Published in final edited form as:

J Orthop Trauma. 2017 March ; 31(3): e81–e85. doi:10.1097/BOT.0000000000000752.

Novel Spiked-Washer Repair Is Biomechanically Superior To Suture And Bone Tunnels for Arcuate Fracture Repair

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Abstract

Objectives—Injuries to the posterolateral corner (PLC) of the knee can lead to chronic degenerative changes, external rotation instability, and varus instability if not repaired adequately. A proximal fibula avulsion fracture, referred to as an arcuate fracture, has been described in the literature, but a definitive repair technique has yet to be described. The objective of this study is to present a novel arcuate fracture repair technique, utilizing a spiked-washer with an intramedullary screw, and to compare its biomechanical integrity to a previously described suture and bone tunnel method.

Methods—Ten fresh-frozen cadaveric knees underwent a proximal fibula osteotomy to simulate a proximal fibula avulsion fracture. The lateral knee capsule and posterior cruciate ligament were also sectioned to create maximal varus instability. Five fibulas were repaired using a novel spiked-washer technique and the other five were repaired using the suture and bone tunnel method. The repaired knees were subjected to a monotonic varus load using a mechanical testing system (MTS) instrument until failure of the repair or associated PLC structures.

Results—Compared to the suture repair group, the spiked-washer repair group demonstrated a 100% increase in stiffness, 100% increase in yield, 110% increase in failure force, and 108% increase in energy to failure.

Conclusions—The spiked washer technique offers superior quasi-static biomechanical performance compared to suture repair with bone tunnels for arcuate fractures of the proximal fibula. Further clinical investigation of this technique is warranted and the results of this testing may lead to improved outcomes and patient satisfaction for proximal fibula avulsion fractures.

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Conflicts of Interest: No conflicts are declared for any of the authors.

Introduction

The posterolateral corner (PLC) is an important knee stabilizer in varus stress, external tibial rotation, and posterior tibial translation. PLC anatomy is complicated and consists of numerous structures. The main structures that provide stabilization to the PLC are the fibular collateral ligament (FCL), which is the main stabilizer against varus stress and provides stability against external rotation of the knee in lower degrees of flexion¹; and the popliteus tendon and popliteofibular ligament (both act to provide stability against external rotation).²

Although previously considered rare, PLC injuries now comprise 16% of all knee ligament injuries.³ The mechanism of injury to the PLC usually consists of an anteromedially-directed force to the proximal tibia in external rotation with the knee in extension.⁴ Because of this, failure to identify and repair injuries to the PLC can result in the development of chronic knee degenerative changes.^{5,6} Additionally, unrecognized PLC injury can lead to greater stresses on a reconstructed anterior cruciate ligament (ACL) or posterior cruciate ligament (PCL), increasing the risk of cruciate ligament reconstruction failure.^{7,8} Therefore, it is important to identify and repair or reconstruct PLC injuries when they occur to avoid recurrent instability and failure of cruciate ligament reconstructions.⁹

One specific type of PLC injury is a proximal fibula avulsion fracture. The radiographic evidence associated with this injury was named the “arcuate sign” by Shindell et al. in 1984, and these fractures have since been referred to as arcuate fractures.¹⁰ The “arcuate sign” is demonstrated by the avulsed fibular styloid fragment, which is most frequently displaced proximal to the fibular head.¹¹ Arcuate fractures are associated with posterolateral instability because important PLC stabilizers that are inserted on the proximal fibula (such as the biceps femoris tendon, the popliteofibular ligament, fibular collateral ligament, fabellofibular ligament, and the arcuate ligament) can be disrupted and are no longer able to function properly.^{12,13} One study found that 72% of arcuate fractures are associated with anterior cruciate ligament (ACL) injuries and 67% had concomitant posterior cruciate ligament tears.¹⁴

Radiographically, arcuate fractures are most easily identified from an anteroposterior (AP) view of the knee and typically have the appearance of a horizontal lucency through the most proximal aspect of the fibula (Figure 1A). Additionally, the use of magnetic resonance imaging (MRI) is important to consider given high rates of associated cruciate ligament and tendon injuries with arcuate fractures.^{4,14} In coronal T1 weighted images, the same horizontal arcuate sign is visible (Figure 1B).

