Insertion Force of Articular Cartilage Transplantation Systems

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ABSTRACT: This study compared the insertion force, plug harvest consistency, and recipient site creation consistency of 4 different articular cartilage transplantation systems (COR, OATS, Mosaicplasty, and New COR2) during plug insertion using a single-impaction technique. Maximum insertion forces fell into 3 statistically different groups: group 1, OATS 8-mm (238 N) and 10-mm (215 N) systems; group 2, COR 6-mm (133 N) and 8-mm (176 N), Mosaicplasty, 6.5-mm (147 N) and 8.5-mm (134 N), and OATS 6-mm (137 N) systems; and group 3, New COR2 6-mm (68 N), 8-mm (55 N), and 10-mm (54 N) systems ($P \leqslant .05$). OATS compaction pressures were 172 N (6 mm), 353 N (8 mm), and 550 N (10 mm). COR, New COR2, and Mosaicplasty donor plugs were created consistently, but the Mosaicplasty system required toggling. OATS plugs had inconsistent lengths but required no toggling. Insertion forces with the New COR2 system were statistically the lowest. Compaction significantly increased surface forces.

[*J Knee Surg*. 2008;21:200-204.]

INTRODUCTION

Isolated full-thickness articular cartilage defects on the femur often are associated with trauma and are found unexpectedly during arthroscopic surgery. Surgical reconstruction of these focal articular cartilage defects using chondral osseous autograft transplantation has demonstrated clinical success.[1,5] Several different systems are available for performing this procedure. All of these systems insert a harvested donor plug (usually by impaction) into a recipient hole to repair the lesion. These compression loads cause articular cartilage chondrocyte injury and death, especially in the superficial zone,[11] on the inserted donor plug. Maintaining the transplanted chondrocyte viability is an important goal of chondral osseous autograft transplantation.

Variations in instrumentation can adversely affect the cell viability of the implanted plug's articular cartilage including cutting tip profile,[12] power harvesters,[7] and most importantly high force during insertion.[2,4,17,24] All chondral osseous autograft transplantation systems place force on the articular surface during the delivery of the plug into the recipient hole. Because the graft insertion technique may affect the chondrocyte viability, knowing what those forces are for the various insertion systems is important. We hypothesized that different instrumentation systems place different loads on the articular cartilage of a chondral osseous plug during transplantation. This study compared the compressive loads on the surface of a harvested plug associated with graft insertion using 4 commercially available systems.

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This research was supported by a grant from DePuy-Mitek.

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MATERIALS AND METHODS

This study compared the following 4 devices:

- OATS system (Arthrex Inc, Naples, Fla) (6-mm, 8-mm, and 10-mm sizes).
- Mosaicplasty system (Smith and Nephew Endoscopy, Andover, Mass) (6.5-mm and 8.5-mm sizes).
- COR system (DePuy-Mitek, Norwood, Mass) (6-mm and 8-mm sizes).
- New COR2 system (DePuy-Mitek) (6-mm, 8-mm, and 10-mm sizes).

TABLE 1

Comparison of Donor Plug Depth and Recipient Hole Length for the Different Instrumentation Systems

Instrumentation System	Recipient Hole Depth (mm)	Inserted Plug Length (mm)
OATS	15	17
Mosaicplasty	15	15
COR	15	15
New COR2	15	15

Figure. The harvested plugs were placed in the delivery tube, aligned above the recipient site in the foam block, and driven into the recipient hole by the Instron actuator using a single impaction.

The substrate for the testing was a solid rigid polyurethane foam block with a density of 15 pounds per cubic foot (Sawbones; Pacific Research Laboratories, Vashon, Wash). This was chosen to provide a material that would respond as consistently as possible for all tests rather than the wide variability demonstrated when either human cadaver or animal bone is used. In addition, the foam block was not bimodal (ie, no "cortical" and "cancellous" layers) to provide a constant density throughout. The foam bone blocks had a density of 0.24 g/cc, a compressive strength of 5.2 MPa, and a compressive modulus of 156 MPa. This was comparable to a published density of bone ranging from 0.09 to 0.41 g/cc,[18] a compressive strength of bone ranging from 2 to 15 MPa,[10] and a compressive modulus of bone ranging from 12 to 488 MPa,[9] 10 to 200 MPa,[8] or 160 to 2800 MPa.[18]

Each size of each device was tested 10 times. To prepare for this testing, 10 recipient sites were prepared in the foam blocks using the equipment in the corresponding instrument kit. All recipient sites were 15 mm deep. The consistency of recipient site creation in the foam block was recorded; this was a secondary endpoint.

After the recipient sites were prepared, a corresponding donor plug was harvested using the appropriately sized instrument from the corresponding equipment set. The length of the donor plug harvested was matched to the depth of the corresponding recipient site using the manufacturer's recommended technique (Table 1). The consistency of donor plug length and ease of harvest was recorded; this was another secondary endpoint.

