Osteochondral Allograft Transplant System

BME 301
March 7th, 2018

Client: Dr. Brian Walczak, UW Madison School of Medicine and Public Health

Advisor: Prof. Kris Saha, UW Madison Department of Biomedical Engineering

Alex Teague (Leader)
Mark Austin (Communicator)
Zach Wodushek (BPAG)
David Fiflis (BWIG/BSAC)

Abstract

Osteochondral allograft transplantation is an increasingly popular procedure that repairs osteochondral defects by introducing mature cartilage and subchondral bone to facilitate defect healing. These defects can arise from trauma, osteonecrosis, osteoarthritis, and other degenerative cartilage disorders. Existing surgical systems are detrimental to chondrocyte viability and limit vertical graft adjustment—both are crucial for successful surgical outcomes. To address both challenges, we developed a novel surgical system that creates threads on the graft and receiving site to produce a screw-in graft. Testing revealed a significant improvement in chondrocyte viability with the screw-in graft over traditional impaction. Despite the promise shown with improved graft viability, flush graft placement was impossible because the surgeon could not screw the graft flush solely by hand. Thus, a custom tool is required to allow the surgeon to implant the graft flush with the surrounding tissue. The tool must reliably screw the graft into the patient while minimizing damage to the articular surface. The *graft screwdriver* will be tested using live/dead cell staining and confocal microscopy to assess the chondrocyte viability of fresh porcine cartilage after threading and inserting the graft. These data will demonstrate the efficacy of the *graft screwdriver* as it allows the surgeon to achieve full graft insertion without jeopardizing chondrocyte viability.

Table of Contents

Introduction

Motivation

Osteochondral allograft (OCA) transplantation is a surgical procedure that fuses a healthy cartilage and subchondral bone implant from cadaver donor tissue into the patient's cartilage lesion site, particularly in young, active adults [1]. The rate of OCA transplantations performed is increasing by 5% annually, and is expected to reach 3500 procedures by the year 2020 [2]. Despite the prevalence of this procedure, the failure rate is as high as 18% due to unsuccessful integration of the donor and recipient tissues. Nevertheless, the benefit of this procedure over total knee arthroplasty is the promising possibility of restoring full-range of motion, and maintaining the patient's quality of life [3]. The motivation in this project, therefore, is to improve full-graft integration and long-term integrity by protecting chondrocyte viability--a significant factor in determining procedure success [4].

Existing Devices

Arthrex Osteochondral Allograft Transfer System (OATS)

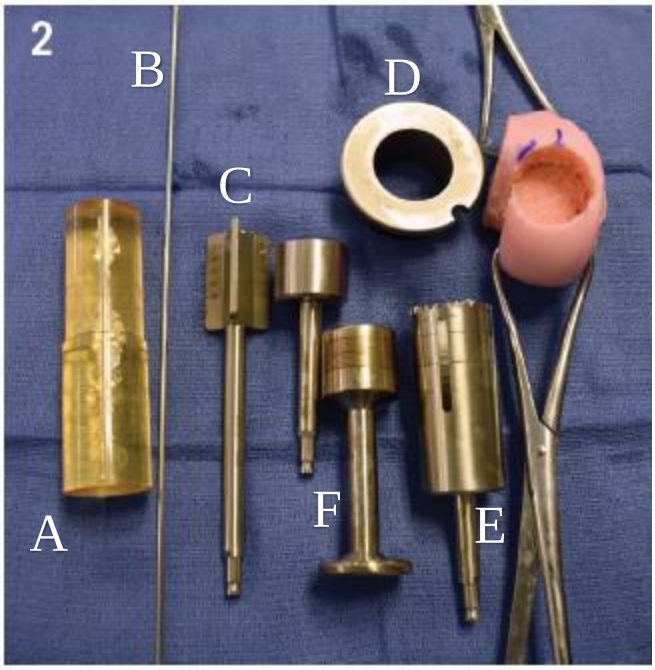


Figure 1: Arthrex Osteochondral Allograft System. (*1A*) Locating and sizing guide. (*1B*) Stainless steel guide wire. (*1C*) Cannulated reamer. (*1D*) Surgical hole saw guide ring. (*1E*) Surgical hole saw. (*1F*) Impacting rods.