As previously stated, the proximal fibula is the insertion site of numerous PLC stabilizing structures, making adequate repair essential for post-operative stability. A PubMed search of the literature revealed only two descriptions of arcuate fracture repair techniques. No information, however, was found quantifying the biomechanical properties of these techniques. One report, by Geeslin and LaPrade, described the utilization of a non-absorbable suture used in whipstitch fashion to attach the proximal fibular bone fragment, along with its associated soft tissue attachments, to the intact proximal fibula through bone tunnels.¹⁵ The other surgical technique, published by Zhang et al., described the

arthroscopic repair of a proximal fibula soft-tissue avulsion with only a tiny fleck of bone remaining attached to the soft tissue structures.⁸

A novel spiked-washer repair method using an intramedullary screw was developed as a new option for treating arcuate fractures. The objective of the present study was to compare the biomechanical performance of arcuate fractures treated with this novel method versus the previously described suture repair method using bone tunnels.

Methods

Specimen Preparation

Ten fresh-frozen cadaver knees (four female, six male, mean age 67) were utilized for this study. The knees were randomized by assigning them consecutive numbers and using the even numbered samples for suture repairs and the odd numbered samples for spiked washer repairs. This was performed separately for the female and male samples to evenly distribute female and male samples between the repairs. The knees were thawed overnight prior to surgical intervention. Briefly, dissections were performed to expose the lateral aspect of the knee joint, including the proximal fibula and the associated soft-tissue connections of the PLC. The PLC and lateral capsule were completely transected using a scalpel, to simulate an associated PLC injury and prevent the PLC from providing additional stabilization during stress testing. A three quarter-inch osteotome and a mallet were then used to create a horizontal osteotomy 1cm distal to the most proximal aspect of the fibula, in a lateral to medial direction in order to simulate an arcuate fracture with a large fragment of the proximal fibula, as described by Geeslin and LaPrade.¹⁵

Repair of each fracture was then performed using either the spiked-washer technique or the suture repair method, with a total of five procedures done for each type of repair. The knees were then stored at 4C overnight and subjected to biomechanical testing the following day.

Spiked-Washer Repair

Krackow locking stitches were passed using a #2 non-absorbable suture (FiberWire®, 4 Arthrex, Naples, Florida) through the fibular collateral ligament and the biceps femoris tendon. Five passes from distal to proximal, and then proximal to distal were made, spanning approximately 1.5cm. A 3.2mm hole was then drilled through the center aspect of the proximal fibular head fragment, in a location centered between the insertion of the LCL and the biceps tendon insertion, and in a proximal to distal fashion. A rongeur and bone curette were used to remove any soft-tissue or debris that might become interposed in the fibular osteotomy repair site. The fibular head fragment was then reduced and a depth gauge was used to ensure easy passage of a 70mm cancellous screw through the intramedullary canal of the fibula, distal the osteotomy site. With the knee flexed at 45° to prevent entrapment of the peroneal nerve, a 14mm WasherLoc® spiked-washer (Biomet, Warsaw, IN) was placed on top of the reduced fibular head, and gently malleted into position until it was fully seated against the fibular head. As the spiked-washer was being positioned on the fibular head, the FiberWire® sutures were passed underneath it so that they would be compressed between the washer and fibular head (Figure 2A). Bone wax (Ethicon,

Somerville, NJ) was then placed on the threads of a 6.5mm × 70mm cancellous screw (Biomet) to prevent binding of the sutures, and the screw was threaded into place through the spiked-washer and into the intramedullary canal (Figure 2B). Mini-C-arm fluoroscopy was used to ensure correct passage of the cancellous screw into the intramedullary canal (Figure 2C). Prior to fully seating the screw, each knee was brought into 30° of flexion, valgus stress and internal tibial rotation.

