GAG content and its correlation with T1ρ relaxation (54). Notably, Keenan et al. reported that T1ρ relaxation time is inversely correlated with the GAG content in cartilage regions with normal T2 relaxation time (55), whereas other researchers (56, 57) observed focal areas of high- and low-T1ρ and T2 values, which cannot be explained by GAG concentration or collagen orientation. Further conflicting evidence regarding the contribution of factors behind the variations in T1ρ and T2 is reported in the literature. However, it has been agreed that these measures are sensitive to alterations in the extracellular composition and macromolecular structure and integrity (54). Although the T1ρ technique has been explored extensively in the knee (58–63) the application of T1ρ mapping to the hip joint (54, 64, 65) has been relatively limited, which is in part related to signal-to-noise (SNR) ratio constraints associated with the thin cartilage layers and the deeper location of this joint.

Literature Review

Early investigations of T1ρ relaxation time mapping in subjects with FAI demonstrated degenerative changes in acetabular and femoral cartilage before gross tissue loss was apparent (65). It was also noted that FAI patients display a different T1ρ distribution pattern across the thickness of the cartilage whereby the control group demonstrated a T1ρ value trend with increasing values from deep to superficial cartilage layers, with the middle third having significantly greater T1ρ relaxation values than the deepest third ($P = 0.008$), whereas the FAI group demonstrated loss of this trend. Furthermore, the deepest third cartilage layers in the FAI group demonstrated greater T1ρ relaxation values than controls ($P = 0.028$).

Using a 3-T MR scanner, Subburaj et al. noted longer T1ρ relaxation times (T1ρ = 39.9 ± 3.3 versus 35.4 ± 2.3 ms; $P = 0.0020$) and longer T2 relaxation times (T2 = 33.9 ± 3.1 versus 31.1 ± 1.7 ms; $P = 0.0160$) in the cartilage of 9 FAI patients than in 12 healthy controls (54). The authors also noted that T1ρ and T2 relaxation times in the anterosuperior cartilage sub-region were different from those of the global cartilage, and that the analysis based on local regions was more sensitive than global measures in differentiating subjects with and without FAI (**Figure 6**). Notably, the *in vivo* hip cartilage T1ρ and T2 measurements were highly reproducible (CV < 5%).

T2 Mapping

Probing the interactions between water molecules and their environment, T2 relaxation time mapping is sensitive to two main components of articular cartilage, collagen, and water (66). It has been shown to correlate with cartilage matrix hydration and collagen fiber integrity whereby early degeneration-induced alterations in water content and collagen fiber arrangement could then be detected by this technique (T2 relaxation time increase) (67, 68). There has been a considerable amount of work on non-contrast-based assessment of early cartilage degeneration using T2 mapping. However, most of these studies relate to the assessment of knee joint cartilage (69) and only a few studies report the application of T2 mapping for the evaluation of hip joint cartilage. This is probably related to long-acquisition times that typically exceed 10 min, and the constraint on 2D acquisitions.

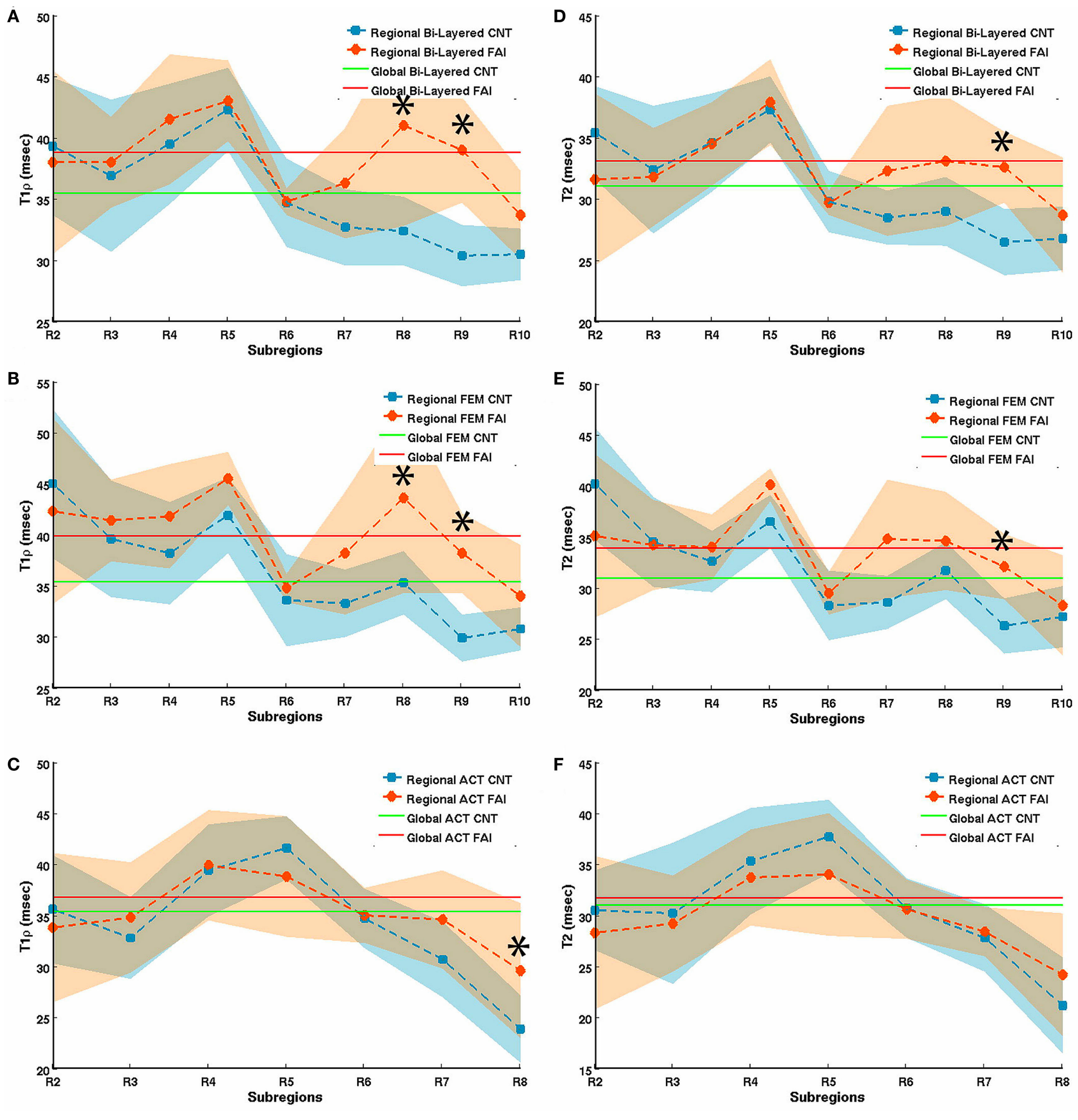

FIGURE 6 | T1rho (A–C) and T2 (D–F) relaxation times in bi-layered (A,D), femoral (B,E), and acetabular (C,F) sub-regions of hip joint cartilage in 12 healthy volunteers (controls) and 9 FAI patients. The segmented regions of interest (ROIs) were automatically divided radially into 12 equal sub-regions (30° intervals) based on the fitted center of the femur head in which R2 represents the posterior–inferior region (5–4 o'clock in a clockwise system, right hip), R5 the posterior–superior (2–3 o'clock), and R8 the anterior–superior (1–2 o'clock) region. Error bars represent SD. *represents a significant difference between relaxation times of controls and FAI subjects. Figure reprinted with permission (54).

Literature Review

Probably because of factors including cartilage matrix composition and magic angle effect, Watanabe et al. (70) noted a topographic variation in the T2 values of hip joint cartilage of 12 healthy volunteers (**Figure 7**). These observations are of great relevance for interpreting and evaluating T2 values in hip joint cartilage before attributing T2 changes to early degeneration. Furthermore, the effect of cartilage compression during loading, which induces water outflow and derangement of the collagen organization, and hence, a decrease of T2 needs to be considered. For that reason, it is recommended to perform T2 mapping at the end of an MR scan to minimize the effects of cartilage loading. Interestingly, Nishii et al., who evaluated the change in cartilage T2 values with loading in 15 patients with hip dysplasia, noted that (1) the decrease in cartilage T2 at the outer superficial zones of the acetabular cartilage with loading was greater in patients with hip dysplasia (T2 change with loading: −7.6 ± 10.6%) than in healthy volunteers (T2 change with loading: −1.2 ± 10.9%) and (2) there was a positive correlation between the center-edge angle on AP radiographs and T2 changes with loading at the outer deep zones of the acetabular cartilage (71).

Ascani et al. studied the correlation of dGEMRIC and T2 with morphologic cartilage assessment at 3 T (72). Whereas the dGEMRIC technique was remarkably sensitive to cartilage damage (71 and 86% for minor and severe lesions, respectively), T2 mapping was very specific (87% for any type of lesion). The authors concluded that a combination of morphologic MRI, dGEMRIC, and T2 could be effective in detecting and staging cartilage damage. As outlined above, Subburaja et al. noted longer T2 relaxation times (T2 = 33.9 ± 3.1 versus 31.1 ± 1.7 ms; $P = 0.0160$) in cartilage of 9 FAI patients than in 12 healthy volunteers (54). Studies on other pre-arthritic hip conditions revealed similar results. Yamamoto et al. noted higher T2 values (T2 = 34.4 ± 3.1 versus 30.8 ± 1.2 ms; $P = 0.001$) of the femoral head cartilage in 10 systemic lupus erythematosus patients (15 hips) with non-collapsed osteonecrosis of the femoral head associated with corticosteroid therapy than in the control group (14 volunteers, 28 hips) (73). Nishii et al. observed a trend of higher T2 values (T2 = 37.1 ± 12.0 versus 33.4 ± 4.5 ms) in acetabular cartilage of 12 dysplastic hips with early (Kellgren–Lawrence grade 1 or 2) OA compared with a control group of 10 volunteers (14 hips) (74). Notably, whereas almost all hips of the control group (visually) demonstrated a characteristic gradient pattern of T2 with T2 values increasing from the deep cartilage zone toward the articular surface, which is consistent with previous reports of normal cartilage T2 values (75, 76), this cartilage T2 pattern became less apparent (pre-arthritic patients) or disappeared (early-arthritic patients).

T2* Mapping

The T2* mapping technique is a recent modality that is relatively easy to implement in clinical routine as no contrast media or special hardware are required and it has the added advantage of short-acquisition times. Furthermore, high-resolution imaging allowing for a 3D cartilage assessment is feasible. Like the T2 mapping technique, T2* mapping reflects bulk water content and interactions between water molecules and collagen fibers within cartilage (53). Correspondingly, a characteristic pattern of T2* values with higher numbers in the superficial zone (somewhat related to high-water content and superior water molecule mobility), and lower T2* values toward the cartilage–bone interface (where the uniform perpendicular collagen fiber orientation and high-proteoglycan content endorse water molecule restriction and T2/T2* decay) is noted in normal articular cartilage (66). Nevertheless, distinct differences between these two techniques should be outlined (77). T2 mapping utilizes a spin-echo sequence that comprises a 180° spin re-phasing RF pulse to compensate for local magnetic field inhomogeneities. In brief (51, 53, 78), local magnetic field inhomogeneities cause some spins of individual nuclei to slow down because of lower local field strength, whereas other spins speed up because of higher field strength. This leads to

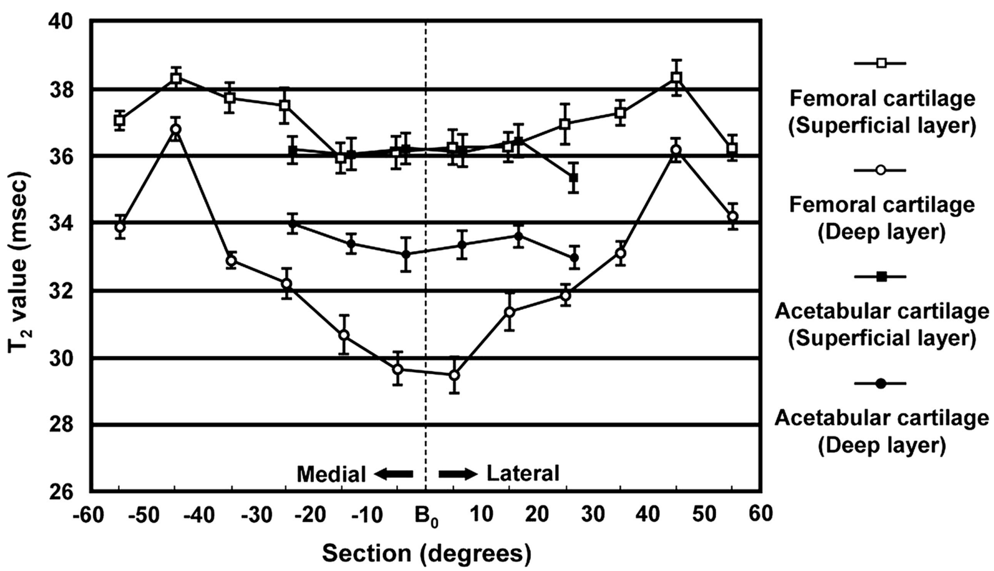

FIGURE 7 | T2 mean values in various of sections (regions) and layers (zones) of femoral and acetabular cartilage. The bar indicates the SE of the mean. Note the topographic variation in the T2 values of hip joint cartilage probably because of factors including cartilage matrix composition and magic angle effect that need to be considered when interpreting and evaluating T2 values in hip joint cartilage. Figure reprinted with permission (70).

spin dephasing and T2 signal decay. The applied 180° pulse causes the spins to rotate 180°, so that the slower spins are ahead and the fast ones trail behind. Subsequently, the fast spins catch up with the slow spins (re-phasing), eventually regenerating the T2 signal. In contrast, T2* mapping is performed with a GRE technique that lacks the 180° refocusing pulse. Therefore, dephasing effects related to local MR field variations that originate from diverse magnetic susceptibilities among various tissues, chemical shifts and main magnetic field heterogeneities are added to the net T2 decay that explains the characteristically lower T2* values when compared with the T2 measures. These differences have several implications. Because only one RF pulse is applied in GRE-based T2* mapping, the echo can be recorded more rapidly, promoting fast imaging. Furthermore, due to higher echo times (TE) in spin-echo sequences (TE ~10–100 ms), the T2 mapping technique reflects to a large extent the relaxation of bulk water, whereas T2* mapping (with shorter TEs) comprises a wider range of T2 relaxation in cartilage tissue, including signals that decay below 10 ms. T2* mapping is also less susceptible to stimulated echoes and magnetization transfers because it lacks the 180° refocusing pulse. However, enhanced susceptibility effects, such as those related to post-surgical debris or unfavorable anatomic circumstances (for example, closely approximated tissue interfaces), can potentially impair T2* articular cartilage assessment.

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T2* mapping of hip joint cartilage was first reported in 2009 (79). In this pilot study, Bittersohl et al. demonstrated the feasibility of 3D GRE-based T2* mapping at 1.5 T with radial evaluation to assess degenerative changes of hip joint cartilage throughout the hip joint. This study, which enrolled 33 patients with FAI, revealed a significant drop of the T2* values in degenerated cartilage. Limitations of the study included the inability to differentiate clearly between acetabular and femoral head cartilage. The bulk T2* values that were obtained included both acetabular and femoral head cartilage as one entity including the interspersed joint fluid, particularly in areas of severe cartilage damage, which may have caused overestimation of the measured T2* values. This issue was resolved in a follow-up study at 3 T (80) in which a sufficient image resolution could be achieved to delineate the cartilage layers of the acetabulum and the femoral head (**Figure 8**). In accordance with their previous work, this study group was able to identify a decrease of the T2* values with increasing morphologically apparent cartilage damage ($P < 0.001$) in 29 patients with FAI. Notably, the collected data of 35 healthy, asymptomatic volunteers provided normative T2* values of hip joint cartilage for subsequent studies.

Apprich et al. performed T2* mapping in the acetabular cartilage of 22 patients with clinical signs of FAI (no or mild signs of degeneration in AP radiographs) and 27 age-matched, asymptomatic volunteers at 3 T shortly after the beginning of MRI (early unloading) and after a period of 45 min (late unloading) (81). Although comparison between the T2* values of FAI patients ($T2^*_{global} = 21.5 \pm 3.0$ ms) and volunteers ($T2^*_{global} = 21.8 \pm 2.4$ ms) did not reveal any difference after early unloading ($P = 0.747$), significant differences between the T2* values of patients ($T2^*_{global} = 21.1 \pm 2.9$ ms) and those of volunteers ($T2^*_{global} = 24.6 \pm 3.1$ ms) were noted after 45 min of unloading. Notably, the T2* mapping values increased with unloading over time in the control group ($T2^*_{global} = 21.8 \pm 2.4$ versus 24.6 ± 3.1 ms; $P = 0.001$), whereas a slight decreasing trend was observed for FAI patients ($T2^*_{global} = 21.5 \pm 3.0$ versus 24.1 ± 2.9 ms; $P = 0.080$).

Siebenrock et al. conducted an experimental ovine FAI model study in which a cam-type FAI was created in eight alpine sheep by performing a closed wedge intertrochanteric varus osteotomy prior to sacrifice 10–14 weeks after surgery and MRI of the hip at 3 T (82). By measuring T2 and T2* values in six locations on the acetabulum (posterior–superior, cranial, anterior–inferior; in each case, centrally and peripherally) and comparing them with histological grades, they found a negative correlation between the histological grading of degenerated cartilage (Mankin grading) and the T2 ($r = -0.79$; $P < 0.001$) and T2* ($r = -0.90$; $P < 0.001$) values. A positive predictive value of 100% and a negative predictive value of 84% were observed for the T2 mapping technique, whereas the T2* technique revealed a positive predictive value of 100% and a negative predictive value of 94%. Topographical T2 and T2* variations were also noted (low values posterior–superior and anterior–inferior at the periphery of the acetabulum).

The most recent report on articular hip joint cartilage assessment by means of T2* mapping in patients suffering from FAI enrolled 28 hips (26 patients) (83). In this retrospective study, the authors correlated T2* maps of acetabular cartilage (superficial, deep, and full-thickness cartilage) with intra-operative arthroscopic cartilage assessment (cartilage degeneration grading according to a modified Beck scale). In this study, lower T2* values were noted for superficial, deep, and full-thickness cartilage in regions with intra-operatively identified cartilage damage (T2* = 20.7 ± 6.0 ms) compared with intra-operatively apparently normal cartilage (T2* = 35.3 ± 7.0 ms, $P < 0.001$). Furthermore, receiver operating characteristic curve analysis (ROC) revealed a threshold T2* value of 28 ms as the threshold for damaged cartilage (91% true-positive and 13% false-positive rate for differentiating normal from abnormal cartilage). Notably, although hip joint arthroscopy was restricted to patients with Tönnis grades 0 and 1, 360 of 532 (68%) regions demonstrated evidence of cartilage damage during arthroscopy. This (again) demonstrates (1) the unreliability of plain radiographs in determining the extent of cartilage damage and (2) the ability of T2* mapping to aid accurate diagnosis of damaged intra-articular cartilage in FAI that could improve our ability to offer a fairly reliable and predictable prognostication of joint status and the appropriateness of intervention in terms of joint preservation or joint replacement.

Pearls and Pitfalls

Given that the femoral head and acetabular cartilage layers are relatively thin (~1–3 mm each in the weight-bearing zone in a normal hip) (84), spherical in shape and quite closely approximated, quantitative assessment of hip joint cartilage is limited by its relative proneness to chemical shift, susceptibility to artifacts,

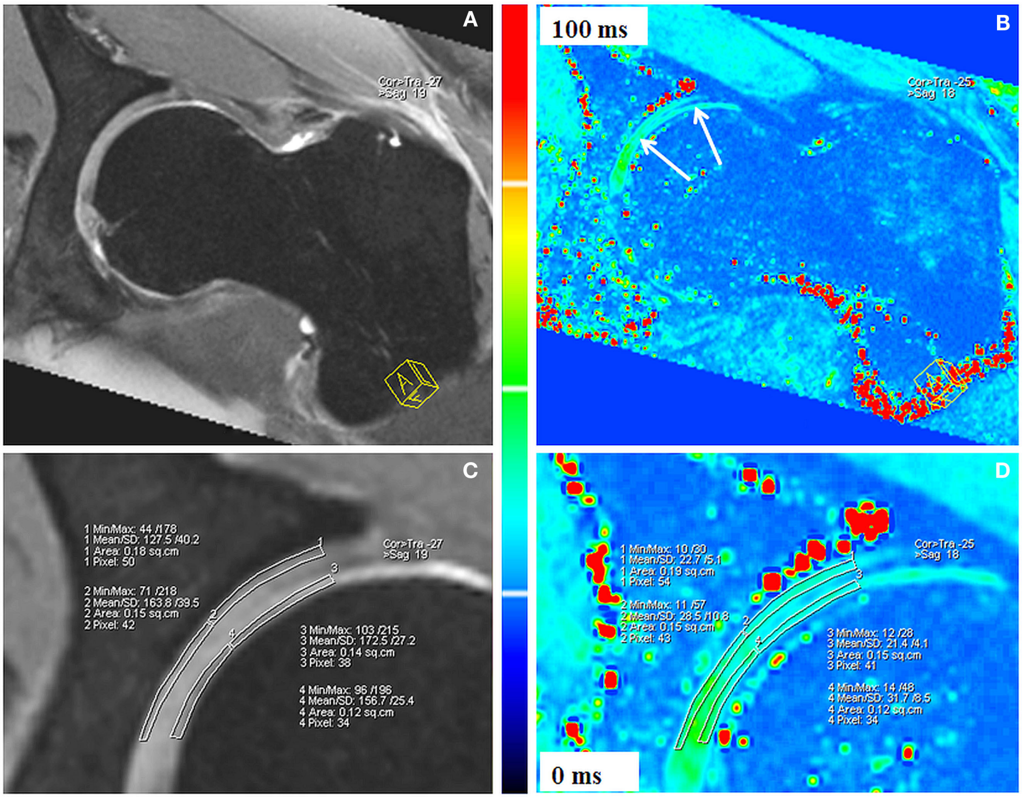

FIGURE 8 | Double-echo steady state (DESS; A,C) and corresponding T2* reformat (B,D) of an asymptomatic volunteer. Sufficient image resolution could be achieved to delineate the cartilage layers of the acetabulum and the femoral head for ROI analysis within peripheral acetabular cartilage, central acetabular cartilage, peripheral femoral cartilage, and central femoral cartilage. The DESS reformats **(A,C)** served as reference for accurate placement of the ROI squares within cartilage. T2* values are illustrated in a color scale **(B,D)**. Figure reprinted with permission (80).

and volume averaging (fitting of square pixels to a curved structure and, thus, averaging hyaline cartilage with subchondral bone or intra-articular fluid). This is particularly so when the imaging plane is not perpendicular to the curvature of the cartilage. The bulk mapping values of the articular cartilage and the intra-articular space comprise the signal of both articulating cartilage surfaces and the intra-articular joint fluid. This may be reasonably acceptable for visualization purposes. However, in terms of cartilage relaxation time quantification, it leads to erroneous measurements that are pronounced in regions with cartilage abrasion (for example, underestimation of the $T1_{Gd}$ values and overestimation of the T2/T2* values). We, therefore, recommend adjusting the image settings for superior cartilage image quality with high-cartilage contrast and image resolution to achieve optimal cartilage delineation. High-spatial resolution mapping in 2D or 3D radial imaging planes, which allows the orthogonal display of the acetabular cartilage around its circumference, can reduce volume averaging as it provides a true cross-section of the cartilage. Notably, although the generation of 2D radial planes in the hip may be challenging, 3D volumetric acquisitions can be radially reformatted relatively easily. Higher field strengths (≥3 T) in combination with a dedicated and reasonably small surface coil will increase the SNR. The coil should enclose the hip joint as the SNR decays considerably if the distance between the ROI and the coil exceeds the capacity of the device although it is understood that this may pose a challenge in obese patients. A tolerable acquisition time and appropriate patient positioning to avoid motion artifacts must also be considered. Select biochemical MRI parameters currently utilized for *in vivo* hip joint cartilage assessment are summarized in **Table 1**.