Each harvested plug was prepared for insertion as needed by placing it into the appropriate delivery system and then aligning the delivery tube above the recipient site in the foam block centered and perpendicular to the recipient hole (Figure). The foam block was rigidly fixed to the base platform with a clamp. The actuator of a model 3345 Instron mechanical testing machine (Instron, Canton, Mass) was moved into position immediately above the insertion plunger for each system's insertion device, and a single impact was applied at a rate of 60 mm/min. The excursion of the impaction was limited to the length of the harvested plug to ensure the plunger stopped at the end of the tube to prevent artificially spiking the force reading by bottoming out of the device. Using a single impact rather than multiple impacts avoids the variation introduced from multiple impacts of potentially varying forces and permits a precise calculation of the impaction force applied. This single-impact technique was chosen to be consistent with prior studies.[14-16,23]

The force curve during plug transfer was recorded and analyzed for peak insertion force to determine whether there was more than one peak force during the plug insertion, such as at the beginning and again at the end of the insertion. For the OATS systems, the maximum compaction force also was recorded. These data represented the primary endpoint.

Statistical analysis was performed using analysis of variance ANOVA. Post-hoc testing for differences between device means was performed using the Duncan multiple range test. Statistical significance was defined as a P value $< .05$.

RESULTS

The primary endpoint was the force placed on the surface of the harvested plugs during plug insertion into the

TABLE 2

COMPARISON OF MAXIMUM INSERTION FORCES FOR THE DIFFERENT INSTRUMENTATION SYSTEMS

Instrumentation System	Maximum Insertion Force (N)	Mean Force per Surface Area (MPa)	End Peak Compaction Force (N)	Mean Force per Surface Area (MPa)
New COR2				
10 mm	54.1±9.1	0.689		
8 mm	54.8±22.7	1.09		
6 mm	68.5±5.2	2.42		
COR				
8 mm	175.9±88.0	3.50		
6 mm	132.6±48.2	4.69		
Mosaicplasty				
8.5 mm	134.2±34.1	2.37		
6.5 mm	147.1±17.1	4.43		
OATS				
10 mm	214.9±70.6	2.74	550.2±44.3	7.00
8 mm	237.8±47.9	4.73	353.3±40.3	7.03
6 mm	136.6±51.8	4.83	172.3±45.3	6.09

recipient hole. These forces for the different systems are shown in Table 2. The maximum insertion forces listed reflect the amount of force needed to pass the plug out of the insertion tube and into the recipient site to a depth of 15 mm. The end peak compaction forces listed for the 3 OATS systems reflect the forces needed to compact the additional 2-mm length on the plug to become flush with the adjacent articular cartilage surface as described in the manufacturer's technique[22] (ie, a 17-mm long plug pushed into a 15-mm deep hole).

Statistical analysis of the maximum insertion forces demonstrated these forces fell into 3 groups that were statistically different from one another. Group 1, which had the highest forces, included the OATS 8-mm and 10-mm systems. Group 2 included the COR 6-mm and 8-mm, Mosaicplasty 6.5-mm and 8.5-mm, and the OATS 6-mm systems. Group 3, which had the lowest forces, included the New COR2 6-mm, 8-mm, and 10-mm systems. All 3 groups were statistically different (Duncan test) at $P < .05$. No statistically significant difference existed between devices within these groups.

A statistical analysis that substituted the end peak compaction forces for the OATS systems for the maximum insertion forces demonstrated the instruments fell into 4 groups that were statistically different from one another. Group 1, which had the highest force, included the OATS 10-mm system. Group 2 included the OATS 8-mm system. Group 3 included the COR 6-mm and 8-mm, Mosaicplasty 6.5-mm and 8.5-mm, and OATS 6-mm systems. Group 4, which had the lowest forces, included the New COR2 6-mm, 8-mm, and 10-mm systems. All 4 groups were statistically different (Duncan test) from each other with $P < .05$. Devices within each group were not statistically different from each other.

Secondary endpoints for this study included the consistency of recipient site creation, the consistency of donor plug length, and the ease of harvest. Recipient site creation was accomplished by using either a drill (COR and New COR2) or a coring punch similar to the harvesters for all systems. The drills produced consistent recipient site depths and easily controlled vertical orientation. Both drill systems have tips on the drill ends to facilitate drill positioning. The punches also were consistent in removing material to the depth required and maintaining a vertical orientation. No inconsistencies were observed for any recipient site creation system.

Donor plug creation was accomplished by the use of a cylindrical chisel harvester for all 4 systems. In this testing system (using a foam block), there was no difficulty maintaining a vertical orientation with any system. The COR and New COR2 harvesters had a "V"-shaped tooth to underscore the cylindrical plug. These consistently harvested plugs of the desired length (15 mm) without the need to toggle the harvester. The ease of harvest was considered to be good for both the COR and New COR2 systems.

The Mosaicplasty harvester had a smooth outlet, without any slots in the harvester wall; it also removed plugs of a consistent depth. However, ease of harvest was a concern. A toggling rotating motion was required to break the plug to be harvested from its base, otherwise the harvester would be removed from the foam block and the plug would remain behind. This toggling technique left a larger hole in the foam block because of compression of the adjacent material during the toggling maneuver.