The Arthrex Osteochondral Allograft Transfer System (OATS) uses several different tools to prepare the donor site, and harvest the graft before impacting it into the patient [5]. As shown in Figure 1, is a translucent plastic sizing guide that is used to determine how large of a graft must be placed to completely repair the defect. The surgeon places this guide over the defect to ensure that it is completely covered, selecting a larger or smaller size as needed. Once the proper size is determined, the sizing rod is held orthogonal to the surface of the defect and the guidewire (1B) is inserted through the hole in the center of the sizing guide, and a drill screws the guidewire through

the center of the defect and into the bone. After the guidewire is positioned, the cannulated reamer (1C) (with a diameter corresponding to the sizing guide) is inserted over the guidewire to drill a receiving hole to the proper depth (typically 7-14 mm). Miscellaneous tools (not pictured) are used to remove loose tissue from the bottom of the hole, as well as from the cartilage surrounding this hole.

To harvest the donor graft, the cadaver tissue is placed in a vice (not pictured) or another similar fixture to secure it for cutting. The shape of the condyle surrounding the prepared donor site is noted and the best geometric match on the donor tissue is selected. A surgical hole saw guide (1D) is held over the matched geometry of the cadaver graft and the hole saw (1E) is then used to cut the graft cylinder. The graft is inserted using the impaction rod (1F) and a surgical hammer until it sits flush with the surface.

Zimmer Chondrofix Osteochondral Allograft System

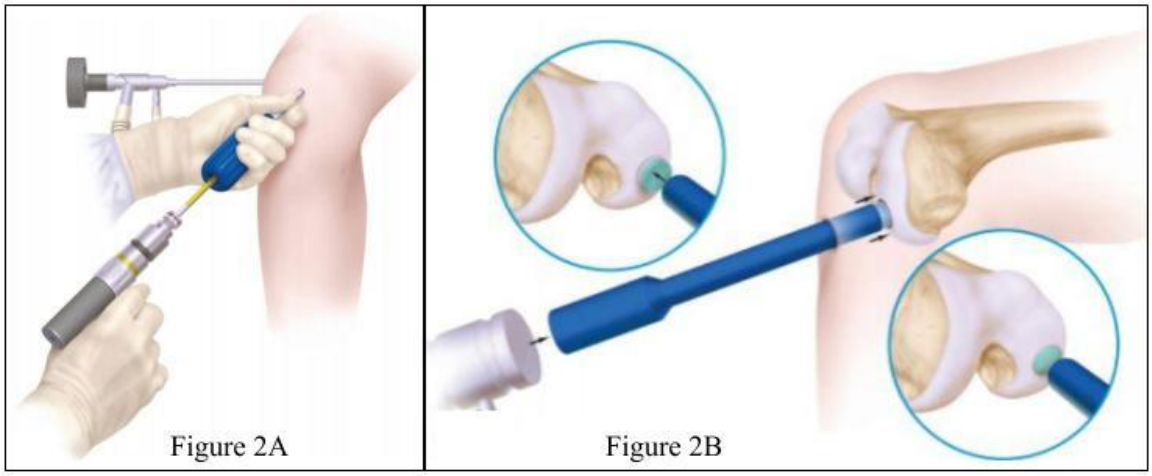


Figure 2: Zimmer Chondrofix Osteochondral Allograft System. (2A) Recipient site arthroscopic drill guide prepares the receiving site. (2B) Arthroscopic impactor secures the decellularized osteochondral allograft into the patient.

The Zimmer Chondrofix Osteochondral Allograft system (Figure 2) relies on a pre-made, decellularized osteochondral graft. This eliminates the need to prepare an allograft from cadaveric tissue during surgery. The steps leading up to graft insertion are similar to the Arthrex system. A plastic sizing rod determines the size of the graft that the surgeon will insert. A hollow punch of corresponding size is pounded into the bone over the defect while the surgeon keeps it perpendicular to the condyle surface. Depth markings on the side of the punch allow for greater control over the depth of the receiving hole. After punch insertion, the impacting handle is removed to expose a center hole that accepts a corresponding drill bit which removes the remaining bone inside the punch and leaves a perfectly sized graft receiving hole. Unlike the Arthrex system, this drilling system has a built-in depth stop allowing greater depth control, which can be challenging for surgeons. The drill bit and punch are removed, and the hole depth is verified before cutting the pre-made graft to length. The graft is inserted using the insertion tool, leaving it slightly proud of the surface, and the impaction tool pushes it flush with the surface. This system is designed for arthroscopic use, unlike with the Arthrex system [6]

Depuy Synthes COR ® Precision Targeting System

Figure 3: COR® Precision Targeting System. (3A) Graft harvesting tool placement. (3B) Graft harvesting tool impacted into bone and rotated to score the graft for removal from the patient. (3C) Graft transfer tube is placed over the receiving site, and a low impact insertion tool secures the graft into the patient.