Cartilage loading, which may vary locally, has an influence on the extracellular matrix (for example, water outflow because of cartilage compression) (70, 85). This certainly has an impact on the mapping values, and therefore, it is recommended that biochemical MRI should be performed at the end of the MR scan in the (standardized) unloaded state (68, 86). With regard to dGEMRIC, a certain time frame between the contrast agent administration and the $T1_{Gd}$ relaxation time measurement is required to obtain an appropriate cartilage penetration of the gadolinium contrast agent. Regarding dGEMRIC of hip joint cartilage, a time frame of 30–90 min after intravenous application (27) or 15–30 min after intra-articular injection (28) is recommended. The same applies for a reproducible protocol of hip joint motion prior to the $T1_{Gd}$ mapping to enhance appropriately and consistently the gadolinium circulation and uptake within articular cartilage.

TABLE 1 | Selected imaging parameters of previously reported studies of dGEMRIC, T1ρ, T2, and T2* assessment of hip joint cartilage.

	Zilkens et al. (35, 44)	Subburaj et al. (54)	Watanabe et al. (70)	Bittersohl et al. (80)
MRI technique	dGEMRIC	T1ρ mapping	T2 mapping	T2* mapping
Imaging parameters				
Field strength (T)	3	3	3	3
Repetition time, TR (ms)	15	n/s	1500	38
Echo time, TE (ms)	2.24	0, 15, 30, 45	10.3–103	4.62, 9.41, 15.28, 21.15, 27.02, 32.89
Flip angle (°)	5, 26	n/s	n/s	25
Number of excitation	1	n/s	1	1
Field of view (mm)	192	140	150	192
Slice thickness (mm)	0.6	4	4	0.6
In-plane resolution (mm)	0.6 × 0.6	0.5 × 0.5	1 × 1	0.6 × 0.6
Slice gap (mm)	0.12	None	None	0.2
Bandwidth (Hz/pixel)	260	62.5×10^3	315×10^3	260
Acquisition time (min)	14.31	13.40	17.41	13.29

n/s, not specified.

Anatomic, inter-subject, and technical variations, such as alterations in acquisition and fitting parameters that can lead to possible misinterpretations with added limited comparability, need to be considered when cartilage-mapping values are read. For example, there are normal regional differences in the composition, ultrastructure, biological activity, and sectoral joint biomechanics of hip joint cartilage (87) that have an influence on the mapping values (for example, higher $T1_{Gd}$ values toward the superior zone reflecting a high-GAG concentration at this weight-bearing region) (25, 39, 42), thereby emphasizing the need for regional analysis of hip joint cartilage. Furthermore, when T2 and T2* mapping is performed in spherically arched cartilage regions, T2/T2* elongation occurs near the so-called "magic angle" of 54.7° relative to the static magnetic field (B_0) (88). Some observers try to obtain "normalized" regional mapping values by dividing these with some reference value (43). This patient-driven normalization somewhat compensates for deviations caused by technical alterations (e.g., effects of different hardware components and imaging settings, infiltration rate of various dGEMRIC protocols) and variations in the extracellular matrix related to age and individual cartilage configuration. Because many FAI chondrolabral lesions typically originate around the acetabular rim before they progress over time to involve the adjacent cartilage, some researchers suggest that the reference mapping values could be obtained from the central region of the femoral cartilage (34, 36). Notably, despite having advantages, such as short acquisition times, high image resolution and the ability to carry out isotropic 3D cartilage evaluation, GRE-based mapping techniques do lack the 180° refocusing pulse, and therefore, they are more sensitive to local magnetic inhomogeneities (origin of susceptibility artifacts) at the bone–cartilage interface or near artificial particles, such as post-surgical debris and orthopedic implants (53). This effect can substantially compromise the mapping of articular cartilage in postoperative studies. In essence, the mapping values should always be interpreted in conjunction with patient history, clinical examination, and morphological MRI evaluation. In addition, co-existing pathologies, such as hip dysplasia, neoplastic synovitis, bone marrow changes, stress fracture, gluteal enthesopathy, ischiofemoral impingement, advanced (secondary) OA, and several others, may be diagnosed in conjunction with FAI and should be appropriately addressed. FAI may also be bilateral even if only one hip is symptomatic at the time of presentation. Conversely, FAI morphology does not necessarily equate to symptomatic (pathological) FAI and so the exact point of transition remains an enigma.

Finally, despite several studies that have specified the advantages or disadvantages of various cartilage-mapping techniques and their contribution to enhancing cartilage status assessment, biochemically sensitive MRI is still in its infancy. A notable drawback today is the limited applicability of threshold values, as they are dependent on anatomic, inter-subject, and technically related variations and the current lack of clinical correlation. To date, no conclusive imaging data exist for determining an ideal cut-off value for or against surgery in an FAI patient. In the future, it is possible that the ability of these techniques to evaluate cartilage degeneration accurately and reproducibly could improve our ability to offer fairly reliable and predictable prognostication in individual cases for clinical decision-making and treatment.

Conclusion

Symptomatic FAI occurs from dynamic mechanical conflict between the proximal femur and acetabulum. Since symptomatic FAI is a pre-arthritic condition, early diagnosis and imaging of the relevant patho-anatomy with treatment is important in changing clinical course of early arthritis. Decision-making in symptomatic FAI largely depends on the reliable evaluation of damage to chondrolabral and sectoral articular cartilage, which determines the eventual outcome. Advanced biochemically sensitive MRI techniques, such as dGEMRIC, T2, T2*, and T1ρ mapping, can distinguish subtle early cartilage matrix alterations, thereby acting as tools for early disease detection and monitoring. Despite mapping variations that mirror anatomical differences in various zones and regions of hip joint with these advanced techniques, there are still many unanswered questions including the standardized application of these techniques and cut-off values to provide an algorithmic cartilage damage-based approach to managing FAI. Therefore, further studies that address protocol issues regarding these techniques for the reproducible, objective, and meaningful evaluation of articular hip joint cartilage are necessary. Sufficiently powered, controlled cross-sectional, and longitudinal studies will help to provide cut-off values in order to delineate an appropriate time-point of intervention that could lead to an improved and more predictable outcome. Additionally, improvements in speed, resolution, and applicability will, hopefully, lead to widespread adoption of these techniques. Finally, biochemically sensitive MR imaging could someday help bridge the gap in understanding when does asymptomatic FAI morphology eventually turn into FAI pathology.

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REVIEW
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Open and Arthroscopic Surgical Treatment of Femoroacetabular Impingement

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Femoroacetabular impingement (FAI) is a common cause of hip pain, and when indicated, can be successfully managed through open surgery or hip arthroscopy. The goal of this review is to describe the different approaches to the surgical treatment of FAI. We present the indications, surgical technique, rehabilitation, and complications associated with (1) open hip dislocation, (2) reverse periacetabular osteotomy, (3) the direct anterior "mini-open" approach, and (4) arthroscopic surgery for FAI.

Keywords: femoroacetabular impingement, hip arthroscopy, open surgical dislocation, surgical techniques, sports medicine, periacetabular osteotomy

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INTRODUCTION

Femoroacetabular impingement (FAI) is a common cause of hip pain and has been correlated to the development of arthritic changes in the young adult. FAI is a dynamic condition in which deformities in the acetabulum and/or femoral head–neck junction limit hip range of motion and generate abnormal intra-articular contact areas, causing early acetabular labrum and articular cartilage damage (1–3). Often affecting a young and active population, FAI presents with hip and groin pain as well as decreased range of motion. Three mechanisms of FAI have been classically described; cam, pincer, and combined. Cam is the femoral head asphericity and malformed femoral head–neck junction with decreased offset. Cam lesions are more frequently seen in males. The acetabular injury pattern includes labral damage and cartilage delamination through shear forces at the abutment between the abnormal femoral head–neck junction "cam" and the acetabular rim (2, 4). Pincer deformities, result from excessive acetabular coverage secondary to deep sockets (coxa profunda and protrusio), increased anterior acetabular coverage and true acetabular retroversion. A pincer impingement compresses the labrum between the acetabular overcoverage and the femoral neck with hip range of motion (3, 5). Combined deformities are a combination of these two mechanisms and are the most common variant of FAI (6, 7).

There are additional extra- and intra-articular anatomical conditions that must be recognized in FAI. Although combined deformities (cam and pincer) are the most common mechanism of FAI, acetabular dysplasia can coexist with cam impingement and must be considered in the surgical plan to avoid worsening of hip instability and early catastrophic failures. Femoral deformities include excessive femoral retrotorsion which promotes anterior impingement and coxa valga with excessive femoral antetorsion which leads to posterior impingement (8). Additionally, coxa vara may cause intra- and extra-articular impingement (9). The degree of pelvic tilt can also impact impingement pathology. Anterior pelvic tilt increases acetabular retroversion and results in early occurrence of FAI. If flexible, this dynamic conflict should improve with non-surgical treatment (10).

The degree of intra-articular deformity in patients with FAI is variable; however, it is the repetitive and extreme ranges of motion commonly seen in the athletic population that exacerbate the impingement and injury pattern to the labrum and articular cartilage. The effects of FAI can be devastating for highly active patients, often requiring activity modification and/or cessation. While often initially managed non-operatively, surgery is indicated for certain FAI patients to correct the osseous deformities and manage the associated chondrolabral lesions. The goal of surgical treatment include pain relief, improved function and range of motion, and possibly delay early onset of osteoarthritis (3, 7).

The aim of this review is to discuss different approaches for the surgical treatment of FAI, including open surgical hip dislocation (SHD), reverse periacetabular osteotomy (PAO), mini-open direct anterior approach, and hip arthroscopy. The decision to proceed with open versus arthroscopic surgery for surgical treatment of FAI should be based on the patient's pathoanatomy, taking into account the surgeon's experience and preference. In experienced hands, both open and arthroscopic treatments of FAI have shown good mid-term and long-term clinical results.

SURGICAL HIP DISLOCATION FOR TREATMENT OF FAI

The Ganz technique of SHD was described as a safe surgical approach to the femoral head and the acetabulum without the risk of avascular necrosis (11). Their observations allowed to refine the concept of FAI as a mechanical cause of hip osteoarthritis. SHD was the first described method of treatment, with satisfactory clinical results published at 5 and 10 years (12, 13).

Surgical hip dislocation is a successful treatment modality for most cases of FAI with the majority of patients returning to sports activities (14). The indications for open versus arthroscopic treatment of FAI are based on surgeon's preference, skills, and experience. A recent systematic review including 16 studies and 600 patients comparing open versus arthroscopic treatment of FAI (level 4 evidence) showed that both approaches had similar clinical results when conversion to total hip arthroplasty was used as primary endpoint (15). In this review, hip arthroscopy was associated with higher postoperative general health-related quality of life scores 12-Item Short-Form Survey (SF-12).

Surgical hip dislocation is the preferred surgical technique for patients with FAI and a high-riding trochanter from old Perthes or slipped capital femoral epiphysis. The main advantage is the possibility of performing a trochanteric advancement and relative neck lengthening, to optimize abductors biomechanics and correct associated extra-articular impingement.

Surgical hip dislocation can also be a better alternative in certain clinical scenarios that are difficult to address with hip arthroscopy, including:

1. Anticipated labral reconstruction (fascia lata or round ligament autograft).
2. Coxa profunda or global overcoverage.
3. Posterolateral (PL) cam lesions extending over the retinacular vessels.

Contraindications for SHD to Treat FAI

1. Patients 40 years old and older (16).
2. Extensive cartilage damage.
3. Anterior hip subluxation.
4. Anterior and posterior cartilage damage (coup–countercoup).
5. Smokers.

Surgical Hip Dislocation Technique

The technique as described by Ganz et al. is basically an anterior dislocation of the hip after a trochanteric flip osteotomy, avoiding injury to medial femoral circumflex artery (MFCA) maintaining the blood supply to the femoral head (11). The patient is placed on the lateral decubitus position, and a 15 cm straight lateral incision centered over the greater trochanter is performed for a Gibson approach to the hip. The trochanteric trigastric (flip) osteotomy is performed starting 5 mm anterior (lateral) to the greater trochanter overhang, cutting with a small oscillating saw from the posterior greater trochanter toward the vastus ridge and anterior greater trochanter. After completing the osteotomy, the gluteus medius tendon, the long tendon of the gluteus minimus, and the vastus lateralis remain attached to the mobile greater trochanter fragment.

The proximal vastus lateralis is elevated to free up the mobile trochanteric fragment. Flexion, abduction, and external rotation of the hip releases tension of the flip osteotomy and facilitates the exposure of the hip capsule. Proximally visualize the attachment of the piriformis tendon into the stable greater trochanter and identify the interval between the piriformis and remnants of gluteus minimus. The hip capsule is approached through this interval by sharp dissection of the gluteus minimus from the capsule. This interval is safe with regard to vascularity of the femoral head as the anastomosis between the deep branch of the MFCA and inferior gluteal artery runs inferior to the piriformis (17).

The capsulotomy is performed starting at the anterosuperior edge of the stable trochanter toward the acetabular rim along the long axis of the neck from distal to proximal. The distal and anterior transverse limb of the capsulotomy is performed and tagged, followed by the proximal and posterior limb of the capsulotomy, performing a Z-shaped capsulotomy for the right hip, and an inverse Z-shaped capsulotomy for the left hip (**Figure 1**). At this point, the peripheral compartment and acetabular rim of the hip joint is exposed, and direct assessment of FAI with range of motion is performed. With a hook around the inferior femoral neck, the hip is externally rotated and subluxated, allowing to cut the round ligament with angled scissors. The femoral head can then be dislocated and pushed posteriorly by abduction, flexion, and external rotation allowing a 360° visualization of the acetabulum. At this point, there is full access to the acetabular rim allowing inspection and management of the labrum and acetabular cartilage (17).

The hip is then adducted for evaluation and management of abnormalities at the femoral head and neck. Hemispherical plastic templates are used to guide bone resection using a high speed burr or osteotomes to restore head sphericity and head–neck offset (**Figure 2**). The hip is then reduced and tested for range of motion and impingement. The tagged ends of the capsule are approximated with interrupted sutures avoiding tension that may adversely affect the perfusion to the femoral head. The mobile

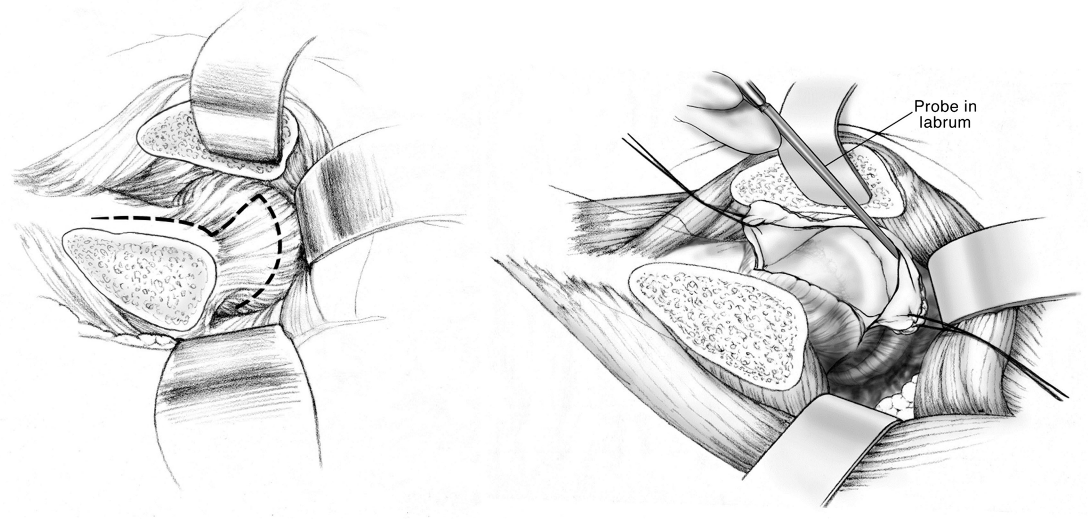

FIGURE 1 | Anterior Z capsulotomy. Adapted with permission from Dr. Rafael J. Sierra and the Mayo Foundation, Rochester, MN, USA.

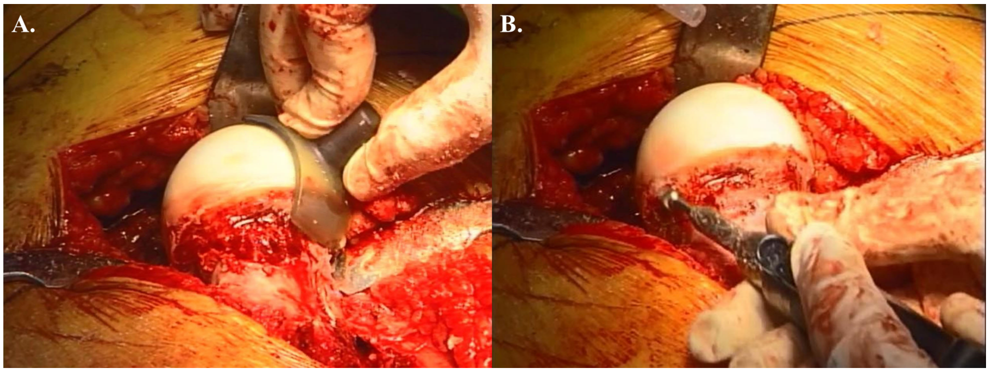

FIGURE 2 | Open treatment of cam lesion. **(A)** Restoration of femoral head–neck offset and head sphericity with intraoperative templates. **(B)** The high speed burr can be used safely in the posterolateral area with direct visualization of the retinacular vessels. Adapted with permission from Dr. Robert T. Trousdale and the Mayo Foundation, Rochester, MN, USA.

trochanteric fragment is reduced in anatomic position and fixed with two 4.5 mm screws aiming toward the lesser trochanter. Layered closure including the fascia, subcutaneous tissues, and skin is then performed.

An extended retinacular soft tissue flap can be performed during SHD in cases of proximal femoral deformities with a high-riding trochanter. This technique allows performing relative neck lengthening and management of intra- and extra-articular impingement, improving pain, ROM, and abductors strength (18).

Rehabilitation After Surgical Hip Dislocation

Patients are mobilized the day following surgery. Passive- and active-assisted internal or external rotation is permitted to protect trochanteric fixation. Passive ROM is initiated immediately with the use of a continuous passive motion (CPM) machine 6 h a day for 6 weeks to decrease the risk of hip joint adhesions. A stationary bike may begin at week 2. The patients are touch weight bearing for the first 4 weeks, and weight bearing is advanced after 4 weeks. Hip flexion is limited to 90°. Muscle weakness may persist for 3 months after surgery, and abductor rehabilitation is continued throughout the ensuing months. The patients are seen at 8 weeks after surgery, and at that time patients are typically using one crutch or no support. A physical therapist supervises the return to high impact pivoting sports, which usually does not occur before 6 months.

Complications Associated with Surgical Hip Dislocation

Surgical hip dislocation is a safe procedure with low reported complication rates. Potential complications include osteonecrosis, femoral neck fracture, trochanteric non-union, nerve injury, heterotopic ossification (HO), and thromboembolic disease. Sink et al. published a multicenter study looking at the complications after 334 SHDs in 302 patients. There were no cases of osteonecrosis or femoral neck fracture in their series. They reported one case of temporary sciatic nerve injury that resolved. Trochanteric non-union was the most serious complication with a prevalence rate of 1.8% (stx cases of 334). There were two cases of deep vein thrombosis and one deep infection. The most common complication was mild HO that did not require treatment (19).

REVERSE PERIACETABULAR OSTEOTOMY FOR TRUE ACETABULAR RETROVERSION

True acetabular retroversion is secondary to an external rotation deformity of the affected hemipelvis and is a known cause of pincer FAI (20). The radiographic findings on a true AP pelvis consist of a positive crossover sign, posterior wall sign, and ischial spine sign (**Figure 3**). FAI secondary to acetabular retroversion is successfully treated with a reverse PAO, which corrects the underlying deformity, improving hip pain, and range of motion (20, 21). Combined FAI consisting in true acetabular retroversion and associated cam lesions can be treated with a reverse PAO. For these cases, the incision is extended distally for an anterior hip capsulotomy, for femoral head–neck osteochondroplasty, and for management of the labrum pathology (20).

The acetabular correction during reverse PAO is a challenging step, and specially attention to avoid increasing the lateral edge angle or ending with a negative Tonnis angle during the anteversion maneuver of the mobile fragment is critical. Overcorrection of the acetabular fragment must be avoided to prevent excessive acetabular anteversion, posterior acetabular impingement, and poor clinical results (21).

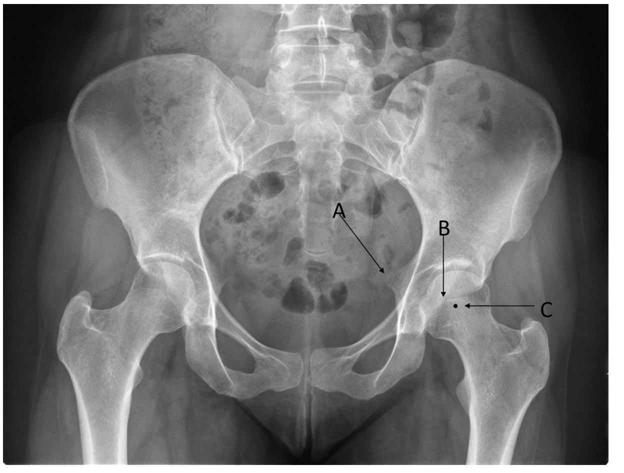

FIGURE 3 | The radiographic findings of acetabular retroversion consist of a positive ischial spine sign (A), crossover sign (B), and a posterior wall sign (C). The small acetabular size and volume represents a challenge for surgical treatment. Adapted with permission from Dr. Rafael J. Sierra and the Mayo Foundation, Rochester, MN, USA.

FIGURE 4 | Longitudinal c-shaped 10–12 cm incision centered over the anterior superior iliac spine for a modified Smith-Petersen approach. Adapted with permission from Dr. Robert T. Trousdale and the Mayo Foundation, Rochester, MN, USA.

Periacetabular Osteotomy Technique

The surgical approach and osteotomies performed for an anteverting PAO (reverse PAO) for acetabular retroversion are performed in a similar manner and sequence as described originally for the treatment of hip dysplasia (22–24). The operation is done with the patient in the supine position through a modified Smith-Petersen approach using a longitudinal c-shaped (10–12 cm) incision centered over the anterosuperior iliac spine (**Figure 4**). The interval between tensor and sartorius is created, followed by subperiosteal elevation of the sartorius and the abdominal oblique muscles from the iliac crest. The subperiosteal elevation is continued down the inner pelvis toward the pelvic rim, and the anterior inferior iliac spine and the origin of the rectus femoris muscle are identified. The tendon of rectus femoris origin can be preserved or transected, tagged, and repaired without affecting the ability to reorient the acetabulum or affecting the clinical outcome (25, 26) The approach is then continued medial to the rectus retracting the iliopsoas tendon medially for exposure of the medial hip capsule, ischium, and the superior pubic ramus. Hip flexion decreases the tension over the iliopsoas and facilitates placement of a medial retractor over the superior pubic rami. A sequence of osteotomies is then performed using fluoroscopic guidance (**Figure 5**). The interval between the inferomedial capsule and iliopsoas is bluntly developed to allow placement of the angled osteotome for the first ischial osteotomy, which is an incomplete osteotomy of 2.0–2.5 cm just inferior to the acetabulum curving toward the posterior acetabular column (24). The second bone cut is an extra-articular and complete osteotomy of the superior pubic rami using osteotomes or a small oscillating saw. The third bone cut is the transverse iliac osteotomy starting just distal to the anterior superior iliac spine (ASIS) aiming slight proximal and stopping approximately 1 cm lateral of the pelvic brim. The fourth and last osteotomy is the retroacetabular osteotomy that connects the first ischial with the third transverse iliac osteotomies. This osteotomy is facilitated with the use of fluoroscopy (false profile view) to avoid exiting into the hip joint or posterior column.