The OATS harvester consisted of a smooth cylinder with 4 slots in the walls to permit viewing the length of the plug harvested. Toggling to remove the plug was not needed for the OATS system, and the defect created was not larger than the plug removed. Consequently, the ease of harvest was considered good. However, the length of the harvested plugs was inconsistent. Attempting to harvest a 17-mm long plug often resulted in a 12-mm or 13-mm long plug. Repeated attempts were needed to produce the correct plug length.

DISCUSSION

Osteochondral autograft transplantation is an established technique for restoring isolated full-thickness articular cartilage defects in the knee.[1,5] Recent research indicates high compressive loads on articular cartilage results in chondrocyte injury and death,[2,4,11,17,24] which may compromise clinical outcomes. This study evaluated the compressive forces experienced at the articular cartilage surface of a transplanted plug using 4 different surgical techniques. A standard 15-mm long plug was harvested and inserted into a recipient hole using each equipment system. Variables were controlled by using manufactured foam blocks to eliminate variations between specimens, and a constant force was applied at a constant excursion speed for the inserter (rather than separate impacts). This allowed an accurate measurement of the force applied to the surface of the transplanted plug as it was implanted.

The mean maximum force placed on the plug surface during insertion (maximum insertion force) was the primary endpoint. The force curve versus time for the different instrument systems was observed to increase rapidly as the first few millimeters of each plug were inserted into the recipient site. The slope of the curve flattened at a peak level and then dropped in the final millimeters of insertion. Because the OATS technique requires compressing a plug 2 mm longer than the recipient hole into that recipient site,[22] the force curve spiked again for the final 2 mm of each OATS system test. Consequently, 2 separate endpoints were identified for the OATS system. These were the first force plateau observed with all of the tested systems (called the maximum insertion force) and the final force spike (called the end peak compaction force).

The New COR2 system placed significantly less maximum insertion force on the plug than any of the other systems ($P < .05$). The previous COR instrumentation system (6 mm and 8 mm), the 6-mm OATS instrument, and the Mosaicplasty system (6.5 mm and 8.5 mm) were statistically equivalent to each other for maximum insertion forces. The highest maximum insertion forces recorded were for the OATS 8-mm and 10mm systems ($P < .05$).

If the end peak compaction forces of the OATS systems are used for comparison of maximum forces (as would be expected if the recommended OATS technique is followed), additional stratification was observed. Specifically, the OATS 10 mm was statistically greater than the OATS 8 mm, which was statistically greater than all of the other systems ($P < .05$). These data emphasize the inadvisability of a technique in which plugs longer than the recipient holes are tamped and compacted into the hole. These compaction forces associated with the OATS technique place statistically increased forces on the hyaline articular cartilage, which may contribute to decreased cellular viability.

Secondary endpoints in this study dealt with the ease and consistency of donor plug harvest and recipient site creation. Recipient site creation was not a problem for any system. Donor plug harvest was variable for the OATS system with inconsistent lengths a common occurrence. The Mosaicplasty system required toggling of the harvester to separate the plug at its base; this created a larger donor site hole outlet than with the other systems. Both the COR and New COR2 systems provided constant donor plug lengths without the need for toggling.

Limitations of this study include the in vitro nature of the testing and the use of a uniform foam block as the test substrate. Although the use of human cadaver bone as test material would introduce several variables including the need to use several different anatomic locations to obtain sufficient test sites and considerable variation in intra-specimen and inter-specimen bone densities resulting in much greater standard deviations, it would be more consistent with the clinical environment. In addition, this test insertion is not equivalent to the clinical technique, and no conclusion about healing or articular cartilage cell death can be drawn directly from the data. Finally, while multiple impacts might be more consistent with the clinical application of this technique, a review of previous in vitro testing[24] led us to conclude that a multiple-strike methodology would be inferior to a single-strike methodology because of the wide variability of the data points and the need to discard some of the data because of bottoming out.

Traumatic impact to joints has been shown to result in chondrocyte death both in humans[13,19] and in experimental animals.[3,6] The biomechanical factors associated with mechanically induced chondrocyte death include the overall compression level.[20,21] Cell death is higher in the upper zone of articular cartilage compared with deeper areas, presumably because the upper area sustains more of the insertion force. This cell viability has been shown experimentally to be affected for several days after insertion.[21] Consequently, a low-impact technique for harvesting and transplanting these plugs is not only desirable but also critical. There is a clear relationship between insertion force placing loads on the articular cartilage and chondrocyte viability.[21] The New COR2 system showed significantly lower forces compared with the other techniques. Because of the inconsistency of harvested plug length, the recipient site creation should follow, not precede, donor harvest for the OATS system to effectively match plug length to the donor site.

CONCLUSION

Plug surface compression loads were statistically less for the New COR2 system than for the COR, Mosaicplasty, or OATS systems ($P < .001$). The OATS technique, which compacts a plug 2 mm longer than the recipient hole, resulted in significantly increased forces on the plug surface ($P < .05$). The Mosaicplasty system required toggling to remove the donor plug. The OATS system did not produce a consistent plug length.

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