The COR ® Precision Targeting System boasts ease of use and improved accuracy, but its claim to protect chondrocyte viability defines it from other systems. Using "no-impact transfer" and "low-impact delivery", it is designed to be used to surgically treat femoral articular cartilage lesions via autograft transplantation. However, the claims of improved chondrocyte viabilities is unsubstantiated by the provided literature. Use of an autograft is another concept unique to this system. To harvest the donor graft, the graft harvesting tool is placed on a non-weight-bearing articular surface (Figure 3A), and a mallet drives the cutter to the desired depth, indicated by measurements on the tip of the tool (Figure 3B). Rotating the tool scores the bottom of the graft to free it from the patient. The graft inside the graft transfer tube is then aligned with the recipient site and impacted until it is fully inserted (Figure 3C) [7].

These three systems indicate that there is little variation in methodology to OCA transplantation procedures. As a result, there is no direct competitor to a screw-in graft system. Every OCA system currently on the market relies on impaction to set the graft in place. This represents a significant gap in the market that an improved osteochondral grafting system can fill.

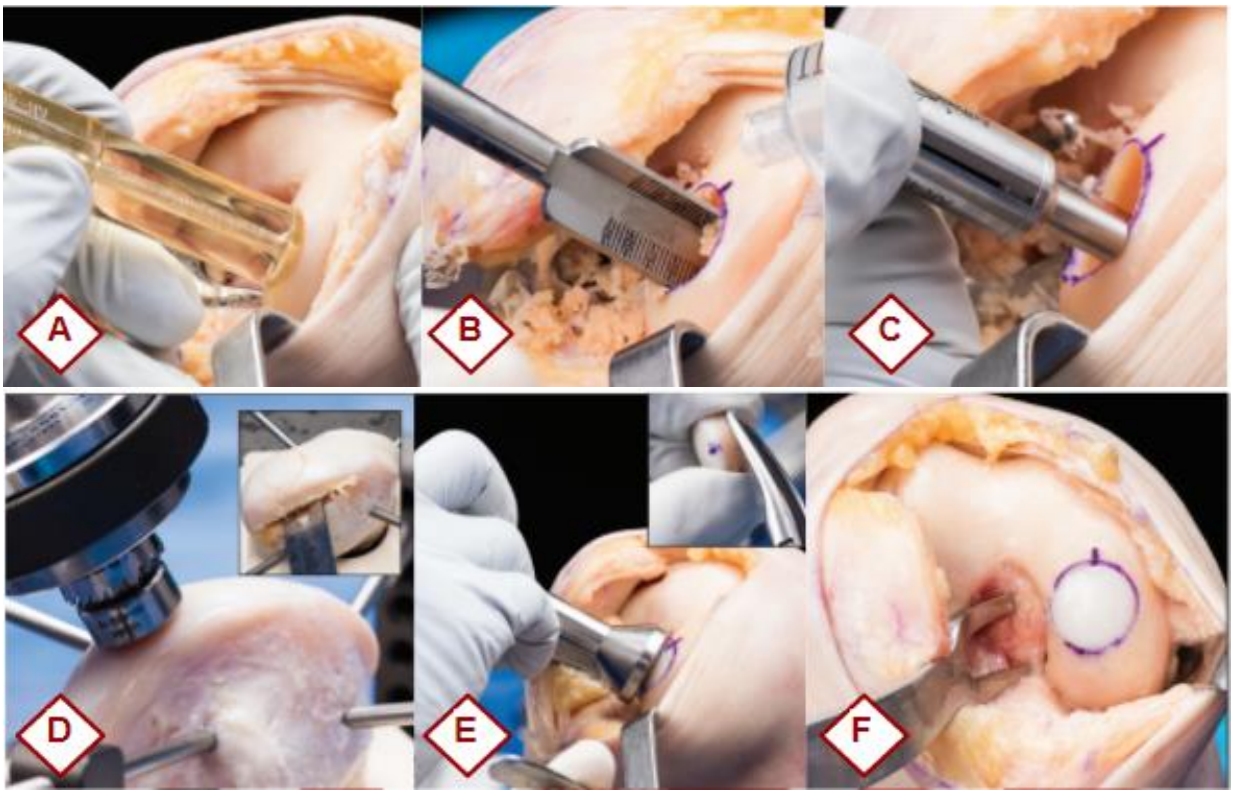
Problem Statement

Treating young, active patients with chondral defects has proven to be surprisingly challenging. Normal treatment presently involves impaction of an osteochondral allograft into the prepared region of the defect. The goal of this treatment is to introduce mature hyaline cartilage and subchondral bone that will ultimately integrate with the native tissue and repair the defect. The problem facing this method is that impaction can jeopardize chondrocyte viability, which directly affects the success of the procedure. We developed a novel OCA surgical system that cuts matching threads on the graft and recipient sites resulting in a screw-in graft. Testing showed marked improvements in chondrocyte viability compared to impaction, but the graft could not be placed flush with the adjacent tissue--this was because the surgeon had no means of grasping the graft during the final few rotations. Thus, the aim is to develop a tool that complements the current prototype and allows for complete graft insertion without compromising chondrocyte viability.

Background

Osteochondral Defect Etiology