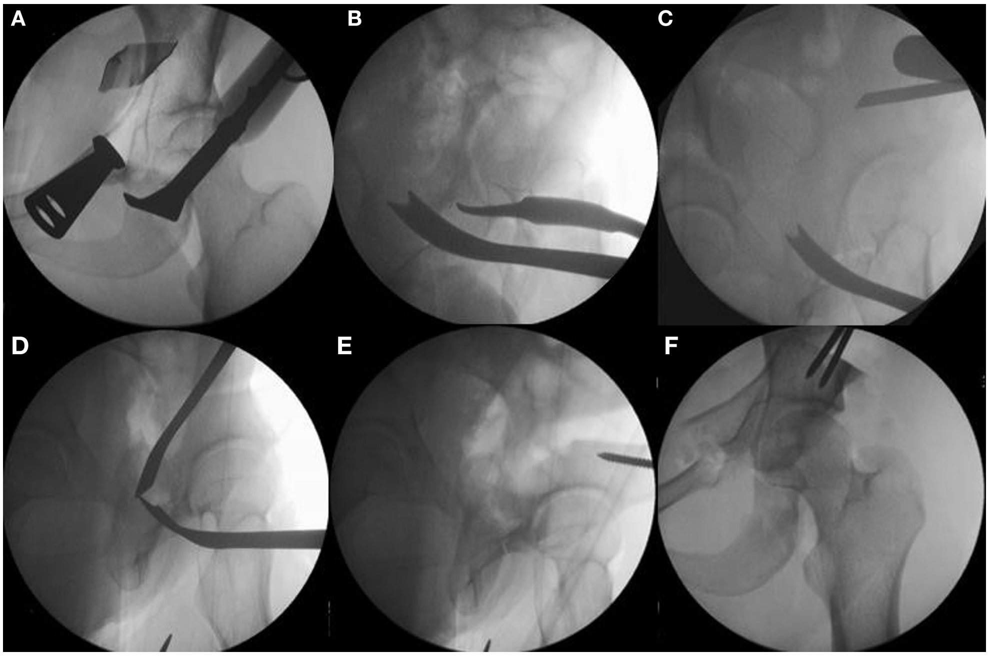

FIGURE 5 | The sequence of periacetabular osteotomies is performed under fluoroscopic guidance. The first bone cut is the ischial osteotomy which is an incomplete osteotomy of 2.0–2.5 cm using a curved "Ganz" osteotome just inferior to the acetabulum [**(A)** the anterior to posterior fluoroscopic view and **(B)** a 65° lateral "false profile" view]. The second osteotomy is done at the superior pubic rami with osteotomes or a small saw. The third is the transverse iliac osteotomy **(C)**. Mark with fluoroscopy starting just distal to the anterior superior iliac spine aiming slight proximal, stop 1 cm lateral of the pelvic brim. The fourth and last osteotomy is the retroacetabular osteotomy that connects the first ischial with the third transverse iliac osteotomies. Use fluoroscopy (65° "false profile" view) to facilitate this osteotomy and avoid exiting into the hip joint or posterior column **(D)**. Once complete, the fragment should be mobile and ready for acetabular correction. Use a Schanz pin in the mobile fragment to facilitate control and mobilization of acetabulum **(E)**. Correct the anteversion of the mobile fragment, pin it, and check the hip range of motion **(F)**. Adapted with permission from Dr. Robert T. Trousdale and the Mayo Foundation, Rochester, MN, USA.

Once complete, the acetabular fragment should be mobile and ready for correction. The use of a Schanz pin in the mobile acetabular fragment helps to control it and to mobilize it. The acetabular reorientation into the correct amount of anteversion is performed and temporarily pinned. If the hip range of motion to impingement and fluoroscopic correction looks satisfactory, the acetabular fragment is fixed with three 4.5 screws from the stable pelvis into the fragment for definitive fixation (24).

DIRECT ANTERIOR APPROACH FOR OPEN TREATMENT OF ANTERIOR FAI

The direct anterior approach for open treatment of FAI was initially described by Ribas et al. (27). Their rationale was that FAI is a mechanical conflict of the anterior hip joint in the majority of cases. As such, it could be safely addressed with open surgery through a direct anterior approach without disrupting the trochanter and abductor mechanism (28).

The direct anterior approach uses a 4–12 cm longitudinal surgical incision starting 2 cm lateral and 2 cm distal to the ASIS aiming to the fibular head over the tensor muscle. Dissect down to fascia and incise the tensors fascia. Elevate the perimysium of the tensor muscle and access the anterior joint capsule trough the interval between the Sartorius and the tensor muscle. Ligate the branches of the lateral femoral circumflex artery and excise the pericapsular fat to access the anterior hip capsule. The capsulotomy is an I-shaped incision over the axis of the femoral neck. Manual traction can be performed to help visualize the central compartment through this approach. The femoral head and neck junction is visualized and the osteochondroplasty of the femoral neck is performed. Access to the labrum is limited to the anterior the acetabular rim.

Postoperatively, the patients are partial weight bearing using crutches for 6 weeks and then allowed full weight bearing. Physical therapy starts 6 weeks after surgery and return to full activity is typically 4–6 months postoperatively. Cohen et al. published a series of athletes with FAI treated with a direct anterior approach (28). They presented satisfactory clinical results with improved postoperative pain and activity levels. However, only 24 of 44 patients (55%) reported a return to their specific preoperative sports at an average follow-up of 22 months. The reported complications included hypoesthesia of the lateral femoral cutaneous nerve (LFCN) (20%) and one temporary femoral nerve palsy.

This technique has no added benefits from hip arthroscopy in the management of FAI. The disadvantages are mainly the limited visualization of the central compartment and the inability to address posterior and PL hip pathology. A single stage combined hip arthroscopy and anterior open cam resection has been described (29). However, the current advances in hip arthroscopy techniques do not justify this approach as cam deformity can be successfully managed at the time of hip arthroscopy.

ARTHROSCOPIC SURGERY FOR FAI

Advances in surgical techniques as well as in our understanding of the anatomic and biomechanical understanding of the native hip joint have prompted a dramatic increase in the arthroscopic management of FAI. While hip arthroscopy had previously been used to address chondral and labral tears, Philippon et al. were the first to report the technique to correct the osseous deformities present in FAI (30). Since 2006, arthroscopic management for FAI has increased over 600%, and one recent systematic review cited arthroscopy for FAI as the "preferred technique," representing 50% surgical approaches compared to 34% for open surgical dislocation and 16% with the mini-open approach (31, 32). Additional improvements in instrumentation, visualization, and capsular management have expanded surgical indications to include a variety of intra-articular hip pathology coincident with FAI (33, 34).

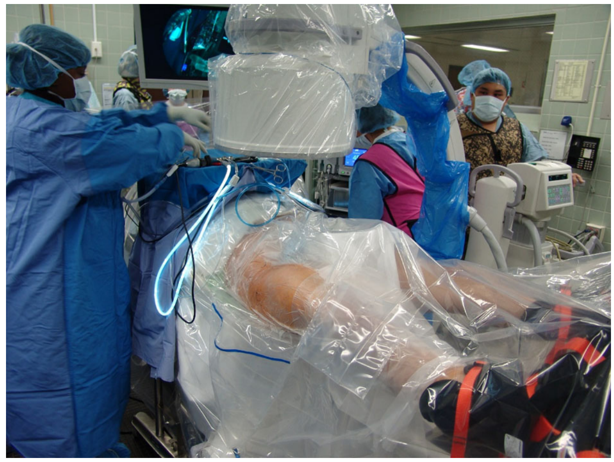

FIGURE 6 | Surgical set-up for right hip arthroscopy. The patient is placed in the supine position on a traction table with attached hip distraction system (Smith and Nephew) and well-padded perineal post. Sterile draping is subsequently performed.

Set-Up and Portal Placement

Hip arthroscopy can be performed on a standard fracture table or specialized traction table, in either the supine or the lateral position depending on surgeon preference (**Figure 6**) (35). Supine positioning is generally preferred, with a recent study reporting 100% of high volume hip arthroscopists preferring the supine over the lateral position (36). However, the lateral position may be favored in obese patients with a large pannus or in patients with large anterior osteophytes as these can hinder visualization in the supine position (37). Distraction is critical to gain access to the hip joint and work in the central compartment, and several distraction systems exist for both supine and lateral positions (35, 37, 38). Traction is typically achieved with the hip in abduction and internal rotation. Slight flexion (≤20°) during distraction is employed by some surgeons in order to relax the anterior capsule, which facilitates distraction and limits risk to femoral and sciatic nerve injury (38–40). A well-padded perineal post is commonly used to supply counter-traction and is padded to prevent postoperative pudendal neuropraxia. Once the hip is distracted, the central compartment can be accessed, initially by the introduction of a fluoroscopically guided spinal needle into the hip capsule. Typically, this occurs at the location of the anterolateral (AL) portal, anterosuperior to the proximal margin of the greater trochanter (35, 39). Penetration of the capsule produces a "vacuum sign" resulting from the equalization of intra-articular and atmospheric pressures (41). Distraction is critical to prevent iatrogenic chondral and labral injury when accessing the hip joint, with a recommended traction distance of at least 10 mm (40).

Accurate portal placement is also important to ensure safety and appropriate visualization during hip arthroscopy in FAI (**Figure 7**). The AL portal is placed 1 cm anterior to the superior margin of the greater trochanter and pierces the gluteus medius before it enters the hip capsule, with the superior gluteal nerve traveling 4cm superior to portal insertion (35, 42). Additional portals involved with the central compartment include the anterior portal, located slightly lateral to the intersection of a horizontal line from the AL portal and a vertical line from the ASIS, and the PL portal, located 1 cm posterior and superior to the greater trochanter (37, 43). The anterior portal pierces the sartorius and rectus femoris before reaching the hip capsule, and branches of the LFCN are most at risk to injury (35). An interportal transverse capsulotomy between the anterior and AL portals is often created to increase visibility and mobility when working in the central compartment (**Figure 8A**) (44). The PL portal perforates the gluteus medius and minimus and enters the joint through the posterior edge of the lateral capsule (35). In a cadaveric study, Thorey et al. report central compartment visualization of the AL portal to be between 2:00 and 6:00, of the anterior portal to be 8:30 and 4:00, and of the PL to be 5:30 and 12:00 (45).

Many accessory portals have also been described and include the mid-anterior portal (MAP), proximal MAP (PMAP), proximal AL accessory (PALA), peritrochanteric space portal (PSP), and the distal AL accessory portal (DALA) (**Figure 7**) (42). After work in the central compartment is completed, traction is released, and the peripheral compartment is commonly accessed via an intra-capsular approach from the AL portal (43, 46). Alternately, for particularly complex cases in which access to the central compartment is difficult, the peripheral compartment can be entered primarily (47–49). As discussed previously, most patients with FAI have a mixed presentation with both pincer and cam deformities; therefore, access to both the central and peripheral compartments is generally required.

Technique: Resection of Cam and Pincer Lesions

Procedures to correct the bony abnormalities in FAI include acetabular rim trimming for pincer lesions and femoral osteochondroplasty to correct cam deformities (**Figures 8B–E**). To

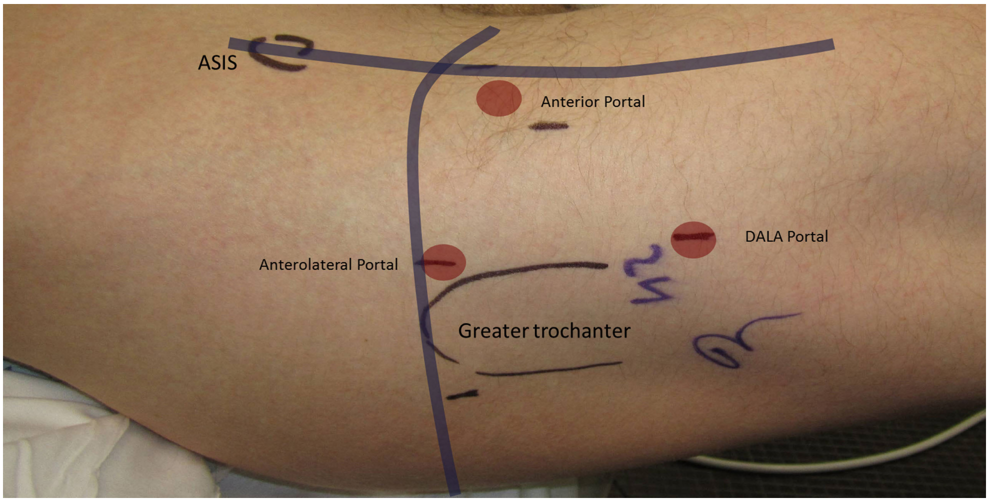

FIGURE 7 | Standard arthroscopic portal placement including the anterolateral, anterior, and distal anterolateral accessory (DALA) portals.

access the pincer lesion, the labrum is usually taken down at the chondrolabral junction and reattached with suture anchors following acetabuloplasty (30, 41). Once the acetabular overcoverage has been identified, the lesion can be resected by trimming with an arthroscopic burr. One recent report describes a technique of labral preservation when addressing pincer lesions, in which the entire chondrolabral complex is lifted subperiosteally off the acetabular rim, and the pincer lesion is resected under fluoroscopic guidance (50). This technique has the advantage of preserving the chondrolabral transitional zone, which has been suggested as having suboptimal healing capabilities (51). Additionally, Redmond et al. recently reported identical 2-year outcome scores and revision rates in patients that underwent labral preservation compared to those that underwent takedown and reattachment for treatment of pincer lesions (52). Management of large pincer lesions can be particularly challenging as the acetabular overcoverage can block access to the central compartment through the AL portal (53). Pincer lesions can be exacerbated by additional hip deformities including acetabular retroversion, acetabular protrusion, and coxa vara/breva (53, 54). Large pincer lesions can be managed through a *capsulotomy first approach* where the hip is distracted following, rather than prior to, a capsulotomy. In this approach, the central compartment can be accessed via an inside–out technique in which the capsulotomy is performed from the peripheral compartment (53). Alternately, an *acetabuloplasty first approach*, in which the pincer lesion is first addressed in the peripheral compartment, until the central compartment can be accessed, can be utilized (53, 54). Notably, these approaches to large pincer lesions use primary peripheral compartment access before completing the operation in the central compartment.

Cam lesions are resected in the peripheral compartment, typically after work in the central compartment is completed. The hip is flexed to 30°, and traction is released to relax the anterior capsule. Work in the peripheral compartment is generally performed through the AL, MAP, and DALA portals (55, 56). In the setting of a cam lesion, the abnormal femoral neck offset is corrected via femoral osteochondroplasty, with adequate resection confirmed via a dynamic fluoroscopic examination (**Figure 8E**) (55). Adequate visualization in the peripheral compartment is critical, as inadequate cam resection remains a common reason for re-operation and inferior outcomes (57, 58). When working through the DALA portal, extension of the transverse capsulotomy from the femoral head/neck junction to the intertrochanteric line creates a T-type capsulotomy that affords increased visualization of cam lesions in the peripheral compartment (**Figures 8C,D**) (44, 56). The T-capsulotomy, while increasing arthroscopic visualization, potentially promotes increased femoral head translation within the acetabulum if left unrepaired (59, 60). In a case-control study of 64 patients, Frank et al. report significantly higher 6 months, 1 year, and 2.5 years hip outcome score-sports subscale (HOS-SS) for patients that had complete repair rather than partial repair of the T-capsulotomy (**Figure 8F**) (61). Conversely, Domb et al. found no differences between repaired and unrepaired capsulotomies when variables, such as age and preoperative cartilage damage, were controlled for (62). Capsular management in hip arthroscopy is controversial and remains an active topic of investigation.

The relative success of hip arthroscopy is often dependent on the adequacy of lesion resection; therefore, methods to improve both preoperative and intraoperative understanding of the bony anatomy are being actively investigated (58). In one recent study, Milone et al. report that 3D CT software reconstructions illustrated larger alpha angles when compared with 2D CT and Dunn lateral radiographs (63). Additionally, intraoperative fluoroscopy can be utilized by the arthroscopist to ensure adequate resection or cam lesions (64). When comparing six standardized intraoperative fluoroscopic views to a reconstructed preoperative CT, Ross et al. found that this method was able to successfully localize and ensure the appropriate amount of cam resection (65). Other forms of intraoperative imaging, such as image-based navigation and computer-aided navigation, have been used on

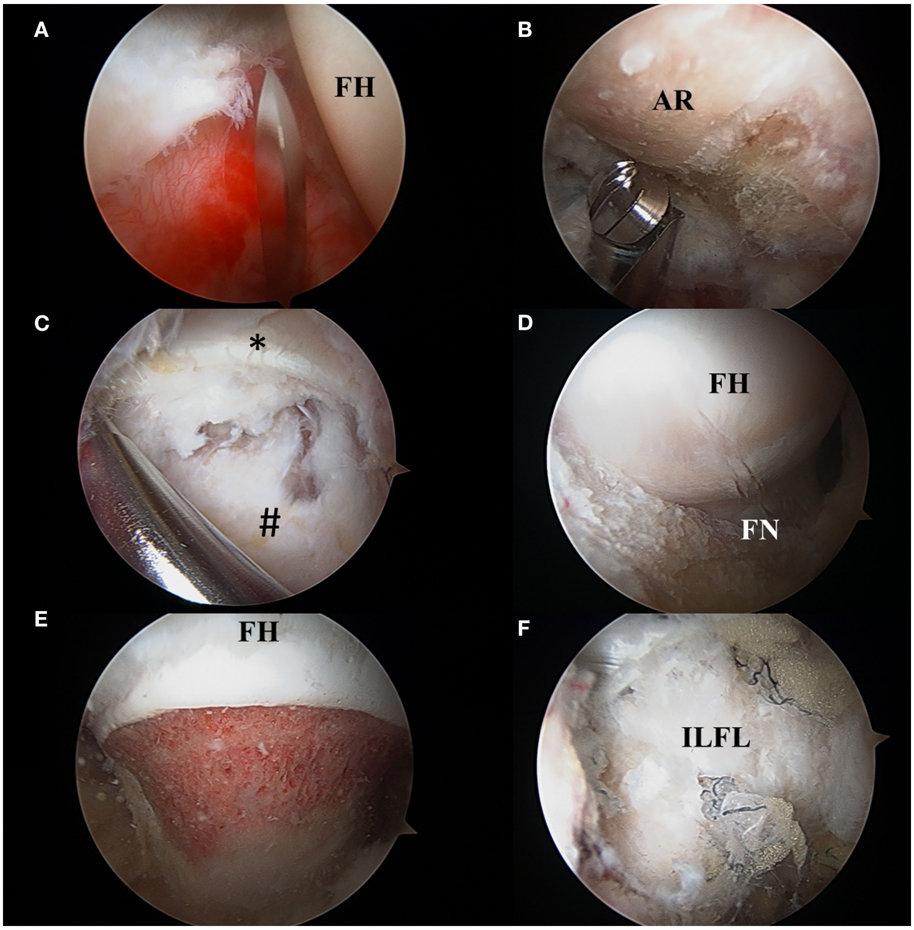

FIGURE 8 | (A) Interportal capsulotomy as seen through the mid-anterior portal. The capsulotomy must begin at least 5 mm from the labrum to ensure repair and is in between 2 and 4 cm in length dependent on central compartment pathology. FH: femoral head. **(B)** Acetabular rim trimming. Viewing through the mid-anterior portal, pincer lesions are resected with an arthroscopic burr in the anterolateral working portal. AR, acetabular rim. **(C)** Viewing from the mid-anterior portal, the peripheral compartment is accessed through a T-capsulotomy. *Reflected head of the rectus femoris. #Iliofemoral ligament. **(D)** T-capsulotomy extends down the femoral neck to expose the cam deformity. FH, femoral head; FN, femoral neck. **(E)** Completed femoral osteochondroplasty with resection of the cam lesion. FH, femoral head. **(F)** Appearance of capsule following complete repair of the T-capsulotomy. ILFL, repaired iliofemoral ligament.

an experimental basis to resect cam lesions but are not used in common practice (66, 67).

Postoperative Management: Rehabilitation, Complications, and Re-Operation

Hip arthroscopy, with its minimally invasive approach, often offers a shorter recovery time than open hip preservation surgery. Return to activity can range from as short as 3 months for elite athletes to 9 months or longer for patients with poor preoperative muscle tone (33, 68). Rehabilitation may also be prolonged for patients with increased time between symptom onset and surgery (33). The overall rehabilitation process consists generally of four phases, and specific protocols are highly dependent on both the surgical procedure performed and surgeon preference (69). In our practice, following arthroscopic resection of cam and pincer lesions, *phase one* begins immediately postoperatively with limited foot flat or toe touch weight bearing for the first three weeks. If microfracture was performed for chondral defects, limited weight bearing is extended to last between 4 and 8 weeks (69). The goals of phase one are to protect the joint by avoiding inflammation and maintain appropriate passive range of hip motion (69–71). *Phase two* focuses on a return to non-compensatory gait with a focus on improving neuromusculature control and restoring full range of motion at the hip (71). *Phase three* emphasizes a return to preoperative levels of strength and conditioning and includes functional exercises designed to strengthen lower extremity and core musculature (70). *Phase four* concentrates on the return to preinjury sport and recreational activity level by working on maximizing plyometric strength, agility training, and sport specific exercises (70, 71). Specific physical therapy techniques tend to vary, with most protocols including CPM, soft tissue mobilization (STM), isometric stretching, and joint mobilization

(69–72). While each phase generally lasts a minimum of 4 weeks, it is critical to ensure that the patient's recovery guides rehabilitation and that any exacerbation in pain or limitation in activity is promptly addressed (69, 73).

Hip arthroscopy for FAI is not without risk, and while rare, reported complications are increasingly scrutinized. Recent literature reviews have found complication rates following hip arthroscopy to range from 1.5 to 7.5%, with most complications being minor and transient (33, 40, 74–77). Common minor complications include neuropraxias related (related to traction, perineal compression, or portal placement), iatrogenic chondral and labral damage, superficial infection, deep vein thrombosis, and HO (40, 76, 77). Comprising 37% of all complications, the most common minor complication is postoperative nerve injury related to either distraction or compression against the perineal post (77). One recent systematic review of 92 studies found a total nerve injury rate of 1.4% with 99% of these being temporary neuropraxias (76). HO following hip arthroscopy is generally rare, occurring in <1% of cases in two recent reviews, but reported rates have been as high as 44% (76–79). The low HO rates currently reported may be attributable to the use of prophylactic postoperative naproxen, which has been shown to dramatically decrease the rate of HO (78). Iatrogenic chondral and labral injuries were found to occur in up to 4.6% of cases; however, the clinical relevance of these injuries remains unclear (76, 80). Additionally, complication rate is dependent on surgeon experience, with one study reporting a statistically significant decrease in traction related complications after the surgeons' first one hundred cases (81). In the largest study to date investigating 2-year outcomes following primarily hip arthroscopy for FAI, Gupta et al. report, out of a cohort of 595 consecutive surgeries, complications included 13 (2.1%) cases of postoperative neuropraxia, 14 cases of (2.35%) HO, three (0.5%) DVTs, five (0.84%) superficial wound infections, and one (0.17%) deep wound infection requiring irrigation and debridement (82).

Occurring in <1% of cases, major postoperative complications can be devastating and include deep infections, pulmonary emboli, skin damage, extra-articular extravasation requiring surgical decompression, vascular injury, avascular necrosis, femoral neck fractures, and frank dislocation (40, 76). Fluid extravasation inducing abdominal compartment syndrome can be a potentially life threatening complication (83, 84). It is recommended to minimize the intra-articular pressure when possible as well as to periodically check for hypotension, which can herald extravasation (40). Iatrogenic hip dislocation is another feared complication that has been related to capsulotomy without repair and excessive acetabular rim trimming (76, 85–89). Femoral neck fractures have also been recorded after femoral osteochondroplasty, often related to a premature return to full weight bearing (76, 77). Avascular necrosis of the femoral head has also been reported and may be caused following damage to lateral epiphyseal branches of the MFCA within the lateral synovial fold following femoral neck osteoplasty or t-type capsulotomy (74, 76, 77).

Revisions' surgery following primary hip arthroscopy is rare, with recent studies reporting rates between 4.0 and 7.7% occurring on average 28 months following the primary surgery (57, 76, 77, 82). Harris et al. found that most re-operations used the open approach (70%) and were primarily for conversion to total hip arthroplasty. Revision arthroscopy is often reserved for loose body removal, lysis of adhesions, and most commonly, resection of residual cam or pincer lesions that were not adequately resected at the primary surgery (76, 77). Revision hip arthroscopies are generally successful, with significantly improved clinical outcomes, and a 5–14.6% re-operation rate (57, 90).