Suture Repair

Two 2mm holes were drilled into the center of the proximal fibular fragment, 1cm apart. A #2 FiberWire® suture was passed through one of the two holes drilled into the fibular head fragment, in a distal to proximal fashion. Krackow locking stitches were then placed into the fibular collateral ligament and the biceps femoris tendon, as described in the spiked-washer repair. The suture was then passed back through the proximal fibular head fragment, passing through the second 2mm hole. Two 2mm drill holes were then made in the distal portion of the fibula, starting near the center of the osteotomy site with 1cm apart that were angled at 45° so that they exited through the anterolateral aspect of the fibula, approximately 1cm distal to the osteotomy site and just above the peroneal nerve. The proximal fibular head fragment was reduced, and the sutures were pulled tight and tied across the bone bridge where they exited the fibular cortex (Figure 3). Reduction and tying was done with the knee in 30° of flexion, valgus stress, and internal tibial rotation as described in the spiked-washer repair.

Biomechanical Testing

Rectangular aluminum bar stock was used to construct a jig in which each knee could be held in a position to allow a varus stress to be placed upon the medial aspect of the femoral condyle. The jig construction was designed to allow freedom of rotation of the distal femur and proximal tibia in a medial to lateral direction, as would be the case during a direct blow to the medial aspect of the knee (Figure 4A). 6.0mm, self-tapping, and partially-threaded Schanz pins (Synthes, Monument, CO) were drilled bicortically through the centerline of each femur and the tibia, in an anterior to posterior direction, 12.5cm proximal and distal to the center of each knee joint, so that the total span was 25cm for each specimen.

The knees were placed in the testing jig in full extension, with the medial aspect of the knees facing upward and the Schanz pins spanning the jig from side to side (Figure 4B). The jig was then placed into an MTS instrument (858 Mini Bionix II, MTS, Eden Prairie, MN) equipped with a 5kN load cell, and a 6 30mm diameter circular loading rod was aligned with the medial femoral condyle (Figure 4C). A monotonic load was then applied to each knee at a rate of 2mm per second, causing a varus stress, until failure of either the repair construct or the PLC structures occurred.

Following the testing, force versus displacement curves were plotted in Excel (Microsoft, Redmond, WA) and stiffness, yield force, failure force (force at construct failure), ultimate force (highest recorded force), and energy to failure were calculated using a set of custom written macros.¹⁶⁻¹⁸

Non-parametric Independent Samples Mann-Whitney U Tests were performed to assess significant differences between repair techniques for each of the parameters as the data were found to be non-normally distributed using an F-test. P-values less than 0.05 were considered significant and all analyses were performed using SPSS (Version 22, SAS Institute, Cary, NC).

Results

The spiked-washer repair group showed superior biomechanical integrity across all calculated parameters (Table 1). Specifically, the stiffness of the spiked-washer repair was more than twice as high as that of the suture repair. The yield force of the spiked-washer repair, a measure that signifies the point at which a material will no longer undergo elastic deformation, was approximately double that of the suture repair group. The failure force, a measure of the point at which permanent deformity occurs and the plastic strength is surpassed, was also more than twice as high for the spiked-washer repair. Similarly, ultimate force, the highest force obtained in testing, was more than double for the spiked-washer. Finally, energy to failure, an integration of stiffness and failure force, was nearly 3-fold higher for the spiked-washer repair compared to the suture repair.