Osteochondral defects arise from any type of pathology or injury that cause the bone and articular cartilage to separate; these include osteonecrosis, osteochondritis dissecans, and idiopathic developmental defects [1], [5], [8] The leading concomitant knee pathology for this defect is a tear in the medial meniscus, which reduces support of the knee and results in greater joint contact forces [4]. Other pathologies leading to osteochondral defects include abnormal bone growth and excessive stress in the knee [9].



Osteochondral Allograft Transplant Procedure

Figure 4: OCA transplant procedure as outlined by the current surgical guide. (4A) Sizing the defect with plastic sizing rod. (4B) Drilling the recipient site to desired depth with a cannulated reamer. (4C) Measuring depth of recipient site with plastic measuring rod. (4D) Cutting donor graft with surgical hole saw. (4E) Impacting donor graft into recipient site with impacting rod. (4F) A successfully implanted graft. [10]

The most common surgical approach to implanting an osteochondral allograft is the dowel technique. This procedure begins by preparing the recipient site for the allograft. The focus of this preparation is to create a cylindrical void that is perpendicular to the surrounding cartilage. To ensure perpendicularity, a guide wire is inserted orthogonal to the condyle at the defect site. A cannulated dowel reamer is passed down the guidewire and advanced to a depth of between 7 mm -14 mm, clearing a void 10 mm-25 mm in diameter.

The allograft is created from fresh cadaver tissue, and its geometry is matched to the recipient site on the patient. To harvest the graft, a surgical hole-saw is passed through a guide ring on the articular cartilage creating a cylindrical dowel. Then, the measurements of the recipient site depths are used to guide the surgeon as they cut the graft to a complementary length with an oscillating saw. The allograft is then positioned directly above the recipient site, and impacted until the graft lies flush with the surrounding cartilage [10].

Physiology

Impaction force used to press fit osteochondral allografts into place during a transplant procedure induces cell death in the superficial portion of the articular cartilage. The impaction impulse deforms mechanoreceptors in the cell. This initiates an intracellular signaling cascade ultimately activating executioner caspases, triggering cell apoptosis (Figure 5).