CONCLUSION

While arthroscopic surgery has shown slightly superior short- and mid-term outcomes, it is not without risk, particularly in light of the steep learning curve to gain technical proficiency. Moreover, there are some instances where complex joint morphology, such as combined dysplasia and FAI, may preclude arthroscopy in favor of an open approach. Currently, there remains a paucity in both long-term outcomes as well as high-level randomized controlled trials comparing the open and arthroscopic approaches. However, four RCTs investigating this question are ongoing and may provide further clarification within the next few years (91). As with other surgeries, the approach taken to FAI must be individualized to reflect both patient anatomy and preference while at the same time accommodate surgeon comfort and technical skill.

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REVIEW
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Techniques and Results for Open Hip Preservation

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While hip arthroscopy grows in popularity, there are still many circumstances under which open hip preservation is the most appropriately indicated. This article specifically reviews open hip preservation procedures for a variety of hip conditions. Femoral acetabular impingement may be corrected using an open surgical hip dislocation. Acetabular dysplasia may be corrected using a periacetabular osteotomy. Acetabular protrusio may require surgical hip dislocation with rim trimming and a possible valgus intertrochanteric osteotomy. Legg–Calve–Perthes disease produces complex deformities that may be better served with osteotomies of the proximal femur and/or acetabulum. Chronic slipped capital femoral epiphysis may also benefit from a surgical hip dislocation and/or proximal femoral osteotomy.

Keywords: hip preservation, open hip, periacetabular osteotomy, femoroacetabular impingement, dysplasia, Perthes, SCFE

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INTRODUCTION

There are many hip pathomorphologies that cannot be addressed arthroscopically. Developmental or acquired deformities of the acetabulum (acetabular dysplasia, protrusio, or retroversion), femur (varus/valgus, torsion, or version), and femoral head or head–neck junction [Legg–Calve–Perthes disease (LCPD), chronic slipped capital femoral epiphysis, MED, MHE] may be more effectively treated with open hip preservation techniques. The present review article summarizes each of these pathomorphologic conditions and the clinical outcomes of techniques used to treat them.

FEMOROACETABULAR IMPINGEMENT

Ganz and colleagues (1) were the first to describe the concept of femoroacetabular impingement (FAI). It is a pathologic process by which an intracapsular collision occurs between the femoral head–neck junction and the acetabular rim. Repetitive collision leads to labral injury, chondrolabral detachment, and degeneration (1–6). Two pathomorphologic categories are described: cam deformity of the proximal femur and pincer deformity of the acetabulum (1). Most often, these pathomorphologies coexist.

Labral and articular damage resulting from FAI is a source of pain and abnormal (dynamic) loading of the hip. Chondral flaps, labral tears, and loose bodies may produce locking and/or catching symptoms and labral tears theoretically disrupt the chondrolabral suction seal that provides constant fluid film lubrication to the joint (7). Patients complain of hip pain with flexion-based activities, such as sitting, squatting, stair climbing, and athletics. Most often pain is localized to the groin but may also be deep within the lateral, anterior, and posterior aspects of the hip, referred to as the "C-sign."

Impingement symptoms are most commonly reproduced with the "FADIR" maneuver: hip flexion to 90°, adduction, and internal rotation (8). Radiographic evaluation begins with various measurements on two-dimensional X-rays. The lateral center-edge angle of Wiberg and Tönnis angle are used to characterize acetabular morphology, while the α-angle and head–neck offset are used to characterize the femoral head–neck junction. A crossover sign showing the posterior acetabular rim crossing medial to the anterior rim, a prominent ischial spine sign showing intrusion of the ischial spine into the true pelvis, and a posterior wall sign showing the posterior rim passing medial to the center of the femoral head all may indicate global or focal acetabular retroversion (9).

Surgical hip dislocation has traditionally been the gold standard for treating FAI. Ganz et al. (10) was first to describe the currently accepted surgical technique. With the patient in a lateral decubitus position, the surgeon initiates the approach using either a Kocher–Langenbeck (KL) type or straight lateral incision. The fascial interval is developed by splitting the gluteus maximus (KL) or the Gibson interval, which spares the anterior half of the gluteus maximus (11). The anterior capsule is then accessed by a trigastric trochanteric osteotomy. The osteotomy can be performed with a step cut, which provides for greater stability and earlier progression of weight bearing (12). As the greater trochanter is osteotomized, the obturator externus muscle remains attached to the intact femur, protecting the deep branch of the MFCA, which is the primary blood supply to the femoral head (10, 12). An anterior Z-shaped capsulotomy followed by a transection of the round ligament facilitates an atraumatic anterior hip dislocation. Laser Doppler flowmetry has confirmed that perfusion to the femoral head is maintained after a trochanteric osteotomy and dislocation (12). The surgeon is left with a 360° view of both the acetabulum and the femur to perform osteochondroplasty and labral repair, debridement, or reconstruction. At the end of the procedure, the trochanter is reapproximated and stabilized with screws (see **Figure 1**). After surgery, patients must follow toe-touch weight-bearing restrictions for 4–8 weeks to allow for osteotomy healing.

Extensive literature has shown good to excellent outcomes following surgical hip dislocation for FAI. At an average of 4.7 years, Beck et al. (2) reported good to excellent Merle d'Aubigne hip scores in 13 of 19 patients who underwent surgical hip dislocation for FAI. Similarly, Kempthorne et al. (13) showed significant improvements in 53 patients' Western Ontario and McMaster University Osteoarthritis Index (WOMAC) scores at 4-year follow-up. These promising outcomes also extend to the athletic population. In a case series of five professional ice hockey players, Bizzini et al. (14) successfully returned all players to full competition at an average of 9.6 months. Naal et al. (15) conducted a larger series of 22 mixed professional athletes and reported a 96% rate of return to competition. At a mean follow-up of 3.8 years, 82% of subjects were still satisfied with their hip surgery.

While the underlying FAI pathology is often successfully treated with open surgical dislocation, complications following this procedure are common with an overall complication rate reported around 6% (16). The most common complication is trochanteric bursitis secondary to prominent hardware at the osteotomy site (26%), followed by greater trochanter non-union (3–20%) and heterotopic ossification (3%) (17–20).

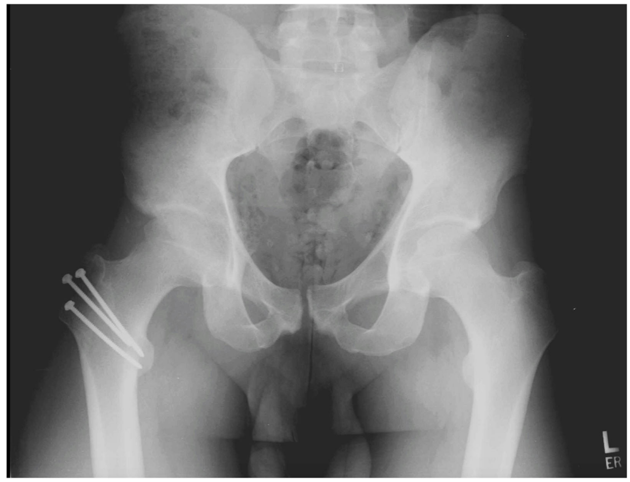

FIGURE 1 | A postoperative radiograph of a surgical hip dislocation secured with screws.

ACETABULAR DYSPLASIA

Hip dysplasia usually starts during early childhood but may not manifest symptomatically until adolescence or young adulthood. An abnormally shallow, smaller acetabulum creates dysfunctional hip mechanics, labral shearing, and cartilage edge loading (21, 22). These pathologic alterations of the joint ultimately lead to early degeneration (23). Stulberg and Harris classically reported that 48% of patients with early degenerative hip arthritis had dysplastic features noted on radiographs (22). Patients most often complain of moderate-to-severe pain located in their groin, which occurs during daily activities. They will present with an antalgic limp, a positive impingement sign, and a positive Trendelenburg sign (24). Radiographically, the lateral center-edge angle of Wiberg is measured on an anteroposterior (AP) view, and the anterior center-edge angle is measured on a false profile view (9). An abduction-internal rotation AP view helps neutralize femoral anteversion, thus simulating the acetabular coverage that would be achieved by a proximal varus femoral osteotomy or a reorientation of the acetabulum (22).

Numerous pelvic osteotomies have been designed to treat hip dysplasia. The primary goal of an osteotomy for dysplasia is to correct the deficiency in acetabular coverage. Reshaping osteotomies include the Pemberton and Dega techniques, which utilize incomplete cuts of the ilium to hinge off the triradiate cartilage. These osteotomies are reserved for skeletally immature individuals (22). Reconstructive osteotomies may be performed in patients with closed physes and utilize complete cuts of the pelvis in order to redirect joint loading forces. LeCouer first described the triple osteotomy in 1965 (22). This osteotomy requires two incisions to make individual cuts through the pubis, ischium, and ilium. The more commonly used technique today in adolescent and adult patients is the Bernese periacetabular osteotomy (PAO) (25). First described by Ganz, this procedure may be done through a single Smith-Peterson approach. It reorients the joint through four to five cuts done closer to the acetabulum than in the traditional triple osteotomy. These cuts maintain stability within the pelvis by not disrupting the posterior column. The osteotomy site is typically secured with screws (see **Figure 2**). Patients remain partial weight bearing with crutches for 6 weeks postoperatively (26).

Ganz et al. reported improvement in clinical outcomes and just one non-union in their original case series of 75 PAOs (25). Steppacher and colleagues rereviewed these 75 PAOs at 20-year follow-up. They found a 60.5% survivorship at 20 years with age and preoperative osteoarthritis grade being risk factors for failure (27). Matheney et al. (28) reviewed 135 PAOs after an average of 9-year follow-up. They reported 76% survival (defined as pain score under 10 and no conversion to arthroplasty). A recent systematic review revealed that a majority of the studies on PAO show significant improvements in radiographic parameters as well as clinical outcomes. The mean increase in anterior and lateral center-edge angles has ranged from 16 to 51° and 20 to 45°, respectively, and mean improvements in Harris Hip Scores have ranged from 14 to 33 points (29).

Major complications are common after PAO and occur in 3–37% of cases (28–30). The most common complications include heterotopic ossification, wound hematomas, transient neuropraxias (femoral and sciatic), inadvertent intra-articular extension, loss of fixation, and malreduction (17, 30). Non-union rates have been as high as 24% (31), and another 12–28% of patients require a reoperation due to symptomatic hardware (29). Surgeons must also be careful to avoid overcorrection, which could cause iatrogenic impingement.

Acetabular retroversion is an uncommon form of dysplasia that results in relative undercoverage of the posterior superior aspect of the femoral head. When the hip is flexed and adducted, the femoral head abuts the anterior wall, which causes pain and possibly induces posterior instability. The diagnosis is confirmed using the parameters described above (crossover sign, prominent ischial spine sign, and posterior wall sign), assessed on an AP pelvis radiograph. In cases of delayed presentation, the radiographs may also reveal fragmentation of the prominent anterior acetabular rim or an os acetabuli (21, 29).

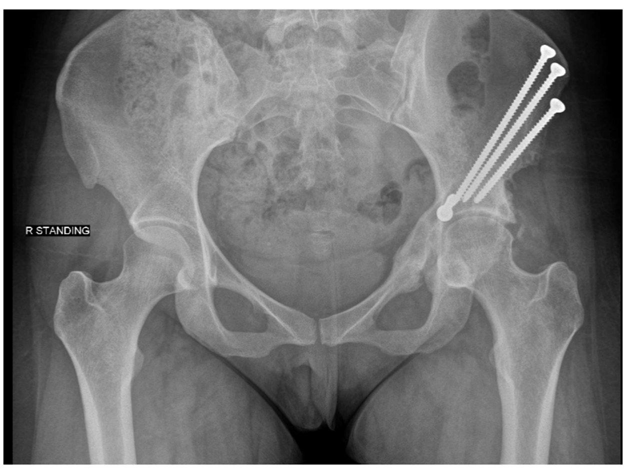

FIGURE 2 | A postoperative radiograph of a periacetabular osteotomy secured with screws.

The primary surgical option to correct acetabular dysplasia with retroversion is a reverse PAO. The osteotomy is performed the same as a Bernese PAO, utilizing a Smith-Peterson approach and 4–5 bone cuts (32). The free acetabular fragment is flexed and internally rotated before screws are used to secure it in place.

Siebenrock et al. (32) showed good to excellent results in 26 of 29 reverse PAOs with an average follow-up of 30 months. The average Merle d'Aubigne score improved from 14.0 to 16.9 and the crossover sign was eliminated in all except four patients. They revisited their cohort at 10 years and found that no patients were converted to total hip arthroplasty (THA) and there was no significant change in Tonnis osteoarthritis grades. Predictors for a poor outcome included not treating concomitant cam deformity and overcorrection of the acetabular version (33). Similarly, Peters et al. (26) showed a statistically significant improvement in Harris Hip Scores from 54 to 86 at 1-year follow-up and confirmed correction of radiographic retroversion in 96% of patients (31). These authors later developed an algorithmic approach in which they emphasized the importance of evaluating for a cartilaginous injury. Retroverted acetabuli without concomitant cartilaginous damage can be safely treated with a PAO; however, if magnetic resonance arthrography (MRA) confirms an injury to the articular cartilage, the authors recommend a surgical hip dislocation and acetabular rim debridement to avoid rotating diseased cartilage to a weight-bearing portion of the joint (34).

PROTRUSIO ACETABULI

Protrusio acetabuli is defined as a socket global overcoverage secondary to a relative medialization of the acetabulum. Protrusio is commonly found in patients with Marfan syndrome and inflammatory conditions like rheumatoid arthritis, but is most often considered to be idiopathic. If a cause is identified, attempted treatment of the underlying condition should precede any surgical intervention (35). A patient typically presents with groin pain and stiffness with daily activities. On an AP radiograph of the pelvis, the acetabular fossa and femoral head project medial to the ilioischial line (36). The decision to move forward with surgery depends on the patient's age and amount of hip degeneration. Surgical options for patients without advanced protrusio include triradiate cartilage closure in skeletally immature patients and a valgus intertrochanteric osteotomy (VITO) with or without a global rim trimming in skeletally mature patients (35, 37, 38).

Steel (39) followed 19 skeletally immature patients who had undergone triradiate cartilage fusion for protrusio acetabuli. An anterior approach was used, followed by elevation of the obturator internus and exposure of the quadrilateral surface and triradiate cartilage. After triradiate closure, 12 of the 19 hips were radiographically graded as normal, four were downgraded to an "acetabular deepening," and three showed no improvement. The only postoperative complication was transient femoral nerve palsy in one patient.

Surgical hip dislocation and/or a VITO are indicated for skeletally mature patients with protrusio acetabuli. A surgical hip dislocation facilitates labral repair or reconstruction and acetabular rim resection to reduce its depth (37). Some cases also require a femoral osteoplasty and relative femoral neck lengthening via a trochanteric advancement (40). A VITO procedure lateralizes the femur to restore normal mechanical alignment of the hip and facilitates femoroacetabular clearance. This procedure is especially indicated for patients with concomitant coxa vara, defined as a femoral neck-shaft angle <110°. With the patient-positioned supine, a direct lateral approach to the femur is used by splitting the vastus lateralis. A closing wedge of bone is removed and the lateral cortex of the proximal fragment is impacted into the distal fragment. The fragments are usually held together in this position using a blade plate. Toe-touch weight-bearing restrictions are enforced for the first 6 weeks after surgery (35, 41).

Results of a VITO procedure have been mixed. Rosemeyer et al. (41) reported good to excellent results in 21 of 25 hips at 6-year follow-up, while Hooper and Jones (38) reported fair to poor results in seven of nine patients at 2- to 7-year follow-up. In a more recent study, McBride et al. (35) presented 12 patients who underwent a VITO for 19 hips. While 83% of patients were satisfied with their decision to have surgery, eight of 19 hips (42%) were revised to THA between 10 months and 15 years after the index VITO. The authors stressed that osteotomy may not necessarily be the definitive treatment for protrusio patients but rather that it may delay the need for THA. They recommended that the procedure not be performed in individuals older than 40 years or who have significant arthritis. In this patient population, THA outcomes have been favorable as long as the acetabular component is lateralized with bone graft so that it aligns with the anatomic center (36, 42–44).

PERTHES-LIKE DISEASES

Legg–Calve–Perthes disease is an idiopathic osteonecrosis of the capital femoral epiphysis in children. It most often affects children between 4 and 8 years old, boys far more commonly than girls. The residual deformity of LCPD after skeletal maturity leads to abnormal hip mechanics and may produce pain. Over 50% of patients develop symptomatic degenerative joint disease by the sixth decade of life (45). Deformity typically presents as a high-riding greater trochanter, a short femoral neck, and a misshapened/enlarged femoral head with variable acetabular dysplasia, retroversion, and joint incongruity (46, 47).

Surgical intervention should be reserved for symptomatic patients. Typical surgical treatment includes open hip dislocation with osteoplasty of the affected femoral head and labral repair. The remainder of the correction is tailored to the specific deformity present. In the setting of femoral retroversion, a proximal femur valgus derotational osteotomy procedure may be of benefit; if acetabular dysplasia is present, a PAO may be of benefit if instability exists following femoral surgery; and, in the setting of acetabular malrotation, an acetabular rim trimming may be of benefit (46, 47). Extra-articular impingement and abductor weakness may result from a high-riding greater trochanter. This can be corrected by advancing the trochanter distally and laterally, which (relatively) lengthens the femoral neck and increases the lever arm of the hip abductors (48). In addition, in LCPD patients with a shortened femoral head, the lesser trochanter may impinge on the ischium and posterior acetabulum. As with the greater trochanter, the lesser trochanter can also be advanced distally to allow clearance over the pelvis (48). Clohisy et al. (49) reported on their experience with surgical hip dislocation, femoral osteochondroplasty and PAO for Perthes-like conditions with acetabular dysplasia. Out of 16 patients with a minimum of 24-month follow-up, only two reported a modified Harris Hip Score (mHHS) <70 (considered a failure) with a median score of 92. They concluded that this procedure was both safe and effective for these less common deformities.

For LCPD patients with an abnormally widened head preventing a concentric joint, a femoral head reduction osteotomy may be performed (40). This is done through the same posterior approach and trochanteric flip osteotomy as described for a surgical hip dislocation. However, in order to visualize the intertrochanteric region, Ganz et al. have recommended an extended retinacular flap (50). The flap is created by subperiosteally dissecting the external rotators, MFCA, and superior retinacular vessels and reflecting them posteriorly until the base of the lesser trochanter is visible. Once adequate exposure is attained, a femoral head reduction osteotomy is performed with the goal of matching the superior femoral head's contour with that of the inferior head. A trapezoidal segment of bone is removed from the superior head–neck junction with osteotomes in the sagittal plane (40). If the acetabulum does not fit properly over the reconstructed femoral head, it is advised to perform a PAO as well. All patients must remain toe-touch weight-bearing for 6–8 weeks (40). In a case series of 14 femoral head reduction osteotomies, Leunig and Ganz found that concomitant acetabular correction was needed in 13 of 14 patients but that no patients developed osteonecrosis after a minimum 3-year follow-up (40). All osteotomies had healed within 8 weeks. Complications are similar to the aforementioned osteotomies, including pseudoarthrosis, painful hardware, superficial infection, and reoperation.

SLIPPED CAPITAL FEMORAL EPIPHYSIS

Slipped capital femoral epiphysis (SCFE) affects adolescent males at a 2:1 ratio compared to females. It is typically unilateral and more common in overweight African-American children. Failure at the hypertrophic zone of the capital physis allows the femoral neck to displace anteriorly and superiorly relative to the femoral epiphysis. Once diagnosed, *in situ* pinning is recommended to stop further slip progression and osteonecrosis. Nevertheless, even after fixation, the hip may remodel into an abnormal femoral head–neck junction causing impingement (51). Some authors have theorized that subclinical SCFE may be a cause of idiopathic FAI, but recent evidence has shown that classic cam deformities have a significantly different physeal tilt angle than SCFE deformities (52).

Surgical treatment for chronic SCFE depends on the severity of the deformity. A small slip angle can be treated with an arthroscopic femoral osteoplasty, but larger slips may require open techniques (53). Surgical hip dislocation with osteoplasty, femoral neck osteotomies, or intertrochanteric osteotomies can be employed. The intertrochanteric osteotomy as originally described by Imhauser in 1957 alters the lateral head-shaft angle to prevent impingement (51). After using a standard lateral approach to the femur, a wedge of bone is removed from the intertrochanteric region to create flexion, abduction, and internal rotation of the distal fragment. A blade plate is used to fix the osteotomy in place. After surgery, the hip is immobilized in flexion, abduction, and internal rotation for 8–12 weeks. Progressive weight bearing is usually allowed immediately after surgery (54).

Spencer et al. (55) demonstrated efficacy using both surgical methods for treating chronic SCFE deformities. Eleven of 13 patients who underwent surgical dislocation and osteoplasty alone either improved or were unchanged after a mean of 12 months, while five of six patients who had a combined osteoplasty and intertrochanteric osteotomy improved. All trochanteric osteotomies healed. Similarly, Rebello et al. (56) showed significant WOMAC improvements in 29 chronic SCFE deformities that underwent femoral osteoplasty and intertrochanteric osteotomy. Positive results continue over the long term as well. Kartenbender et al. (54) followed a cohort of 35 patients (39 hips) for an average of 23.4 years after intertrochanteric osteotomy. Nine hips had no pain and 22 hips had only slight pain with exercise, as 77% of patients were rated as good to excellent clinically (54). Schai et al. (57) reported the radiographic findings of 51 patients at an average of 24 years after osteotomy, showing that 55% had no degeneration, 28% had moderate degeneration, and 17% had severe osteoarthritis. Complication rates after the Imhauser intertrochanteric osteotomy have been as high as 48%. Acute joint space narrowing with a loss of motion may be seen in 29% of patients with a 5% loss of reduction and 10% delayed union rate (58).

For severe deformities, a subcapital realignment can be performed. After surgical hip dislocation, a second trochanteric osteotomy is made to develop a retinacular flap. The short external rotators along with the superior retinacular vessels are subperiosteally lifted until the entire femoral neck is exposed. Then an osteotomy is made through the remodeled physeal scar, the appropriate correction is made, and pins are placed in a retrograde fashion (59). Ziebarth and colleagues (60) showed that the operation was relatively safe and reported that 100% of their patients (40) had no evidence of osteonecrosis at 1-year follow-up. Anderson et al. (59) reported that at 61 months, the average change in Harris Hip Score was 23 (54–77). Complications occurred in four of the 12 cases with avascular necrosis in two patients (59).

CONCLUSION

Open hip preservation techniques have been shown to relieve pain, improve function, and slow the progression of arthritis in adolescent and young adult patients with hip pathology. Larger, more complex deformities may require a more radical correction than can be achieved arthroscopically. All open techniques carry a significant risk of complications, but the surgeon must balance these risks with the benefits of surgery and individual circumstances of their patients. Overall, hip preservation can provide good to excellent outcomes, especially at major referral centers with a high volume of experience.

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REVIEW
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Capsular Management in Hip Arthroscopy: An Anatomic, Biomechanical, and Technical Review

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Hip arthroscopy has become an increasingly utilized surgical technique for the treatment of the young, active patients with hip pain. The clinical outcomes of hip arthroscopy in this patient population have been largely successful; however, there is increasing interest in the contribution of hip capsule in postoperative clinical and functional outcomes. The structure and function of the normal hip capsule will be reviewed. Capsular contributions to hip stability will be discussed in the setting of hip arthroscopy with an emphasis on diagnosis-based considerations. Lastly, clinical outcomes following hip arthroscopy will be discussed as they relate to capsular management.