Discussion

Compared to suture fixation, the novel repair technique in this study using a spiked washer and screw demonstrated significant improvements, on the order of 2 to 3-fold, for all calculated biomechanical parameters in fixation of the rare but devastating arcuate fracture. These results show promise in offering a new and reliable method to treat an ill-described problem in orthopedic surgery. The only previously described methods^{8, 15} provided inadequate biomechanical repair fixation. Major limitations of this study include the fact it was a cadaveric study only designed to test initial biomechanical fixation as well as the fact that the testing jig did not allow free translation across the support points as is typical in 3-point bending. Future studies by our group will include varus stress loading to PLC failure of knees with intact posterolateral corner structures and proximal fibulas, so that comparisons may be drawn between the anatomic strength and stability of intact proximal fibulas and the strength and stability of proximal fibula fractures repaired by the methods tested here. Additionally, studies should be conducted to include investigation and analysis of these same arcuate fracture repair techniques, under external tibial rotation and posterior tibial translational forces, to approximate the other mechanism typically seen in PLC injuries. This would include cyclic performance of this fixation method. Given the biomechanical superiority of the new method in single load-to-failure testing, this would examine how our repair survives repetitive loading compared to the screw fixation/tunnel method. In addition, it would be interesting to compare a typical soft tissue washer to the tested spiked washer to determine if the spikes are materially contributing to the success of this repair technique. With a broader sample size and patient application, clinical studies should be conducted to evaluate time to fracture healing and rates of malunions and nonunions, as well as patient satisfaction and outcomes, versus other repair methods. Of note, a standard length screw of 70mm was used for all repairs. It is from the senior Author's experience that shorter screws can pull out when placed in the proximal fibula and

the longest screw available, 70mm, is therefore what is used clinically. In addition, placement of the spiked washer in the lateral collateral ligament can be used to tighten laxity in the ligament concomitantly with fixation of the fracture.

As demonstrated by our cadaveric testing, our spiked-washer and intramedullary screw repair technique for arcuate fracture repair shows biomechanical superiority when tested in single load to failure than the previously described suture repair technique. Future biomechanical studies need to be performed to evaluate the performance of this technique in cyclic loading as well as to assess its ability to restore normal biomechanics. Limited clinical testing to evaluate *in vivo* performance would then be warranted. Utilization of this repair method may result in more stable postoperative outcomes, earlier induction of physical therapy, earlier patient range of motion and weight-bearing, and a quicker return to regular patient activities. Ultimately, this may result in better outcomes for patients with arcuate fractures with PLC injuries.

Acknowledgments

Special thanks to Brian James and Biomet for providing implants used in this study, their assistance is greatly appreciated.

Source of Funding: Biomet provided the spiked-washers and cancellous screws used in this study.

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Figure 1. Proximal Fibula Arcuate Fracture

A) AP x-ray view of a right knee with a proximal fibula avulsion fracture demonstrating an arcuate sign (white arrow). B) Coronal MR T1 view of a right knee with a proximal fibula avulsion fracture demonstrating an arcuate sign (black arrow).

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A

B **C**

Figure 2. Spiked Washer Repair

A) Schematic showing sutures, washer, and screw positions. B) Photograph of completed spiked washer repair. C) Fluoroscopic image verifying proper screw placement.

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Figure 3. Suture Repair
Image of completed suture repair.

Figure 4. Biomechanical Testing

A) Image of the jig designed to hold the knees in position for application of a varus force. B) Image of a knee positioned in the jig. C) Image of the knee in the instrument prior to testing.

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Biomechanical Results

Table 1

This table presents the biomechanical testing results for the suture and spiked washer repairs. Parameters and units are listed in the top row, followed by group means and standard deviations. The last row presents p-values arising from Mann-Whitney U tests.

	Stiffness (N/mm)		Yield Force (N)		Failure Force (N)		Ultimate Force (N)		Energy to Failure (mJ)	
	Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev	Mean	StDev
Suture	43 ± 13		352 ± 120		526 ± 126		555 ± 115		4926 ± 1998	
Washer	88 ± 21		714 ± 212		1155 ± 364		1209 ± 384		14844 ± 6670	
p-value	0.016		0.016		0.008		0.008		0.016	