Keywords: hip arthroscopy, hip capsule, hip instability, hip joint, capsulotomy technique, capsular repair

INTRODUCTION

In recent years, hip arthroscopy has become the surgical technique of choice for the treatment of a variety of symptomatic disorders of the hip, including femoroacetabular impingement (FAI). This meteoric rise in hip arthroscopy is in large part due to the minimally invasive nature of the surgical approach. When indicated, hip arthroscopic procedures have demonstrated excellent short- and mid-term functional outcomes and high satisfaction and return to activity rates beginning with patients as young as 11 years of age (1). The ability to successfully treat a spectrum of hip disorders is limited by the arthroscopic exposure of the offending pathology whether it is in the central, peripheral, or peri-trochanteric compartments. Surgical management of the hip capsule is crucial to provide exposure to the aforementioned regions during arthroscopy, and described techniques include capsulectomy, capsulotomy, and capsulotomy with repair. The selected approach should consider various factors, including patient symptoms, patient baseline general ligament laxity, underlying hip pathology, and surgeon skill level. Failure to consider each of these unique factors for any given surgical case may lead to incomplete treatment of the underlying pathology or postoperative complications related to iatrogenic hip instability. This article will review the anatomy of the hip capsule with an emphasis on structure and function. Diagnosis-based considerations for capsular management will be discussed with an emphasis on surgical techniques and resultant clinical outcomes.

HIP JOINT ANATOMY

The hip capsule is a fibrous structure surrounding the hip joint comprising three external ligaments directed longitudinally as well as internal fibers directed circumferentially. The external ligaments are the iliofemoral ligament (Y ligament of Bigelow; ILFL), ischiofemoral ligament (ISFL), and pubofemoral ligament (PFL). The internal circular fibers of the capsule define the zona orbicularis (ZO) and are lined with synovium encircling the femoral head and neck (2). The native anatomy of these ligaments, including their attachments, thickness, and fiber direction, has been well-documented in numerous reports (**Figures 1A–C**) (2–6). The hip capsule contains the articulation of the femoral head within the acetabulum, as well as the labrum, transverse acetabular ligament, and ligamentum teres, all of which act to protect and stabilize the joint. Additionally, the capsule is perforated by numerous blood vessels responsible for perfusing the hip joint.

Ligaments

Knowledge of the anatomy of the hip capsule, as well as its pericapsular musculotendinous attachments, has increased significantly over the past decade. In 2011, Nam et al. illustrated the acetabular origins using precise clock-face positioning, as popularized by Blankenbaker (7, 8). The authors localized the centers of the ILFL, ISFL, and PFL on average to the 1:26, 10:15, and 4:44 positions, respectively. They also found that the origin of the PFL had the smallest insertional footprint running from 4:02 to 5:27, compared to the ILFL, which spanned the 12:35 to 2:18 region and the ISFL between 8:44 and 11:45. This was similar to a study by Telleria et al., who found the PFL, ILFL, and ISFL running from 3:30 to 5:30, 12:45 to 3:00, and 7:45 to 10:30, respectively (9). In a recent cadaveric study, Walters et al. reported the hip capsule to originate 5 mm proximal and medial to the acetabular rim (5). This proximal origin creates a pericapsular recess, which is an important landmark when evaluating capsular laxity on magnetic resonance imaging (MRI) (10).

The ligaments overlap in a way that may be difficult to appreciate distinct capsular contributions arthroscopically. The PFL travels inferoposteriorly under the medial arm of the ILFL and blends with the ISFL near its acetabular insertion (11). The ISFL spirals superolaterally to insert at the base of the greater trochanter anterior to the femoral neck axis (11). Martin et al. described the insertion of the two arms of the ILFL, where the medial arm descends vertically onto the distal intertrochanteric line, and the lateral arm traverses horizontally along the femoral neck to insert onto the anterior greater trochanteric crest (3). The ZO is a distinct structure of the inner capsule comprising circular fibers surrounding the femoral neck. In a study of seven cadavers, Ito et al. found the ZO to increase the stability of the hip in distraction and postulated that it acted as a locking ring around the femoral neck (12).

Capsular thickness is another important feature of the capsular anatomy, especially when choosing where to establish arthroscopic portals. Walters et al. found the capsular origin to be thickest posterosuperiorly (4 mm) and thinnest anteroinferiorly (1.3 mm) (5). Moving distal to its origin, the mid portion of the capsule is thickest superiorly just underneath the attachment of the gluteus minimus (6). This region represents the ILFL and, during arthroscopy, it is the site of interportal capsulotomy between anterolateral and mid-anterior arthroscopic portals. Finally, the capsular insertion is thickest anterosuperiorly and located 26 mm distal to the femoral head–neck junction, creating a large distal intracapsular recess along the femoral neck (5, 8).

Telleria et al. have investigated the arthroscopic applications of our increasingly robust understanding of capsular anatomy. After performing arthroscopy on cadaveric hips, the authors found that an anterolateral (AL) portal generally pierces the ILFL just inside its lateral border, while the mid-anterior portal pierces it medially (9). Thus, the interportal capsulotomy traverses the width of the ILFL and, in this way, may have ramifications on capsular laxity and stability if not properly repaired. The posterolateral portal penetrates the ISFL superolaterally (9). In the peripheral compartment, Telleria et al. found the PFL to be 6 mm lateral to the medial synovial fold (MSF) at the level of the ZO, and the ISFL was 11.7 mm posterior to the lateral synovial fold (LSF). The medial arm of the ILFL was 6 mm lateral to the MSF, and the

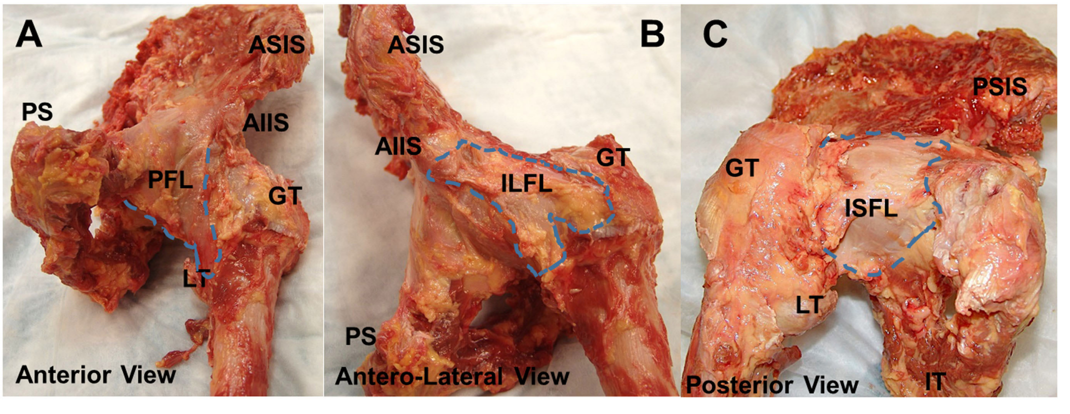

FIGURE 1 | **Anatomy of joint capsule**. Superficial gross anatomy of the hip capsule. The anterior capsule **(A)** is seen with the pubofemoral ligament visualized medially. The ILFL is best appreciated in the anterolateral position **(B)**, and the ischiofemoral ligament can be seen posteriorly **(C)**. AIIS, anteroinferior iliac spine; PFL, pubofemoral ligament; GT, greater trochanter; LT, lesser trochanter; ILFL, iliofemoral ligament; ISFL, ischiofemoral ligament.

lateral arm was 3 mm anterior to the LSF (9). It should be noted that the individual ligaments comprising the capsule could not be seen arthroscopically, but rather their discernment required preoperative dissection and border demarcation with 18-gauge needles (9).

Dynamic Stabilizers

Muscular contributions to the hip capsule include the iliocapsularis, the indirect head of the rectus femoris, and the gluteus minimus (**Figures 2A–C**). The iliocapsularis was found to adhere anteromedially (2:30) and had the largest capsular contribution of any musculotendinous structure, originating at the AIIS and inserting on the distal lesser trochanter (4–6). The function of the iliocapsularis is believed to tighten the anterior hip capsule, which can help stabilize the femoral head in dysplastic hips with decreased anterolateral acetabular coverage (5, 13). In an anatomic study comparing dysplastic vs. normal hips, Babst et al. found iliocapsularis hypertrophy in dysplastic hips to support this hypothesis (14). The indirect or reflected head, of the rectus femoris attaches to the capsule near the anterosuperior acetabular rim between 11:30 and 2:00 (4, 5). There is also a fat pad situated between the iliocapsularis attachment and reflected head of the rectus femoris (**Figure 2A**). The gluteus minimus inserts broadly onto the anterosuperior border of the greater trochanter, and the conjoint tendon and obturator externus run along the posteroinferior capsule (2, 5). While these tendons do not directly insert into the posterior hip capsule, there are adhesions consistently found near the posterior acetabular rim (6). From an arthroscopic standpoint, Walters et al. describe a "stability arc" viewed in the peripheral compartment comprising the superolateral gluteus medius, superomedial reflected head of the rectus femoris, and anteromedial iliocapsularis (**Figure 2B**) (5). They postulate that the stability arc functions to prevent anterior dislocation and can be used as a guide for a capsulotomy during hip arthroscopy.

Neurovascular Supply

The capsular blood supply receives contributions from the medial femoral circumflex artery (MFCA), lateral femoral circumflex artery (LFCA), superior gluteal artery (SGA), and inferior gluteal artery (IGA) (15). In a study of 20 cadaveric hips, Kalhor et al. reported that both the MFCA and LFCA give off capsular branches running circumferentially from the distal to proximal capsule, while the IGA and SGA supplied the posterior capsule (15). They also found that many of these branches form a circumferential periacetabular anastomotic ring between distal and proximal vessels. McCormick et al. have shown that the MFCA pierces the periosteum of the posterosuperior femoral neck, medial to the greater trochanter between 10:30 and 12:00 on the neck–shaft axis (16). These authors described the arthroscopic safe zones along the anterior femoral neck for osteochondroplasties and along the middle third of the medial capsule for psoas tenotomies. Kalhor et al. argued that proximal, rather than distal, capsulotomies avoid the femoral head's vascular supply, as these arteries enter the joint distally (15).

The nociceptive innervation of the capsule was studied histologically by Haversath et al. and found to be evenly distributed throughout the capsule (17). This finding was is in stark contrast with the earlier work of Gerhardt et al. showing an increased concentration of neural fibers in the superolateral capsule (17, 18). However, Haversath et al. had taken samples from diseased arthritic hips during arthroplasty, so their findings of diffuse pain fibers may not be generalizable to patients without arthritis. Overall, precise anatomic knowledge of the hip capsule and surrounding structures can help the arthroscopic surgeon identify intraoperative landmarks and safe zones.

CAPSULAR BIOMECHANICAL CHARACTERISTICS

Violation of the capsulolabral suction seal is required during arthroscopic hip surgery, and as such has provided the opportunity to clinically study the role of the capsule in overall hip stability. Stability is achieved in part by the ZO spiral configuration acting as a screw home mechanism to stabilize the joint in extension and external rotation (12, 19). This mechanism loosens when the hip is brought into flexion, which may make the joint less stable and prone to injury in this position (3, 19, 20). In a cadaveric study, the anterior capsule was shown to withstand a significant amount of tensile force due in large part to the ILFL acting as the strongest capsular constraint (21). In a range of motion study of 12

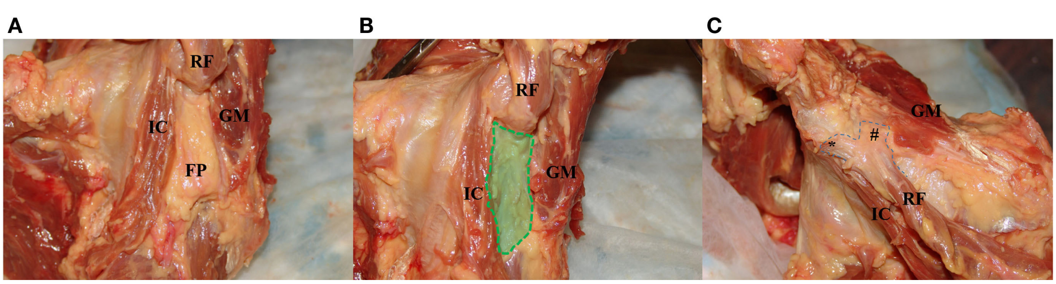

FIGURE 2 | Images of the dynamic stabilizers of the hip capsule. **(A)** With the hip capsule positioned laterally, the rectus femoris is resected to reveal a fat pad between the iliocapsularis and gluteus minimus. **(B)** The fat pad is resected to demonstrate the "safe zone" for capsulotomy between the iliocapsularis and gluteus minimus overlying the anterior superior capsule. **(C)** With the hip in the anterior position, the gluteus minimus is partially resected to show the proximal attachment of the rectus femoris to the AIIS (*) and the attachment of its reflected head to the anterior superior capsule (#). IC, iliocapsularis; RF, rectus femoris; FP, fat pad deep to the rectus femoris; GM, gluteus minimus.

cadaveric hips, Martin et al. found that the lateral arm of the ILFL controls external rotation in both flexion and extension, whereas the ISFL constrains internal rotation in these positions (3). They also reported that the ILFL limits internal rotation in extension, which is in contrast to a biomechanical study by Myers et al. that found the ILFL limits external rotation only (3, 22). By applying 5 Nm of external or internal rotation torque in varying degrees of flexion and extension, Myers et al. reported that ILFL resection increases femoral head rotation and anterior translation, while repair of the ILFL reverses these trends. In this same study, Myers et al. reported that a labral repair alone was insufficient to restore the hip to its native range of motion, with complete restoration occurring only after combined labral and capsular repair.

Biomechanical studies have attempted to quantify the degree to which capsulotomies affect femoral head translation, rotation, and axial strain within the acetabulum with and without repair (3, 23). In a cadaveric study of 13 hips after capsulotomy, Bayne et al. reported qualitative increases in anterior femoral head translation in neutral rotation and increased posterior translation with the hip in flexion (23). One biomechanical study investigating the effect of different capsulotomies on hip stability found that the larger the capsulotomy, the greater the degree of hip rotation, and hip capsulectomy and the unrepaired T-type resulted in the greatest degree of rotation. However, complete repair of the capsule decreases hip rotation similar to the unrepaired interportal capsulotomy suggesting that complete repair can improve the rotational profile (24). With these data in mind, it is critical to weigh the benefits of capsulotomy with its risk of iatrogenic instability and to consider repairing the capsule completely. Additional basic science and biomechanical studies are required to further elucidate the role of the capsule in maintaining hip stability in both pre and postoperative FAI populations.

HIP INSTABILITY SUBTYPES: TRAUMATIC, FAI-INDUCED, ATRAUMATIC, AND IATROGENIC

The hip capsule enhances the stability of the hip joint, and capsule-specific pathology has been implicated in hip instability conditions. Hip instability comprises a spectrum of pathological entities ranging from traumatic instability, FAI-induced instability, atraumatic microinstability, and iatrogenic instability (**Table 1**). Traumatic hip instability itself includes frank dislocations following major trauma, hip subluxation from more minor trauma, and microtrauma following repetitive motion (25). For posterior hip dislocations, the most common injury mechanism is a high energy dashboard injury following a motor vehicle accident in which an axial force is directed against the femoral shaft with the hip in a flexed position (26) (**Figures 3A,B**). In addition to other injuries outside the hip, this mechanism often produces posterior hip dislocation with a posterior wall fracture, and can include concomitant injury to the labrum, capsule, and chondral surfaces of the femur and acetabulum (27, 28). On the other hand, anterior dislocations occur when a force is directed against an abducted and externally rotated hip with the degree of flexion at the time of injury, determining whether the dislocation is superior or inferior (29). Lower level trauma, such as that seen in athletic competition, can also induce traumatic instability. In a study of 14 traumatic dislocations in professional athletes, Philippon et al. found additional intra-articular pathology on arthroscopy, including labral tears (100%), chondral defects (100%), ligamentum teres tears (78%), and capsular tears (14%) (30). Additionally, in a series of American football players with traumatic posterior subluxation, Moorman et al. report that this cohort presented with the attendant triad of posterior acetabular lip fracture, ILFL disruption, and hemarthrosis (31). Further, sports involving repetitive motion such as golf, hockey, soccer, ballet, and figure skating can induce labral and capsular wear, which promote microinstability resulting in increased femoral head translation within the acetabulum (32).

TABLE 1 | Subtypes of hip instability.

Types of hip instability	Characteristics
Traumatic	Two types: (1) high impact event with frank joint dislocation; (2) hip subluxation resulting from microtrauma of repetitive supraphysiologic motion
Atraumatic	Associated with the borderline dysplasia and ligamentous laxity
FAI related	Posterior subluxation in the setting of FAI
Iatrogenic	Presents as gross dislocation (rare) and could be a mechanism for postoperative pain. Associated with non-repaired capsulotomy

Femoroacetabular impingement has also been implicated in the development of hip instability, and the concept of FAI-induced instability has been recently described. Philippon et al. report evidence of FAI in 9/14 (64%) in football players treated for posterior hip subluxation. In addition, a study by Krych et al. demonstrated radiographic evidence of FAI in 81% of patients that presented with a posterior acetabular lip fracture following subluxation (33). Of these, 45% had evidence of a CAM deformity, while 55% had both CAM and pincer deformities. FAI-induced instability differs from traumatic hip dislocations, as these are lower energy injury on the athletic playing fields. Krych and colleagues proposed that the mechanism of injury is a result of hip flexion, and internal rotation creates abnormal contact between the CAM lesion and the anterior acetabulum, which would then lever the femoral head posteriorly (33).

The treating hip arthroscopist should be aware of hip atraumatic microinstability in the borderline dysplastic patient or patient with generalized ligamentous laxity. Acetabular dysplasia is defined by a lateral center edge angle (LCEA) of <20° and Tönnis angle >12° with borderline dysplastic patients having LCEA angles between 20° and 25° (**Figures 3C,D**). Hip dysplasia results in undercoverage of the femoral head by the acetabulum, which alters hip joint biomechanics, placing additional stress on the labrum, anterior capsule, and dynamic stabilizers (34, 35). These hips force the dysplastic and borderline patients to rely on the hip soft tissue stabilizers (cartilage, labrum, and capsule) for stability of the hip through the full range of motion. Notably, the iliocapsularis has been found to hypertrophy in dysplastic patients, with a recent imaging study reporting that the ratio of the iliocapsularis to the rectus femoris

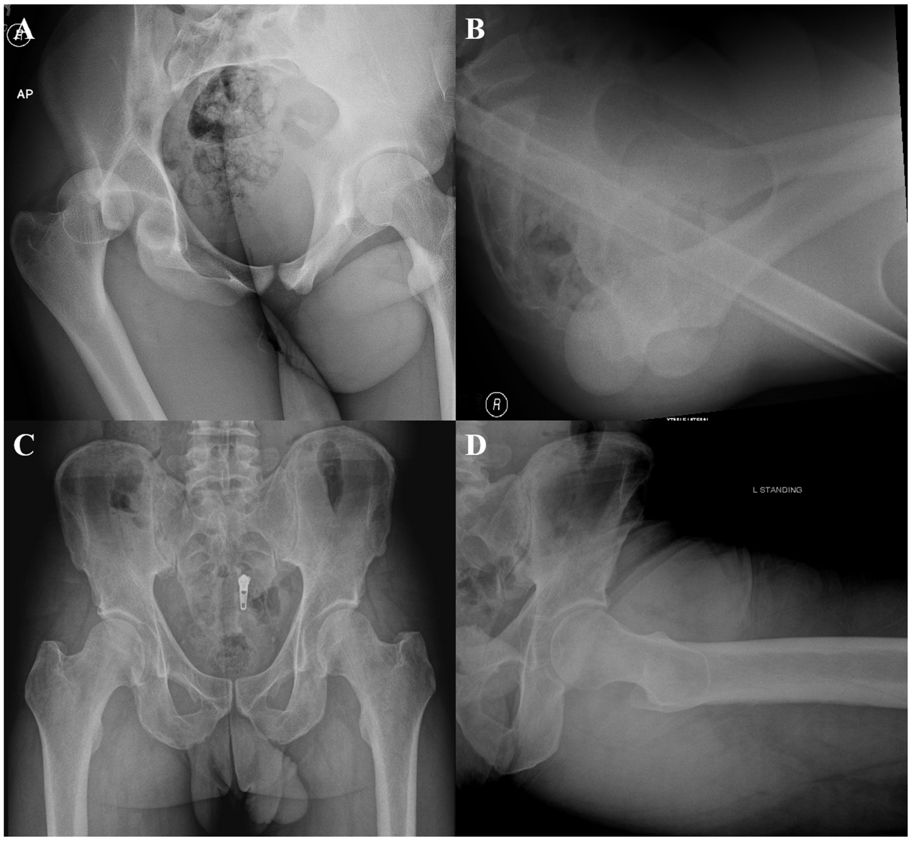

FIGURE 3 | Anteroposterior (A) and cross table (B) radiographs demonstrating a posterior hip dislocation. Anteroposterior **(C)** and Dunn **(D)** views demonstrating a borderline dysplastic patient (LCEA 21.6) with a cam deformity (AA 63).

can be a subtle marker of instability in this cohort (14, 36). This marker may help aid the hip arthroscopist in determining whether symptoms are resulting from the instability of dysplasia, or impingement from cam deformities in patients presenting with radiographic signs of both dysplasia and impingement (36). While true dysplasia is generally managed with periacetabular osteotomy, borderline dysplasia has been treated arthroscopically with conflicting results (35, 37, 38). In a recent study of 22 patients with borderline dysplasia, the authors report good outcomes for patients that underwent arthroscopic labral preservation and repair with capsular plication (35). Capsular management is especially critical in patients with borderline dysplasia, as iatrogenic injury to the capsule without appropriate repair will destabilize the hip joint (34, 35). Additionally, more overt atraumatic microinstability has been described in patients that have generalized capsular laxity (39). Capsular laxity arises secondarily to connective tissue disorders, such as Ehlers Danlos and Marfan syndromes, but can also be seen in patients subjected to repetitive microtrauma (25, 32). While previously managed by thermal capsulorrhaphy, capsular laxity is currently addressed through suture-based plication techniques (2, 39). Microtrauma-associated hip instability remains an evolving topic of interest, as it contains elements of both traumatic and atraumatic hip instability (32, 40).

There have been at least eight published case reports of gross dislocation after hip arthroscopy (41–48). While rare, iatrogenic hip instability is a feared and devastating complication (42, 43, 46). Risk factors for postoperative instability include an open capsulotomy without repair, as well as patients having acetabular dysplasia, hypermobility, or ligamentous laxity (19, 24, 49). It is thought that the number of cases of macroinstability (hip dislocations) is underreported; however, there is a group of patients with iatrogenically induced microinstability that may be much more common and unrecognized after hip arthroscopy. McCormick and colleagues reported on 25 patients that required revision surgery over a 1-year period, and 16 of the 25 patients had residual FAI that necessitated revision surgery. The remaining nine patients had capsular abnormalities on magnetic resonance arthrography (MRA), and seven of nine had capsular defects that required revision surgery to repair the non-healing portions of the capsule (50).

SURGICAL TECHNIQUE

Capsulotomy

With the substantial increase in hip arthroscopy over the past decade, several different techniques, to both incise and repair the capsule, have been described. These techniques include capsulectomy, extensile interportal capsulotomy with or without repair, or a T-capsulotomy with partial or complete repair. Once AL portal and modified-anterior portal (MAP) are established, a transverse interportal capsulotomy is performed 5–10 mm from the labrum, running between 11:00 and 2:00 measuring approximately 2–4 cm depending on the location of the pathology (**Figures 4A–C**) (2, 19, 49, 51). A blade is generally preferred to a radiofrequency ablator to minimize the risk of iatrogenic labral and cartilage injury while also making capsular closure more precise, if warranted (2, 19, 49). Once the chondrolabral pathology has been treated, the instruments are removed from the central compartment, and the traction is suspended flexing the hip approximately 30°. Some surgeons prefer a T-capsulotomy by extending the interportal capsulotomy distally at its midpoint through a distal anterolateral accessory (DALA) portal (**Figure 4D**). In this case, it is critical to identify the intercapsular plane between the two limbs of the ILFL located between the attachment sites of the gluteus minimus and ilocapsularis. Correct identification of this plane will facilitate capsulotomy, as the medial capsule will retract with the iliocapsularis and the lateral capsule will retract with the gluteus minimus (2). Advantages of the T-capsulotomy include improved access in the peripheral compartment and visualization of the head–neck junction for cam deformity correction (**Figures 4E,F**) (2, 49). The capsular suspension technique can facilitate visualization by placing horizontal mattress traction sutures through the medial and lateral leaflets of the ILFL. These stitches are clamped outside the portals with a hemostat to elevate the leaflets for improved visualization, and their closure facilitates a tension-free repair (52). A limited or focal capsulectomy may provide advantages in cases of capsular hypertrophy or stiffness, but this comes at the expense of permanently altering hip joint biomechanics and likely imposes an as yet undefined degree of instability (2, 19, 24, 49). A recent survey of 27 high-volume hip arthroscopists found that they uniformly prefer capsulotomy over capsulectomy (53).

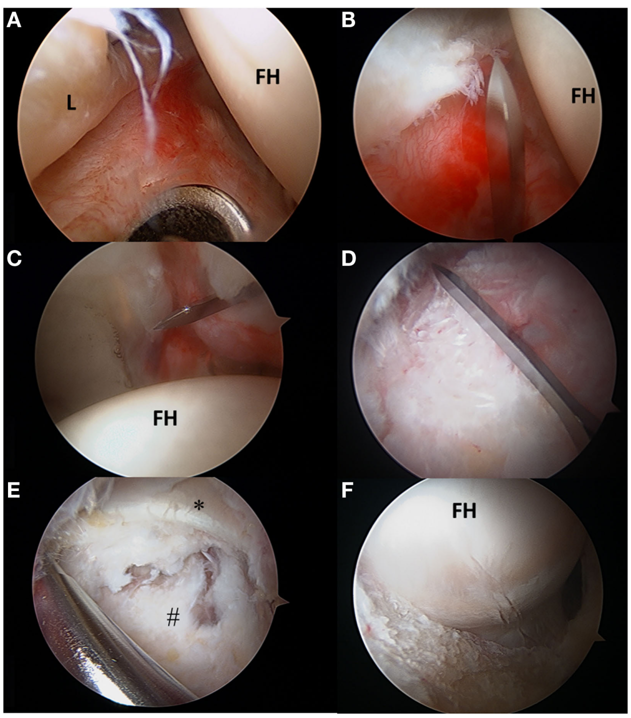

FIGURE 4 | **(A–F)** Transverse and T-type capsulotomy. **(A)** The anterolateral portal is seen penetrating the capsule with the scope viewing through the mid-anterior portal. **(B)** The interportal capsulotomy as seen through the mid-anterior portal. The capsulotomy must begin at least 5 mm from the labrum to ensure adequate tissue for repair. **(C)** Complete interportal capsulotomy to a final length of 2–4 cm depending on the central compartment pathology. **(D)** To view the peripheral compartment, a T-capsulotomy is performed along the ILFL perpendicular to the interportal capsulotomy between the gluteus minimus and iliocapsularis. **(E)** The ILFL leaflets (#) and the reflected head of the rectus femoris (*) can be visualized in proximity to the T- capsulotomy. **(F)** The T-capsulotomy extends down the femoral neck to expose the CAM deformity. FH, femoral head; L, labrum.

Capsular Repair and Plication

Capsular repair is growing in popularity, particularly in cases of capsular incompetence, atraumatic instability, or hyperlaxity. In a cross-sectional survey, Gupta et al. explained that only 11% of high-volume hip arthroscopists never close the capsule compared to 48% that close the capsule >50% of the time (53). Seventy-eight percent of these surgeons decided whether or not to close the capsule based on the risk for instability conditions and intraoperative findings. Capsular repair techniques are varied based on size, type, location of the capsulotomy as well as surgeon preference.

Harris et al. described a technique to employ an InJector II suture passer (Stryker Sports Medicine, Greenwood Village, CO, USA) for closing the capsulotomy through a single portal and for complete closure of both limbs of the T-capsulotomy (49). In the case of the T-capsulotomy, the vertical arm is closed distally to proximally, starting at the base of the ILFL using a suture shuttling technique (Slingshot, Stryker Sports Medicine, Greenwood Village, CO, USA). With the arthroscope in the MAP, an 8.5 mm cannula is placed in the AL and the DALA portals. The Slingshot is placed through the AL portal to penetrate the lateral ILFL (**Figure 5A**), and the suture is retrieved using the Slingshot through the DALA portal (**Figure 5B**). Via the DALA portal, a suture retriever is used to grasp the suture from the AL portal to allow for arthroscopic knot tying (**Figure 5C**). Capsular plication or capsulorrhaphy can be considered to limit capsular redundancy (19, 54). Capsular plication is performed with the hip in 45° flexion, so that side-to-side stitches take larger bites to reduce extraneous capsular elements and decrease the capsular volume (2). Once the vertical limb of the T-capsulotomy is closed, the interportal capsulotomy can be closed with two to three sutures using the InJector II or Slingshot. The posterolateral extent of the interportal capsulotomy is closed though the AL portal. The suture is passed through the acetabular side of the ILFL and then the femoral side of the ILFL. The anteromedial extent of the interportal capsulotomy is closed through the DALA portal using similar steps (**Figures 5D,E**). The authors' preference is to pass the sutures before tying in order to facilitate proper visualization, then the sutures can be tied sequentially until the capsule is closed entirely (**Figure 5F**).

CLINICAL OUTCOMES

When indicated, arthroscopic correction of FAI has produced high functional outcomes over the short- and mid-term (**Table 2**).

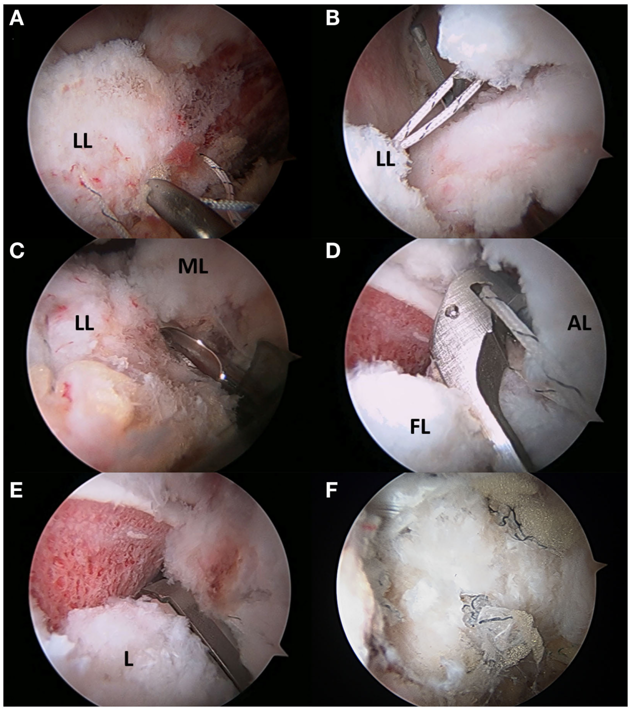

FIGURE 5 | **(A–F)** Capsular repair. **(A)** Capsule repair is initiated by using a tissue penetrating device to pass suture through the lateral leaflet of the ILFL. **(B)** Suture is then passed through the medial leaflet of the ILFL **(B)**, and a knot is tied after each successive stitch has been passed **(C)**. The interportal capsulotomy is repaired by passing suture through the acetabular side of the ILFL **(D)** and femoral side of the ILFL **(E)**. The repaired capsule visualized through the mid-anterior portal.

While it has generally proven successful for the treatment of FAI, further research is required to assess the utility of arthroscopy in the setting of hip dysplasia, preexisting osteoarthritis, and cartilage damage (35, 55–58). Exposure of the cam and pincer deformities is another limitation of hip arthroscopy. This requirement often necessitates a capsulotomy to ensure adequate visualization of the offending pathology. Given the variation in capsulotomy and capsular repair techniques, recent research has focused on the clinical outcomes as they relate to differences in capsular management. A recent review found that unrepaired capsulotomy may be preferred for patients with preoperative stiffness, rheumatologic conditions, or synovial proliferative disorders, such as pigmented villonodular synovitis (PVNS) (19). Another recent study evaluated 2-year patient-reported outcome scores (PROs) in 168 patients with and 235 patients without capsular repair. The authors found that the Hip outcome score-activities of daily living (HOS-ADL) and non-arthritic hip scores (NAHS) improved significantly in the capsular repair group compared to the non-repair group (59). They reported that patient age, gender, and the extent of chondral damage were predictive of the capsular management strategy (59). In contrast, another recent study showed improved outcomes for patients who received complete rather than partial repair of a T-type capsulotomy (51). In this study, Frank et al. compared 32 partial repairs of just the vertical arm of the T-capsulotomy with 32 complete repairs of both the vertical and horizontal arms. The authors found that patients with complete repair had improved Hip Outcome Score-Sports Specific subscale (HOS-SS) at the 6-month, 1-, and 2-year time points. Additionally, the patients in the partial repair group had a higher revision rate at 13%, compared to 0% in the complete repair group. Nevertheless, preoperative to postoperative PROs improved for all groups of patients in both studies. The initial clinical studies suggest that complete capsular repair can improve hip functional outcomes and return to athletic activity. Moreover, there appears to be a higher revision rate in cases in which the hip capsule is not repaired completely (50). Finally, the importance

TABLE 2 | Outcomes of hip arthroscopy for FAI.

Reference	Design	Patients (hips)	Follow-up (months)	Functional outcome scores
Ilizaliturri et al. (71)	Retrospective case series	13 (14)	30	9.6 point increase in WOMAC
Philippon (61)	Retrospective case series	112	28	24 point HHS increase, median satisfaction 9/10
Byrd and Jones (68)	Retrospective case series	200 (207)	16	20 point HHS increase, 1.5% complication rate
Larson and Giveans (72)	Retrospective cohort–control	76	21	Higher 1-year HHS scores in labral refixation (94.3) compared to debridement (88.9) groups ($p < 0.01$)
Schilders et al. (66)	Retrospective cohort–control	96 (101)	29	Higher improvement in 2-year HHS scores in labral refixation (33) compared to labral debridement (26) ($p = 0.034$)
Malviya et al. (62)	Retrospective case series	612	38	Quality of Life increase from 0.946 to 0.974 ($p < 0.001$)
Skendzel et al. (67)	Retrospective cohort–control	323	73	Average HHS, HOS-ADL, ad HOS-SS scores increased significantly from preoperative values. Patients with joint space >2 mm had higher increases in HOS-ADL (15 vs. −6; $p = 0.035$) and HOS-SS (34.8 vs. 3.6; $p = 0.005$)
Frank et al. (51)	Retrospective cohort–control	64	30	Average HHS, HOS-ADL, ad HOS-SS scores increased for significantly from preoperative values ($p < 0.001$). Patients with full T-capsulotomy repair had higher HOS-SS outcome scores (83.6 vs. 87.3; $p = 0.001$) than partially repaired capsulotomy
Domb et al. (59)	Retrospective cohort–control	403	24	Average HHS, HOS-ADL, ad HOS-SS scores increased for significantly from preoperative values ($p < 0.001$). No differences in HHS, HOS-ADL, HOS-SS, and NAHS for patients with repaired vs. unrepaired capsulotomy

of hip capsular stability to overall clinical outcome was elegantly illustrated by examining a patient cohort that was painful following index hip arthroscopy without capsular closure (60). Wylie and colleagues performed revision hip arthroscopy with routine capsular closure on this patient cohort and demonstrated significant improvements in all PROs at >2 years of follow-up. While these clinical outcome studies are not without limitations, the overall body of literature to date demonstrates the importance of capsular stability to clinical outcomes following hip arthroscopy.

Hip arthroscopy is an emerging field, and additional basic science, translational, and clinical research is required to provide both insight into the natural history of the disease as well as continue to improve patient outcomes. Currently, the state of the literature remains limited to small to medium sized case series reporting short to medium term outcomes. To date, there are no published randomized controlled trials evaluating operative vs. non-operative management for FAI. As the rates of hip arthroscopy have increased substantially over the past decade, ongoing investigations into patient clinical and functional outcomes are required to justify the increase in case volume. At this point, numerous studies have demonstrated that hip arthroscopy, when indicated, is successful at relieving patient pain and improving both patient-reported clinical outcomes as well as return to activity and sport in cohorts of elite and recreational athletes (**Table 2**) (61–68). Further, several studies have shown that arthroscopic surgery on non-arthritic patients with FAI is cost-effective when compared to observation (69, 70). Capsular management remains one of the many topics in the field of hip arthroscopy that is continually evolving. Additional investigation into capsular biomechanics, alternate closure techniques, and long-term patient outcomes is required to further develop the fund of knowledge surrounding capsular management in hip arthroscopy.

CONCLUSION

Hip arthroscopy for the treatment of chondrolabral pathology as well as FAI has been growing exponentially. The structure and function of the hip joint capsule is not well understood. There have been recent scientific studies that suggest that a capsulotomy may affect the ability to maintain normal hip translation, rotation, and axial strain, and therefore, the hip may become unstable due to altered hip joint kinematics. Clinical outcomes after hip arthroscopy also suggest a more predictable and reliable hip function with complete capsular repair with a lower rate of revision surgery. The modern strategy of stabilization of chondrolabral pathology, comprehensive treatment of FAI, and complete capsular repair appear to show pain relief, improvement in activities of daily living, the ability to return to athletic activity, and minimize revision surgery.

AUTHOR CONTRIBUTIONS

All authors listed, have made substantial, direct and intellectual contribution to the work, and approved it for publication.

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frontiers in Surgery

MINI REVIEW
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Labral reconstruction: when to perform and how

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Over the past decade, the understanding of the anatomy and function of the hip joint has continuously evolved, and surgical treatment options for the hip have significantly progressed. Originally, surgical treatment of the hip primarily involved resection of damaged tissue. Procedures that maintain and preserve proper hip anatomy, such as labral repair and femoroacetabular impingement correction, have shown superior results, in terms of pain reduction, increased function, and ability to return to activities. Labral reconstruction is a treatment option that uses a graft to reconstruct the native labrum. The technique and outcomes of labral reconstruction have been described relatively recently, and labral reconstruction is a cutting edge procedure that has shown promising early outcomes. The aim of this article is to review the current literature on hip labral reconstruction. We will review the indications for labral reconstruction, surgical technique and graft options, and surgical outcomes that have been described to date. Labral reconstruction provides an alternative treatment option for challenging intra-articular hip problems. Labral reconstruction restores the original anatomy of the hip and has the potential to preserve the longevity of the hip joint. This technique is an important tool in the orthopedic surgeon's arsenal for hip joint treatment and preservation.

Keywords: surgical techniques, hip arthroscopy, labral tear, labral reconstruction, labral pathology

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Background

Hip arthroscopy is a relatively new frontier in orthopedic surgery, with the first documented arthroscopy of the hip performed less than a century ago in 1931 (1, 2). Originally, arthroscopic treatment of the hip primarily involved diagnosis or, at most, irrigation, or simple resection of damaged tissue (1). Since that time, the understanding of the anatomy and function of the hip has continuously evolved, and surgical treatment options have significantly progressed to include a multitude of different procedures (1, 3).

Labral pathology is one of the most common diagnoses among adolescent and adult patients who present for treatment of hip pain (4, 5). The estimated prevalence of labral pathology is not well understood, but previous reports range from 22 to 55% in clinical population (4, 6, 7). Although the prevalence is not well understood, the understanding of the role of the acetabular labrum to biomechanical functioning of the hip has improved significantly in recent years. The labrum plays a crucial role in the stability, lubrication, and kinematics of the hip (8–15). Consequently, surgical procedures that maintain and preserve proper hip anatomy, such as labral repair (versus labral debridement) and FAI correction, have shown superior results in comparison, in terms of pain reduction, increased function, and ability to return to activities (5, 8–10, 16–19).

Labral reconstruction was first described in 2009 and is a treatment option that uses a graft to reconstruct the native labrum (20). The technique and outcomes of labral reconstruction have been described relatively recently, and labral reconstruction is a cutting edge procedure that has shown promising early outcomes. The aim of this article is to review the current literature on hip labral reconstruction. We will review the indications for labral reconstruction, surgical technique and graft options, and outcomes that have been described to date.

Indications for Surgery

Biomechanical Advantages

The labrum plays an important role in maintaining normal hip function. A previous cadaveric study indicated that partial labral resection resulted in loss of fluid pressurization and change of the hip seal (10). Labral reconstruction not only improved fluid pressurization, but maintained it over time, even better than labral repair in that study (10). While early biomechanical research supports labral reconstruction overall, one study does suggest that labral reconstruction may not prevent fluid efflux compared to labral repair or intact labral state (21).

The acetabular labrum also plays an important role in stabilization of the joint to distraction forces (9). Similar to the study of hip fluid pressurization, labral reconstruction was found to significantly improve stability to distractive forces compared to partial labral resection (9).

More recently, a cadaveric study assessed the contact area, contact pressure, and peak force in hips with labral pathology compared to hips with a reconstructed acetabular labrum (15). Hip contact pressure increased in the presence of labral resection but was reduced with labral reconstruction (15). In addition, labral reconstruction reduced peak forces in the hip compared to labral resection. These studies suggest that certain types of labral pathology may be indicated for labral reconstruction.

Patient Characteristics

Arthroscopic labral repair has shown promising patient outcomes (22); however, there exists a population of patients in which labral repair is less optimal. The primary indications for labral reconstruction include irreparable labral tears or insufficient labral tissue (Table S1 in Supplementary Material) (8, 18, 20, 23–27). In these cases, a labral repair may not be feasible or adequate to restore the fluid seal of the hip joint (25, 26). When the tissue is too small, it lacks surface area to heal or the repair may not provide an adequate seal with the femoral head (9, 10). For this reason, a labrum <2–3 mm is considered an indication for labral reconstruction (28). On the contrary, when the tissue is too large, compression often cannot be achieved to allow the labrum to heal. Therefore, a labrum >8 mm is considered an indication for labral reconstruction, although this threshold has not been formally established in the literature. Labral tissue that is degenerative with intrasubstance cystic degeneration is also an indication for reconstruction. Revision procedures following previous labral debridement or resection often provide a challenging situation in which adequate labral tissue may not be available (18, 27). Labral reconstruction provides a viable alternative for maintaining and preserving labral function in patients with irreparable labral tears or insufficient labral tissue for repair.

Labral reconstruction may also be indicated for a variety of other reasons. In the presence of capsulolabral adhesions from previous surgery, it may not be possible to excise the scar tissue while preserving enough labral tissue to repair (25). Patients with rim ossification or global over coverage of the acetabulum may also benefit from labral reconstruction (8, 20, 23). Although contraindications for labral reconstruction have not been well-described, older patient age and preoperative joint space ≤2 mm have been proposed (Table S1 in Supplementary Material) (25). Overall, labral reconstruction should be considered in cases where the ability to maintain and preserve the native hip anatomy is compromised.

Surgical Technique

Open Technique

Sierra and Trousdale first reported hip labral reconstruction in 2009 (20). The original technique was described in association with an open surgical hip dislocation (20). Briefly, the technique described use of a ligamentum teres capitis autograft. The ligamentum teres was detached from the fovea and fixed to the acetabular rim in the same manner as labral refixation. In cases where the size of the ligamentum teres was not sufficient to adequately reconstruct the labrum, the ligament was opened longitudinally in order to lengthen the graft.

Open surgical dislocation remains an option for patients who meet indications for reconstruction. However, in recent years, hip arthroscopy has emerged as a new, less invasive treatment. While once considered the gold standard for surgical treatment of the hip, several recent studies have questioned the superiority of open surgical dislocation to arthroscopy (29–32). Although randomized comparative studies of open and arthroscopic techniques are lacking, hip arthroscopy has significantly fewer complications and re-operations versus open surgical dislocation (29–32).

Arthroscopic Technique

Several arthroscopic techniques for labral reconstruction have been previously described (18, 27, 33–35). A modification of the original arthroscopic technique is presented here, including a front-to-back fixation technique (18, 28), and publication of the technique is currently in press (36). Briefly, the procedure is performed with the patient in a supine position on a fracture table. Combined general and spinal anesthesia is used, with an epidural anesthetic utilized in younger patients (<20 years). Rocuronium, a heavy paralytic agent, is employed at a loading dose of 1.5 mg per 1 kg. Total traction time does not exceed 90 min (in ≤45 min intervals).

Three arthroscopic portals are created for this procedure, including an anterolateral, mid anterior, and accessory portal. Three portals are necessary to maintain appropriate graft tension throughout the procedure. The anterolateral portal is located slightly anterior to the superior tip of the greater trochanter. The mid anterior portal is located 6 cm medial to the anterolateral portal and roughly 1 cm distal. The third, accessory portal is placed roughly 2–3 cm distal and 1–2 cm posterior to the mid anterior portal.

A femoral osteoplasty is performed to correct head-neck offset to eliminate any cam impingement and provide an excellent bleeding environment for graft incorporation. The acetabular rim is also reshaped in order to establish an improved anatomic shape, remove the pincer lesion, and expose a flat, congruent bleeding surface on the acetabular rim for graft incorporation. Torn and damaged labral tissue are fully excised from the low anterior portion of the acetabulum at the origin of the transverse acetabular ligament (7:30 on the left hip and 4:30 on right) to the posterior aspect of the acetabulum (typically 3:00 on the left hip and 9:00 on the right hip). No native labral tissue is retained in the anterior quadrant of the acetabulum because it is felt that loss of connection to the circumferential labrum leads to loss of hoop strength.

In preparation for graft placement, the labral defect is measured, and the graft length is overestimated to avoid the graft being too short. Anchors are placed close to the acetabular edge, without breeching the joint, roughly 11–14 mm apart. They are inserted from the distal accessory portal into the acetabular rim. The most antero-inferior anchor is placed as close to the origin of the anterior transverse acetabular ligament as possible.

For this technique, an iliotibial band allograft (AlloSource, Centennial, CO, USA and MTF Sports Medicine, Edison, NJ, USA), freeze dried or frozen, is preferred. The graft is prepared on the back table by soaking it in a 250 cc saline and 80 mg Gentamycin solution. Once thawed, the graft is measured and rolled to create a final tubularized graft measuring roughly 5–6 mm in diameter. The graft is folded into thirds and a 2-0 Vicryl suture is placed at each end of the graft using an accordion-type suture technique, where several small bites are taken across the end of the graft (**Figure 1A**). When tied, the tension bunches the graft and begins the tubularization process. Each suture is secured in the Graftmaster and another 2-0 absorbable Vicryl suture is run up and down the length of the graft to tubularize the graft (18).

The cannula is placed from the distal accessory portal through the intact antero-inferior capsule. The graft is then introduced into the joint, by fixing it to the non-post end of the first suture and pulling it into the joint with the post end. The suture is then tied with alternating half hitch sutures once the graft is provisionally placed in an appropriate position along the rim of the acetabulum. Circumferential sutures are tied from the distal accessory portal working from anterior to posterior. The second to last suture is passed but not tied to allow for mobility at the end of the graft. Excess graft is removed by cutting the graft with a beaver blade from the anterolateral portal, while maintaining tension with a grasper from the distal accessory portal. The most posterior suture is passed through the end of the graft with an ElitePass (Smith & Nephew, London, England) and then passed under and around the graft, creating a Mason-Allen type of suture construct. The graft is inspected after traction is taken down to ensure there is a complete, continuous seal between the graft and the femoral head (**Figures 1B,C**). Dynamic testing of the joint is done to assess the shape of the joint and to ensure there is no impingement. To complete the procedure, the anterior portion of the capsule is closed.

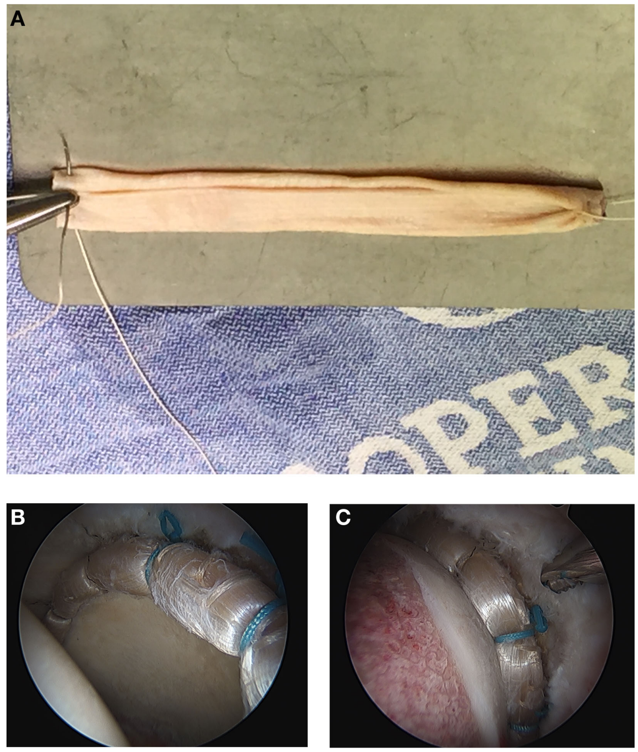

FIGURE 1 | (A) The iliotibial band allograft is measured and rolled to create a final tubularized graft, measuring roughly 5–6 mm in diameter. The graft is folded into thirds and a 2-0 Vicryl suture is placed at each end of the graft using an accordion-type suture technique, where several small bites are taken across the end of the graft. (**B**) After the labral reconstruction, this is a view of a left hip from the anterolateral portal, showing an 11 cm labral reconstruction using iliotibial band allograft and nine anchors in traction. (**C**) After the labral reconstruction, this is a view of a left hip from the anteromedial portal showing an 11 cm labral reconstruction using iliotibial band allograft and nine anchors. The joint is reduced with a view of the re-established seal between the reconstructed labrum and the femoral head.

Graft Options

Several graft options for labral reconstruction have been previously proposed. Allograft tissue provides several benefits over autograft tissue, including the ability to control graft thickness, length, and consistency and the ability to eliminate donor site morbidity. In addition, allograft tissue is aneural, providing a potential benefit in pain reduction. In contrast, native labral tissue likely remains innervated during and following the repair process, which could lead to future pain. Other proposed graft options include iliotibal band autograft (18, 27), local capsular autograft (33), gracilis autograft (34), ligamentum teres capitis autograft (20), fascia lata autograft (23), and quadriceps tendon autograft (35). Advantages and disadvantages of these graft options have not been thoroughly explored in existing literature at this time; however, a recent study of comparing biomechanical properties of the native labrum to iliotibial band, gracilis, semitendinosus, and anterior tibialis grafts found similar biomechanical properties but differing levels of variability in elongation and geometry (37). Another recent study compared iliotibial band autograft to semitendinosus allograft and found no significant difference in contact area, contact pressure, or peak force (15).

Postoperative Management

Rehabilitation for labral reconstruction is similar to that for labral repair; however, patients are cautioned regarding the aneural properties of their graft. Patients begin supervised physical therapy within 1 week of surgery. The focus of rehabilitation is gaining motion, strengthening the gluteus medius, rebalancing the hip musculature, and establishing a normal gait pattern. Weight bearing is typically restricted to 30% body weight for 4 weeks or 20% body weight for 6 weeks if a concomitant microfracture procedure is performed. Advanced rehabilitation focuses on building strength and returning to sport and activity. In our experience, full recovery typically occurs approximately 6 months postoperatively.

Outcomes

Open Labral Reconstruction Outcomes

Two published studies have analyzed the results of labral reconstruction performed during open surgical dislocation (**Table 1**) (20, 23). The first study of outcomes accompanied the original report of the open technique for labral reconstruction (20). The second published study was a case series of 20 hips that underwent labral reconstruction using ligamentum teres capitis or fascia lata autograft in conjunction with FAI treatment (23). The authors reported no complications in either study; however, at a minimum of 1-year follow-up (mean: 26.4 months), 13 hips (65%) underwent 19 subsequent operations, including removal of hardware ($n = 12$), lysis of adhesions ($n = 2$), iliopsoas release ($n = 1$), unspecified arthroscopy ($n = 1$), and THA ($n = 3$) (23).

Arthroscopic Labral Reconstruction Outcomes

Promising patient-reported outcomes and low revision rate have been achieved with arthroscopic labral reconstruction. The lead author has performed over 1,000 labral reconstructions to date (July 2009–March 2015) and, overall, has found superior results with reconstruction compared to repair or debridement in patients with complex intra-articular pathology. Minimum 2-year outcomes from allograft labral reconstruction by the authors are currently in press (38). Among 152 allograft reconstructions, 118 hips were primary reconstructions and 34 were revision reconstructions. One hundred and thirty-one hips were available for follow-up (86%). Thirteen hips (10%) converted to THA and five hips (4%) underwent revision hip arthroscopy at mean 28 months follow-up. Patients who underwent subsequent surgery were found to have significantly lower preoperative MHHS and LEFS, higher VAS pain scores, and were more likely to have undergone previous open dislocation procedure. Of the remaining hips that did not undergo subsequent procedure ($n = 113$), there was significant improvement in MHHS, LEFS, and VAS for pain at rest, with ADLs, and with athletic activities (**Table 1**) ($p < 0.0001$). Overall patient-reported satisfaction was 9 on a VAS scale from 1 to 10 (10, extremely satisfied). Future studies will identify outcome in specific patient subsets, compare procedures, and report long-term outcome.

A recent literature review identified five additional published reports of outcomes from arthroscopic labral reconstruction (**Table 1**) (18, 24–26, 39). The original report of arthroscopic labral reconstruction in 2010 included early outcomes following arthroscopic labral reconstruction with iliotibial band autograft (18, 28). The study reported promising early outcomes (**Table 1**). No complications were reported, and four hips (9%) progressed to THA at a mean follow-up of 18 months. Continued promising clinical results were reported in this patient population at a mean of 49 months (minimum 3 years) postoperatively (**Table 1**) (25). The proportion of hips that converted to THA increased to 24% ($n = 18$), with one additional hip converting to resurfacing. Identified patient factors associated with conversion to THA were patient age and preoperative joint space $\leq$2 mm (18, 25). In an additional report in an elite athlete population, the authors found that 18 of 21 athletes were able to return to the elite playing level following surgery, and 17 of those athletes returned to their previous level of performance or better (24).

Outcomes of arthroscopic labral reconstruction with gracilis autograft have also been reported (26, 39). The first study compared a cohort of eight patients who underwent labral reconstruction to a cohort of 46 patients who underwent labral refixation (26). A second study compared a cohort of 11 patients who underwent labral reconstruction to a cohort of 22 matched patients who underwent arthroscopic segmental labral resection (39). No major complications were reported in either study, but two patients who underwent labral reconstruction had pudendal nerve neuropraxias that resolved within 3 months (26). There were no conversions to THA reported (26, 39). Overall, the labral reconstruction group appeared to have better outcomes than both the labral refixation group and the labral resection group (**Table 1**) (26, 39).

Conclusion

Labral reconstruction provides an alternative treatment option for challenging intra-articular hip problems. The primary indications for labral reconstruction are irreparable labral tears or insufficient labral tissue. Labral reconstruction provides several biomechanical advantages as a treatment option for labral pathology, including improved fluid pressurization, stabilization of the hip to distractive forces, and reduced contact pressure in the hip joint (9, 10, 15). Labral reconstruction should be considered in cases where the ability to maintain and preserve the native hip anatomy is compromised.

Several surgical techniques and graft options have been proposed for labral reconstruction, including open surgical dislocation and arthroscopic techniques and autograft and allograft options (18, 20, 27, 33–36). The lead author prefers the arthroscopic front-to-back surgical technique for labral reconstruction with iliotibial band allograft. The technique described here differs from other arthroscopic techniques in that previous techniques fix the graft in the front and back first, followed by fixation in between. The success of that technique relies on creation of the perfectly sized graft, which can be challenging. The front-to-back technique described here allows the surgeon to make a graft that is 1–2 cm longer than necessary and cut excess graft after front-to-back fixation. The resulting graft is correct size, and the procedure is reproducible; however, it is important to note that the procedure is also technically demanding. Some tips for the "experienced hip arthroscopist" but "novice labral

TABLE 1 | Published open and arthroscopic labral reconstruction outcomes.

Study	Open vs arthroscopic/ graft	*n*	Sex	Age	Follow-up	Convert to THA	Preoperative outcome	Postoperative outcome
Sierra and Trousdale (20)	Open/ ligamentum teres capitis autograft	5	3 M, 2 F	33 (19–50) years	10 (5–20) months	1 (20%)	– 3 "severe pain" – 2 "moderately severe pain" – UCLA:5 (2– 6)	– 3 "no pain" – 1 "moderate pain" – 1 "same pain as preoperatively" – UCLA: 8 (6–10)
Walker et al. (23)	Open/ ligamentum teres capitis autograft or fascia lata autograft	20	5 M, 14 F	29 (16–50) years	26 (12–56) months	3 (15%)	Not reported	– UCLA: 8.5 (5–10)
White et al. (38)	Arthroscopic/ iliotibial band allograft	152	64 M, 78 F	39 (16–58) years	28 (24–39) months	13 (10%)	– MHHS: 54 – LEFS: 41 – VAS rest: 5 – VAS ADLs: 6 – VAS sport: 8	– MHHS: 88 – LEFS: 68 – VAS rest: 2 – VAS ADLs: 2 – VAS sport: 3 – Satisfaction: 9/10
Philippon et al. (18)	Arthroscopic/ iliotibial band autograft	47	32 M, 15 F	37 (18–55) years	18 (12–32) months	4 (9%)	– MHHS: 62	– MHHS: 85 – Satisfaction: 8/10
Geyer et al. (25)	Arthroscopic/ iliotibial band autograft	76	42 M, 33 F	39 (18–64) years	49 (36–70) months	18 (24%) + 1 (1%) resurface	– MHHS: 59 – HOS-ADL: 69 – HOS-Sport: 41 – SF-12 physical:42 – SF-12 mental:55	– MHHS: 83 – HOS-ADL: 81 – HOS-Sport: 67 – SF-12 physical: 50 – SF-12 mental: 53 – Satisfaction: 8/10
Boykin et al. (24)	Arthroscopic/ iliotibial band autograft	21	19 M, 0 F	28 (19–41) years	41 (20–74) months	2 (10%)	– MHHS: 67 – HOS-ADL: 77 – HOS-Sport: 56 – SF-12 physical: 44 – SF-12 mental: 49	– MHHS: 84 – HOS-ADL: 85 – HOS-Sport: 77 – SF-12 physical: 51 – SF-12 mental: 54 – Satisfaction: 8/10 – Returned to play: 18 (86%)
Matsuda and Burchette (26)	Arthroscopic/ gracilis autograft	8	7 M, 1 F	35 (18–58) years	30 (24–37) months	0 (0%)	– NAHS: 42	– NAHS: 92 – Satisfaction: 7 "high,"1 "moderate"
Domb et al. (39)	Arthroscopic/ gracilis tendon autograft	11	7 M, 4 F	33 (18–45) years	26 (24–32) months	0 (0%)	– NAHS: 53 – HOS-ADL: 59 – HOS-Sport: 39 – MHHS: 55 – VAS: 7	– NAHS: 78 – HOS-ADL: 80 – HOS-Sport: 60 – MHHS: 82 – VAS: 3 – Satisfaction: 8/10

[a] *Data are expressed as count (%) or mean (range).*
MHHS, modified harris hip score; HOS-ADL, hip outcome score-activities of daily living; HOS-sport, hip outcome score-sports-specific subscale; SF-12 physical, short form-12 physical component; SF-12 mental, short form-12 mental component; NAHS, non-arthritic hip score; VAS, visual analog scale for pain; ADLs, activities of daily living.

reconstructionist" are provided in Table S2 in Supplementary Material. Adequate training and practice in hip arthroscopy and labral reconstruction are necessary in order to ensure proficiency in placing the anchors in the most anterior and posterior position on the acetabular rim and being able to manage and appropriately fix the graft to obtain a perfect seal with the femoral head.

Long-term outcomes are necessary to determine the longevity of this procedure, but promising early outcomes of have been achieved (18, 20, 23–26, 38, 39). The published literature indicates few complications, improved subjective patient scores, and a low revision rate. Short-term improvement in patient symptomology and function were appreciated with both open and arthroscopic labral reconstruction. Labral repair remains an option in the young, healthy patient with healthy labral tissue; however, labral reconstruction should be considered in patients who do not meet these criteria.

Overall, labral reconstruction increases function, decreases pain, leads to a high level of patient satisfaction, and allows patients to return to activities of daily living and athletics. Labral reconstruction restores the original anatomy of the hip and has the potential to preserve the longevity of the hip joint. This technique is an important tool in the orthopedic surgeon's arsenal for hip joint preservation.

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Supplementary Material

The Supplementary Material for this article can be found online at http://journal.frontiersin.org/article/10.3389/fsurg.2015.00027

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REVIEW
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Rehabilitation following hip arthroscopy – a systematic review

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Context: Rehabilitation following hip arthroscopy is an integral component of the clinical outcome of the procedure. Given the increase in quantity, complexity, and diversity of procedures performed, a need exists to define the role of rehabilitation following hip arthroscopy.

Objectives: (1) To determine the current rehabilitation protocols utilized following hip arthroscopy in the current literature, (2) to determine if clinical outcomes are significantly different based on different post-operative rehabilitation protocols, and (3) to propose the best-available evidence-based rehabilitation program following hip arthroscopy.

Data sources: Per PRISMA guidelines and checklist, Medline, SciVerse Scopus, SportDiscus, and Cochrane Central Register of Controlled Trials were searched.

Study selection: Level I–IV evidence clinical studies with minimum 2-year follow-up reporting outcomes of hip arthroscopy with post-operative rehabilitation protocols described were included.

Data extraction: All study, subject, and surgery parameters were collected. All elements of rehabilitation were extracted and analyzed. Descriptive statistics were calculated. Study methodological quality was analyzed using the modified Coleman methodology score.

Results: Eighteen studies were included (2,092 subjects; 52% male, mean age 35.1 ± 10.6 years, mean follow-up 3.2 ± 1.0 years). Labral tear and femoroacetabular impingement were the most common diagnoses treated and labral debridement and femoral/acetabular osteochondroplasty the most common surgical techniques performed. Rehabilitation protocol parameters (weight-bearing, motion, strengthening, and return to sport) were poorly reported. Differences in clinical outcomes were unable to be assessed given heterogeneity in study reporting. Time-, phase-, goal-, and precaution-based guidelines were extracted and reported.

Conclusion: The current literature of hip arthroscopy rehabilitation lacks high-quality evidence to support a specific protocol. Heterogeneity in study, subject, and surgical demographics precluded assimilation of protocols and/or outcomes to generate evidence-based guidelines. Strengths and limitations in the literature were identified. Future studies should recognize and report the essentials of rehabilitation following hip arthroscopy.

Keywords: hip, arthroscopy, rehabilitation, physical therapy

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Introduction

Femoroacetabular impingement (FAI) is a common cause of pain that may lead to osteoarthritis of the hip (1). Cam and pincer FAI are two distinct anatomic entities that may lead to abnormal articular congruity and subsequent chondrolabral dysfunction (1). The acetabular labrum is an important structure in hip preservation based on improved surgical outcomes after repair vs. debridement during FAI surgery (femoral osteochondroplasty and acetabular rim trimming) (2). Early- and mid-term follow-up after FAI surgery has revealed significant improvements in hip-specific (3), general health-specific (4), and quality of life (4) questionnaires. Nevertheless, it is unknown whether FAI surgery and labral repair may prevent long-term degenerative changes of the hip (5). In addition to FAI and labral tears, several other intra- and extra-articular causes of hip pain may warrant arthroscopic/endoscopic treatment including synovial chondromatosis, loose bodies, snapping iliopsoas or iliotibial band, ligamentum teres tear, hip abductor tears, trochanteric bursitis, and proximal hamstring tear.

Rehabilitation following hip arthroscopy has long been recognized as an integral component of the clinical outcome of the procedure (6). The wide variety of bony and soft-tissue procedures precludes a standard post-operative rehabilitation for "hip arthroscopy." Over the past decade, the incidence of hip arthroscopy has risen dramatically (7). Given the increase in quantity, complexity, and diversity of procedures performed, a need exists to define the role of rehabilitation following hip arthroscopy. The purposes of this systematic review are (1) to determine the current rehabilitation protocols utilized following hip arthroscopy in the current literature, (2) to determine if clinical outcomes are significantly different based on different post-operative rehabilitation protocols, and (3) to propose the best-available evidence-based rehabilitation program following hip arthroscopy. The authors hypothesize that (1) post-operative rehabilitation protocols are infrequently and poorly reported with significant heterogeneity, and (2) there is little to no evidence that supports or refutes specific post-operative rehabilitation protocols and that current protocols are based on theory and biomechanical, rather than clinical, investigations.

Methods

A systematic review was conducted according to preferred reporting items for systematic reviews and meta-analyses (PRISMA) guidelines using a PRISMA checklist (8). Systematic review registration was performed using the PROSPERO International prospective register of systematic reviews (registration number CRD42013003760) (9). Two reviewers conducted the search separately on January 31, 2013 using the following databases: Medline, SportDiscus, CINAHL, and PEDro. A specific electronic search citation algorithm was utilized[1]. English language Level I–IV evidence [2011 update by the Oxford Centre for Evidence-Based Medicine (10)] clinical outcome studies with minimum 2-year follow-up were eligible. Medical conference abstracts were ineligible for inclusion. All references within included studies were cross-referenced for inclusion if missed by the initial search. Duplicate subject publications within separate unique studies were not reported twice. The studies with longer duration follow-up, greater number of subjects, or more explicit reporting of rehabilitation were retained for inclusion. Level V evidence reviews, letters to the editor, basic science, biomechanical studies, open hip surgery, imaging, surgical technique, and classification studies were excluded. Inclusive studies necessarily reported post-operative rehabilitation protocols. Qualitative and quantitative reporting of specific rehabilitation parameters was analyzed. Those studies that otherwise would have been eligible for inclusion and analysis (e.g., 2 years clinical follow-up after hip arthroscopy) that failed to include any post-operative rehabilitation protocol were excluded.

Subjects of interest in this systematic review were enrolled in a clinical trial with a minimum of 2 years follow-up following hip arthroscopy (intervention). Specific outcomes of interest regarding post-operative rehabilitation included weight-bearing status, motion, continuous passive motion (CPM), stationary bike, crutches, brace, anti-rotation boots, heterotopic ossification (HO) prophylaxis, and return to sport. Specific surgical outcomes of interest included intra- and extra-articular procedures including arthroscopic femoral osteochondroplasty, pincer acetabuloplasty, labral debridement or repair, loose body removal, articular cartilage surgery, capsular repair/plication or release, iliopsoas release, ligamentum teres debridement, gluteus medius/minimus debridement or repair, iliotibial release or windowing, and greater trochanteric bursectomy. Study and subject demographic parameters analyzed included year of publication, years of subject enrollment, presence of study financial conflict of interest, number of subjects and hips, gender, age, body mass index (BMI), diagnoses treated, and surgical procedures performed. Clinical outcome scores sought were the non-arthritic hip score (NAHS), international Hip Outcome Tool-12 (iHOT-12), hip outcome score (HOS), modified Harris hip score (mHHS), and hip disability and osteoarthritis outcome score (HOOS). Study methodological quality was evaluated using the modified Coleman methodology score (MCMS) (11). The authors declare that no financial conflict of interest influenced the topic of this manuscript.

Study descriptive statistics were calculated. Continuous variable data were reported as mean ± SD from the mean. Categorical variable data were reported as frequency with percentages. For all statistical analysis either measured and calculated from study data extraction or directly reported from the individual studies, $p < 0.05$ was considered statistically significant.

Results

Study, Subject, and Surgical Demographics

Eighteen studies were identified for analysis (**Figure 1**) (3, 4, 12–27). Eligible subjects were enrolled between 1992 and 2010. Eight studies (44%) denied and five studies (28%) reported the presence of a financial conflict of interest, while five studies (28%) did not report the presence or absence of a financial conflict

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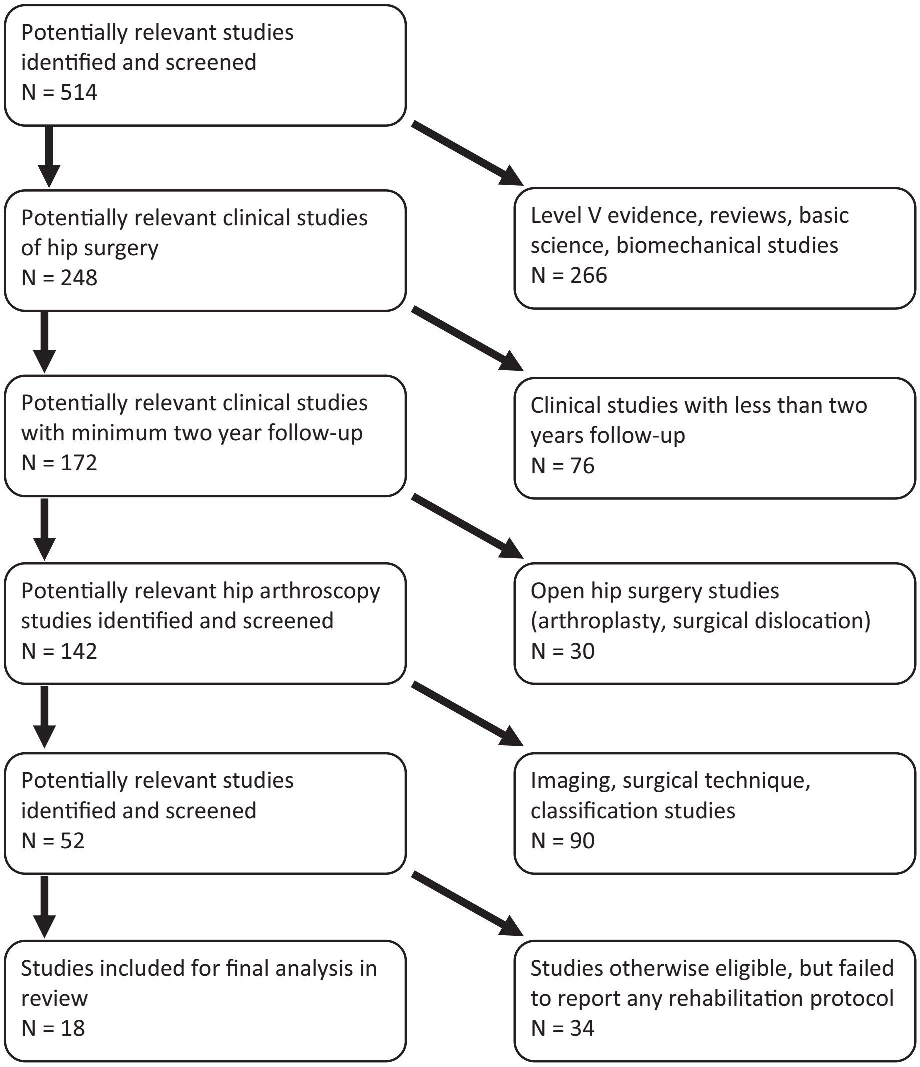

FIGURE 1 | PRISMA flowchart for selection of included and analyzed studies.

of interest. Fifteen studies (83%) were Level IV evidence, two (11%) were Level III, and one (6%) was Level I evidence. There were 2,092 subjects (2,099 hips) analyzed with 52% male (48% female), 48% right (52% left) hips, with mean age 35.1 ± 10.6 years (range 16.9–56.5 years) and mean BMI 24.3 ± 2.4 kg/m^2. When present, the mean time from symptom presentation to surgery was 23.1 ± 15 months. Sixty-seven percent of surgeries ($n = 1,408$ subjects) were performed in supine position (33% lateral; $n = 691$ subjects). Mean length of follow-up was 3.2 ± 1.0 years.

Fifty-four percent ($n = 1,127$) and 80% ($n = 1,676$) of hips were diagnosed with FAI and labral tears, respectively. When reported, 67% ($n = 634$), 5.5% ($n = 52$), and 28% ($n = 28\%$) were diagnosed with cam, pincer, and mixed FAI, respectively. Other primary diagnoses treated were osteoarthritis (35% of all hips; $n = 744$), ligamentum teres tear (27%; $n = 568$), chondral defects of acetabulum, femur, or both (16%; $n = 330$), loose bodies or synovial chondromatosis (5%; $n = 98$), and iliopsoas tendon pathology (3%; $n = 62$). Labral debridement was the most common surgical technique performed (66%; $n = 1,383$), followed by femoral osteochondroplasty (52%; $n = 1,093$), ligamentum teres debridement (29%; $n = 599$), acetabuloplasty rim trimming (17%; $n = 355$), labral repair (16%; $n = 346$), microfracture of femoral head and/or acetabulum (9%; $n = 186$), loose body removal (5%; $n = 115$), and iliopsoas release (3%; $n = 62$).

Mean MCMS was 33.8 ± 9.6 (poor quality). Study strengths (via MCMS) were length of follow-up, treatment description, and description of rehabilitation protocol. Study limitations were blinding, randomization, number of patients needed to treat analysis, and power analysis and alpha error calculations. MCMS question 13 (description of rehab protocol – graded 0, 2, or 4) was adequately described in 4 studies, not adequately described in 14 studies, and not described in 0 studies.

Current Rehabilitation Protocols

Rehabilitation protocols were variably and poorly reported (**Table 1**). Allowance of immediate weight bearing as tolerated

TABLE 1 | Rehabilitation protocols used in all analyzed studies.

Study	Weight-bearing status	WBAT permitted	CPM use	Brace use	Anti-rotational boots
McDonald et al. (12)	Flat-foot WB (max 20 lbs) × 8 weeks (Mfx) Flat-foot WB (max 20 lbs) × 2 weeks (no Mfx)	8 weeks (Mfx) 2 weeks (no Mfx)	6–8 h/day × 8 weeks (Mfx) 6–8 h/day × 3 weeks (no Mfx)	Prevent hip extension and external rotation; 10–21 days; while ambulating	2 weeks
Krych et al. (3)	Flat-foot PWB	2 weeks	–	–	–
McCormick et al. (13)	Flat-foot WB	Immediately post-operatively	–	–	–
Kalore and Jiranek (14)	50% WB × 1 week	1 week	–	–	–
Philippon et al. (15)	PWB × 2–3 weeks	2–3 weeks	–	–	3 weeks
Malviya et al. (4)	PWB × 4 weeks	4 weeks	–	–	–
Stafford et al. (16)	TTWB × 4 weeks	4 weeks	–	–	–
Byrd and Jones (17)	WBAT (unless Mfx, then protected × 2 months)	Immediately post-operatively (no Mfx)	–	–	–
Marchie et al. (18)	WBAT	Immediately post-operatively	–	No	No
Nho et al. (19)	20 lbs foot-flat WB × 2–3 weeks	3 weeks	4 h/day	Yes × 6 weeks	–
Haviv and O'Donnell (20)	WBAT	Immediately post-operatively	–	–	–
Horisberger et al. (21)	WBAT (unless Mfx: 15–20 kg WB for 4–6 weeks)	Immediately post-operatively (no Mfx)	–	–	–
Streich et al. (22)	Toe-touch WB 10 kg × weeks	2 weeks	–	–	–
Philippon et al. (23)	20 lbs WB (for 6–8 weeks if Mfx)	Nr	8–12 h/day × 4 weeks	10 days	10 days
Kim et al. (24)	WBAT	Immediately post-operatively	–	–	–
Fox (25)	WBAT	Immediately post-operatively	–	–	–
O'Leary et al. (26)	WBAT	Immediately post-operatively	–	–	–
Farjo et al. (27)	WBAT	Immediately post-operatively	–	–	–

following surgery was reported in seven studies when treatment was labral debridement, synovial chondromatosis loose body removal, osteoarthritis debridement, septic arthritis debridement, and trochanteric bursectomy. When labral repair, femoral osteochondroplasty, and pincer acetabuloplasty were performed, a partial weight-bearing protocol was initiated. Three studies described partial weight bearing as "foot-flat," while two described it as "toe-touch" or "touchdown." Performance of microfracture warranted partial weight bearing for 4–8 weeks in four studies. Use of CPM was reported in only three studies, with between 4 and 12 h/day use for between 4 and 8 weeks. Brace/orthosis use was reported in only four studies: one study denied the use of a brace, two reported only the duration of time used (10 days, 6 weeks), and the other one did report the duration (10–21 days) and motion restrictions (prevent hip extension and external rotation) and situation (while ambulating). Anti-rotational boot use was reported in only four studies: one study denied their use, and the other three only reported the duration of time used (10 days, 2 and 3 weeks). Only five studies reported the permission and progression to return-to-sport protocols (**Table 2**). Initiation of low-impact sports began at 6 weeks at the earliest and high-impact sports between 3 and 6 months.

Four studies (**Table 3**) recommended specific phase-based rehabilitation protocols following hip arthroscopy (28–31). All four studies described four phases that generally reported formal timeline-based (**Table 3**) and criteria-based (**Table 4**) protocols

TABLE 2 | Description of permission to RTS in all studies analyzed.

Study	Permit RTS
McDonald et al. (12)	Impact sports at 3–6 months
Krych et al. (3)	–
McCormick et al. (13)	Impact loading exercises and deep squatting allowed at 4 months
Kalore and Jiranek (14)	–
Philippon et al. (15)	–
Malviya et al. (4)	–
Stafford et al. (16)	Resume pre-operative activity levels at 3 months
Byrd and Jones (17)	Impact loading allowed at 3 months
Marchie et al. (18)	–
Nho et al. (19)	–
Haviv and O'Donnell (20)	–
Horisberger et al. (21)	Low-impact RTS at 6 weeks; high-impact sports at 3 months
Streich et al. (22)	–
Philippon et al. (23)	–
Kim et al. (24)	–
Fox (25)	–
O'Leary et al. (26)	–
Farjo et al. (27)	–

TABLE 3 | Phase-based description of rehabilitation protocols.

	Phase I	Phase II	Phase III	Phase IV
Edelstein et al. (29)	0–6 weeks post-op	4–12 weeks post-op	8–20 weeks post-op	12–28 weeks post-op
	20% foot-flat WB × 2 weeks	Re-education of psoas, using eccentric exercises	Re-build strength, endurance	Improvements in explosive power
	If microfracture or gluteus medius repair, foot-flat WB 6 weeks	Re-education of transversus abdominis firing	Core control during all activities	High, low velocity strength
	No ROM restrictions unless capsular repair or iliopsoas release	Gluteal and pelvic/hip strengthening	Increase volume, intensity of aerobic activities	Sport-specific speed
	CPM × 3 weeks, brace × 10 days		Proprioception on varying surfaces, with perturbations	Repetition work
	Manual skills, soft-tissue mobilization		Plyometrics (able to squat 150% BW)	Incorporation of rest time
Wahoff and Ryan (30)	Foot-flat WB × 3 weeks (no Mfx)	Wean off crutches (depending on WB status – ±Mfx)	Continue circumduction, prone lying, soft-tissue mobilization	Return to sports
	Foot-flat WB × 6–8 weeks (Mfx)	Continue circumduction, prone lying	Gluteal activation and core and pelvis stabilization	Sport-specific training
	Brace limiting external rotation, extension × 3 weeks	Continue deep soft-tissue massage and mobilization	Double-leg strengthening advancement to single-leg strengthening	Power, plyometric, performance training
	CPM 30–70° in 10° abduction, 4-6 h/day × 2 weeks (Mfx 6–8 weeks)	Gluteal firing, core and pelvis control	Sport progressions to functional activities	
	Stationary bike 20 minutes 1–2×/day × 6 weeks	Progress cardiovascular and upper extremity fitness	Restored cardiovascular fitness	
	Circumduction 2×/day × 2 weeks; 1×/day × 10 weeks	Pilates recommended vs. yoga	Advanced power, plyometrics, performance, conditioning	
	Prone lying × 2 h/day	Reassure mental and physical rehabilitation		
	Isometrics quads, gluteus maximus, transverse abdominis	Add resistance to cycling at week 6		
	Deep soft-tissue massage			
Voight et al. (28)	Variable WB status – if biological healing required, foot-flat WB 8–10 weeks; otherwise WBAT within 1 week	Begins at week 4	Proprioceptive re-training	Return to sports
	Restore passive ROM, especially internal rotation and flexion – prevent adhesions	Pain-free full ROM	Dynamic stabilization exercises, encouraging co-contractions	Individualized based on hip pathology and surgery performed
	Stretching only to tolerance, not beyond	Continue strengthening and stabilization	Begin advanced strengthening in pool before land	
	Stationary bike without resistance	Add WB and resistance exercises	Progress exercises	
	Isometrics of gluts, quads, adductor, abductor, hamstrings, abdominals	Address muscle imbalances: tight hip flexors and erector spinae, weak gluteals and abs (forward pelvic tilt and lumbar lordosis increase)	Slow to fast Simple to complex Stable to unstable	
	Aquatic program	Core stabilization and strengthening	Low to high force	
Garrison et al. (31)	Weeks 0–4	Weeks 5–7	Weeks 8–12	Weeks 12+
	50% WB for 7–10 days (unless labral repair – toe-touch WB × 3–6 weeks)	Emphasis shifts from motion to strength	Integrated functional strengthening	Safe, effective return to sports
	Flexion limited to 90° for 2 weeks (no limit extension, rotation, or abduction) for labral debridement	Continue manual therapy	Manual therapy as needed	Careful, frequent re-assessment to prevent loss of mobility as strengthening continues to advance
	Flexion limited to 90° for 2 weeks, extension to 10° for 2 weeks, rotation gentle for 2 weeks, abduction 25°2 weeks	Aquatic therapy	If full ROM not achieved by week 10, terminal stretches should be initiated	
	Prone lying 1–2 h/day	Kneeling hip flexor stretch once tolerated	Multi-planar muscle strengthening	
	Stationary bike without resistance	Passive ROM should become more aggressive, especially rotation	Core strengthening	
	Isometrics abductors, adductors, extensors, transverse abdominals	Hip and core and pelvis strengthening	Plyometrics in water	
		Add resistance to bike	Running at end of phase	
		Build cardiovascular endurance	Agility drills	

TABLE 4 | Criteria-based progression from phase to phase in post-operative rehabilitation.

	Phase I–II	Phase II–III	Phase III–IV	Phase IV to unrestricted sports
Edelstein et al. (29)	Normalized gait without assistance No Trendelenberg 80% full ROM Core stabilization	Normal ADL's without pain Full ROM Core stability Sahrmann 2 × 30 s 5/5 manual muscle strength Good control in single-leg squat	Recreationally asymptomatic Maintenance of core control "10 rep triple"	Pain-free competitive state Micromanagement of return to sport to consistently and painlessly perform motion responsible for initial injury
Wahoff and Ryan (30)	Minimal pain with all Phase I Minimal "pinching" before 100° flexion Tolerated full WB	Pain-free normal gait Full ROM Core, pelvic stability Balance, proprioception	Passing of a sports test, allowing return to practice without limitations Perform all Phase III exercises pain free and with correct form	Physician clearance Full return to practice without restrictions
Voight et al. (28)	Close to full ROM Normalized gait without crutches Minimal to no pain	Pelvic tilt test, pelvic rotation test, torso rotation test, bridge with leg extension test	Proprioceptive and neuromuscular control	Depends on hip pathology treated and specific demands of sport played
Garrison et al. (31)	ROM ≥ 75% contralateral side Ability to do side-lying straight-leg raise	Normal gait without Trendelenberg sign Symmetric passive ROM No pain	Symmetric motion Symmetric flexibility of psoas, piriformis No Trendelenberg with higher level functional strengthening	Completion of return-to-play test using sportcord test Dynamic functional activities with resistance from sportcord: single-leg squat × 3 min, lateral bounding × 80 s, forward/backward jogging × 2 min

TABLE 5 | Precautions recommended at each phase in post-operative rehabilitation.

	Phase I	Phase II	Phase III	Phase IV
Edelstein et al. (29)	Not lifting leg on its own Not crossing legs Not pushing ROM to point of pain	Avoid hip flexor tendonitis (iliopsoas, TFL, sartorius, rectus femoris)	Avoid sacrificing quality for quantity during strengthening	Avoid breakdown to acute inflammatory response
Wahoff and Ryan (30)	No hip extension past neutral × 3 weeks No external rotation × 3 weeks No flexion beyond 120° No abduction beyond 45°	Avoid treadmill (shear stress) Avoid hip flexor and adductor inflammation Avoid ballistic stretching	Avoid treadmill Avoid hip flexor and adductor inflammation Avoid ballistic stretching and high-velocity activities	None
Voight et al. (28)	No recumbent bike No aerodynamic bike riding position	Avoid arthrokinetic inhibition Avoid synergistic dominance Avoid reciprocal inhibition	Depends on tolerance to advancement of activities	Avoid compressive forces generated by sports, depending on hip pathology and surgical treatment
Garrison et al. (31)	Avoid tight hip flexors and erector spinae Avoid inhibited gluts and abs Avoid hip flexion straight-leg raises to avoid hip flexor tendonitis	Avoid pain	Avoid any loss of motion Avoid loss of core strength	Avoid loss of flexibility as strength continues to increase

with precautions (**Table 5**) advised during each phase. Phase I was a period of protection, between 0 and 6 weeks following surgery, with limited weight bearing, restoration of early motion, limited core abdominopelvic, and hip isometric strengthening, with avoidance of excessive hip extension (beyond neutral), external rotation, deep flexion, and iliopsoas tendonitis. Phase II was a period of advancement to pain-free normal weight bearing and gait and motion, between 4 and 12 weeks post-operatively. Recommendations were for continued strengthening of core and hip muscles, while still avoiding hip flexor tendonitis. Phase III ranged between 8 and 20 weeks after surgery, with focus on endurance, in addition to strength, and progression to sport-specific training. Advancement to Phase IV generally required pain-free full motion, strength, without any subjective or objective deficits during training. Phase IV began at a minimum of 12 weeks following surgery, with progression to safe and unrestricted return to normal activities and sports as well as avoidance of any regression to pain, stiffness, or weakness. All four studies also described a permission to return to running and unrestricted sports protocols (**Table 6**). One study reported an explicit requirement of passage of a return-to-sport test to permit running and a different study reported an explicit requirement of passage of a test to permit unrestricted return to sports.

Clinical Outcomes

Clinical outcomes were variably and poorly reported (**Table 7**). Significant improvements were demonstrated for multiple

TABLE 6 | Criteria-based permission to return to running and return to sports described in each study.

	Permission to run	Unrestricted sports
Edelstein et al. (29)	"10-rep triple": 10 front step-downs and 10 single-leg squats without kinetic collapse, 10 side-lying leg raises against resistance with at least 4/5 manual muscle strength	Consistent and painless repetitions of the movement responsible for the mechanism of injury
Wahoff and Ryan (30)	Pain-free, progressive, predictable Initiate pool running several weeks prior to land in runners	Physician clearance after return to unrestricted practice
Voight et al. (28)	Not reported	Depends on hip pathology and surgical treatment performed
Garrison et al. (31)	Pool running at 2–3 weeks Once good eccentric control, muscular endurance, ability to generate power	Completion of return-to-play test using sportcord test – Dynamic functional activities with resistance from sportcord: single-leg squat × 3 min, lateral bounding × 80 s, forward/backward jogging × 2 min

TABLE 7 | Salient outcomes in all studies analyzed.

Study	Level of evidence	Subject population	Study design	Intervention	Primary outcome
McDonald et al. (12)	3	Elite athletes	Case-control	Microfracture (case) vs. no microfracture (control)	• Return to sport: 77% in microfracture vs. 84% in non-microfracture ($p > 0.05$)
Krych et al. (3)	1	Females	RCT	Labral repair vs. debridement	• Better HOS (ADL, sport) in repair group ($p < 0.05$ for both) • Better subjective outcome in repair group ($p < 0.05$)
McCormick et al. (13)	3	Patients with labral tears	Case-control	Labral repair vs. debridement	• Presence of OA at arthroscopy predictive of worse outcomes • Age >40 years predictive of worse outcomes
Kalore and Jiranek (14)	4	Patients with labral tears	Case series	Labral repair vs. debridement	• Higher ($p < 0.05$) re-operation rate in ○ Borderline vs. adequate acetabular coverage ○ Labral debridement vs. repair
Philippon et al. (15)	4	FAI, 11–16 years of age	Case series	FAI and labral treatment	• Significant ($p < 0.05$) improvement in mHHS (57–91 at 3 years) • 8/60 (13%; all girls) needed repeat arthroscopy (adhesions)
Malviya et al. (4)	4	FAI, 14–75 years of age	Case series	FAI and labral treatment	• Significant ($p < 0.05$) improvement in QoL • 74% of patients happy with results
Stafford et al. (16)	4	FAI, chondral defect acetabulum	Case series	Microfracture with repair of delaminated cartilage using fibrin adhesive	• Significant ($p < 0.001$) improvement in mHHS at 2 years
Byrd and Jones (17)	4	FAI	Case series	FAI and labral treatment	• Significant ($p < 0.001$) improvement in mHHS at 2 years
Marchie et al. (18)	4	Synovial chondromatosis	Case series	Loose body removal	• 48% good/excellent outcomes at 5.3 years • 17% underwent total hip arthroplasty at mean 4.3 years
Nho et al. (19)	4	High-level athletes, FAI	Case series	FAI and labral treatment	• Significant improvements in mHHS and HOS at 2 years • 79% return to sports at mean 9.4 months
Haviv and O'Donnell (20)	4	Osteoarthritis	Case series	FAI and labral treatment	• 16% of patients eventually underwent total hip arthroplasty • Age <55 years and mild osteoarthritis predictive of longer time to arthroplasty
Horisberger et al. (21)	4	Osteoarthritis	Case series	FAI and labral treatment	• 40% of patients eventually underwent total hip arthroplasty • Mean index time to arthroplasty was 1.4 years (range 0.4–2.2)
Streich et al. (22)	4	Labral tears, no FAI	Case series	Labral treatment	• Significant improvements in Larson hip score and mHHS • Presence of acetabular chondral defect worse prognosis
Philippon et al. (23)	4	FAI, 38–44 years of age	Case series	FAI and labral treatment	• Significant improvements in mHHS at 2 years • 11% of patients underwent total hip arthroplasty at mean 16 months
Kim et al. (24)	4	Septic arthritis	Case series	Arthroscopic debridement and drainage	• Excellent results obtained at 4.9 years • No complications, no re-operations
Fox (25)	4	Trochanteric bursitis	Case series	Trochanteric bursectomy	• 85% excellent/good results at 5 years; 96% satisfaction • Only 2 recurrences of pain
O'Leary et al. (26)	4	Various	Case series	Various arthroscopic techniques	• 60% significant improvements at 2.5 years • OA and AVN had significantly worse outcomes (vs. labral tears) • 21% underwent total hip arthroplasty at mean 8.4 months
Farjo et al. (27)	4	Labral tear	Case series	Labral debridement	• 46% good, 54% poor results • 29% underwent total hip arthroplasty at mean 23 months

diagnoses treated with various surgical techniques utilizing NAHS, HOS, HOOS, and mHHS. However, given the heterogeneity between subjects and surgeries performed, no comparison could be made between any group of subjects based on the rehabilitation protocol following surgery.

Discussion

The purposes of this systematic review were to determine the current rehabilitation protocols utilized following hip arthroscopy in the current literature, if clinical outcomes are significantly different based on different post-operative rehabilitation protocols, and to propose the best-available evidence-based rehabilitation program following hip arthroscopy. The authors hypothesized that post-operative rehabilitation protocols are infrequently and poorly reported with significant heterogeneity. The authors also hypothesized that there is little to no evidence that supports or refutes specific post-operative rehabilitation protocols and that current protocols are based on theory and biomechanical, rather than clinical, investigations. The study hypotheses were confirmed, thus strengthening the previous assertion by Cheatham et al. that there is a paucity of evidence surrounding post-operative rehabilitation protocols following hip arthroscopy (32).

Rehabilitation following hip arthroscopy is an integral part of a successful outcome in treatment of various intra- and extra-articular hip pathologies. The current medical climate mandates assimilation of evidence-based medicine and patient-reported outcomes into everyday clinical practice. This includes assessment of basic science and clinical outcomes literature and incorporation of this evidence into discussions with patients. This mandates that the rehabilitation literature following hip arthroscopy significantly improve. The authors selected clinical follow-up studies with minimum 2-year follow-up to accurately identify current rehabilitation protocols. Although 18 studies were identified for inclusion and analyzed, nearly twice as many studies ($n = 34$) would have also been included (**Figure 1**), but those studies did not report a single word about rehabilitation in the entirety of the study. Even within the 18 studies included for final analysis, evaluation of the quality of their reporting was poor (via MCMS) and significant heterogeneity was demonstrated. Little recognition of the importance of rehabilitation was exhibited in the current literature. This does not necessarily mean that the quality of rehabilitation or the conduct of the trial is poor, only that the quality of reporting is poor.

Given the inability to extract evidence-based guidelines from clinical outcome studies of hip arthroscopy rehabilitation in this systematic review, the authors utilized narrative review articles (**Tables 3–6**) to summarize and report the best-available evidence on the topic.

Principles of Rehabilitation

Rehabilitation following hip arthroscopy should be individualized and evaluation based rather than time based. Circumduction is key in enhancing early motion and preventing intra- and extra-articular adhesions. Weight bearing and motion progression is based upon the specific surgical techniques performed. Thus, a "cookbook" rehabilitation program after arthroscopic surgery of the hip is not recommended. Nevertheless, when protection or biological healing is required (labral repair, capsular repair or plication, femoral osteochondroplasty), rehabilitation should progress more slowly vs. procedures in which no protection or healing is needed (labral debridement, loose body removal, ligamentum teres debridement, synovectomy). Avoidance of hip flexor tendonitis is recommended throughout rehabilitation [not only primary hip flexors (iliopsoas) but also secondary flexors (rectus femoris, sartorius, tensor fascia lata)]. Given that the iliopsoas is largely inhibited early after surgery, the activation and over-activation of secondary flexors may occur, thus relegating them to potential inflammatory overuse.

Patients undergoing hip arthroscopy are young (mean age 35 years in this review) and active. As such, rehabilitation protocol efficacy should be assessed using patient-reported outcome instruments that are appropriate for use in this patient population. HOS, the International Hip Outcome Tool (iHOT-33/iHOT-12), and the Copenhagen hip and groin outcome score (HAGOS) have been recommended to guide therapy progression (33). Wahoff et al. described a comprehensive, criteria-driven algorithm for safe integration and return to sport rehabilitation following hip arthroscopy. Emphasis is placed on various criteria to advance through the six phases including healing restraints, patient-reported outcomes, range of motion, and other sport-specific tasks. As a part of the minimum criteria for advancement, the HOS was chosen as it contains both ADL and sports subscales. These separate scales make it appropriate for use in both early rehabilitation and late as it is responsive during higher levels of physical ability (34).

Return to sport is a very relevant component of the surgical outcome. Too early return may lead to recurrence of pain. Progression through phases of rehabilitation necessitates meeting specific goals and milestones as described above. Passing these thresholds improves the likelihood of safe return to sport. Return-to-sport tests are gaining acceptance in return to play following ACL reconstruction (35, 36). The same standards should be applied to patients undergoing hip arthroscopy, as the subject demographics, rehabilitation timelines, and sport goals are similar.

Limitations

The limitations of any systematic review are dependent upon the included studies, which it analyzes. Selection bias in this review was minimized by the inclusive nature of study selection. However, bias is also recognized by exclusion of studies with <2 years follow-up. Performance bias was also minimized by the inclusive nature of study selection, allowing all subject diagnoses and surgical treatments available to be included. It is recognized, however, that no study reported subject compliance with rehabilitation, including weight-bearing status, motion restrictions, CPM use, brace or boot use, or return to sports. Heterogeneity in definitions of rehabilitation phases, protocols, goals, precautions, and return to sport variables introduces detection bias. Study design bias is present in the retrospective nature of 17 out of 18 (94%) included studies. Publication bias is present in that the authors excluded medical conference abstracts, non-English language studies, and non-published English language studies.

Conclusion

The current literature of hip arthroscopy rehabilitation lacks high-quality evidence to support a specific protocol. Heterogeneity in study, subject, and surgical demographics precluded assimilation of protocols and/or outcomes to generate evidence-based guidelines. Strengths and limitations in the literature were identified. Future studies should recognize and report the essentials of rehabilitation following hip arthroscopy.

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