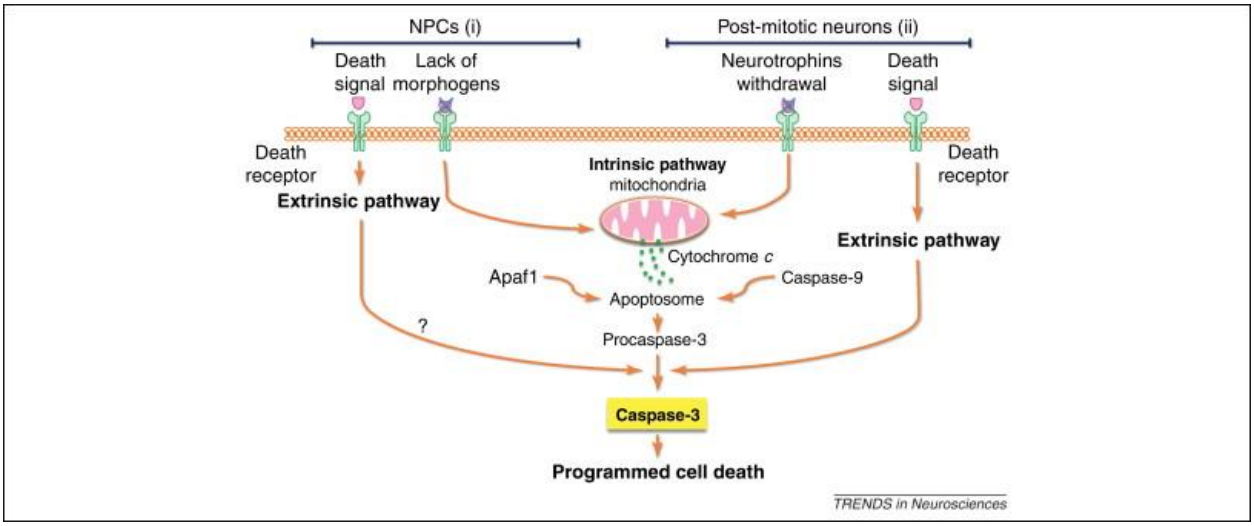


Figure 5: Bio-signaling pathway leading to chondrocyte death following impaction. Mechanoreceptors initiate a signal cascade ultimately activating executioner caspases and leading to apoptosis [11].

This mechanism was discovered in a study to assess the effects of impaction on chondrocyte viability during OCA transplantation. In this study, grafts were taken from the distal aspect of the femoral head and inserted into their recipient sites. Additional grafts were taken from each donor knee and used as controls. The grafts were assessed after forty-eight hours, and the impacted grafts had an average of 47% greater cell death, particularly on the superficial layer of the cartilage (Figure 6). The impacted grafts showed increased levels of caspase 3 activity which is a known enzyme involved in programmed cell death [11].

A separate study was conducted to assess the optimal ratio between the number of impacts, and the total force required for graft implantation. Allografts were impacted with 37.5, 75, 150, and 300 N loads 74, 37, 21, and 11 times respectively. One unimpacted allograft was kept as a control. The researchers found a direct relationship between cell viability and the force to strike ratio: lower impulses with more strikes yielded higher cell viability. The unimpacted control allograft had little to no cellular death [12]. This study demonstrated that graft impaction forces during OCA are deleterious to chondrocyte viability.

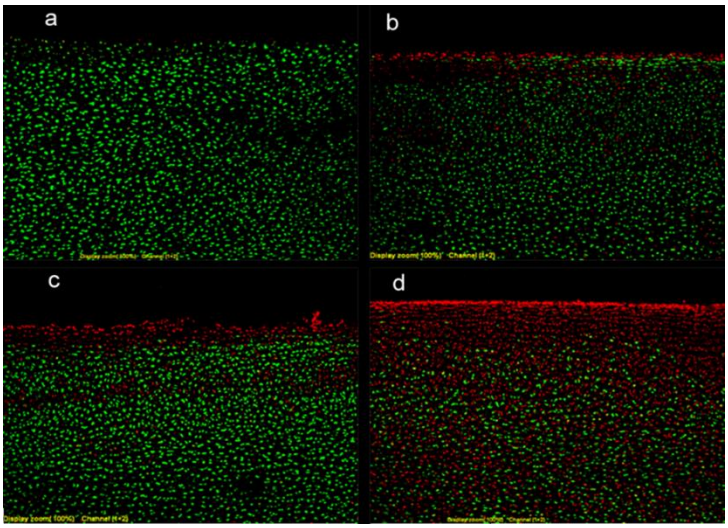


Figure 6: Live/dead chondrocyte cell staining following impaction at varying loads. Red indicates cell death; green indicates viable cells. (a) control (b) 75 N (c) 150 N (d) 300 N [12].

The effects of impaction on chondrocyte viability is an important medical concern for this procedure as chondrocyte viability at the time of impaction is the primary determinant of allograft success. A study was performed in canine models to assess the effects of chondrocyte viability at the time of impaction on allograft success. Subjects received an osteochondral allograft and graft cell viability was assessed at the time of impaction where viability ranged from 23-99%. Six months post-surgery, procedural success was compared to initial chondrocyte viability. The researchers found that no graft with an initial chondrocyte viability below 70% was successful [2]. While other factors contributed to procedural success, none were as significant as initial chondrocyte viability.

Required Project Research

Threaded Graft Mechanical Integrity

Given the novel method of using a threading system to secure the graft into the patient, it is critical to characterize its mechanical strengths and ensure that the graft will not fail unexpectedly. In this case, the graft is usually unsupported at the bottom of the hole—this space is left to afford the surgeon a degree of adjustment to the vertical graft placement. Consequently, the only portion of the graft supporting tibiofemoral contact forces is the thread. Given contact forces applied to the axis of the graft, the threads are most likely to experience shear-stress failure.

Shear stress at the threads can be modeled based on the applied axial compressive load, and the geometry of the thread [13]. In this case, the thread shear area (AS_S in mm^2) is related the length of engagement (LE); thread pitch (p); the maximum minor diameter of the internal thread (D_{1max}); and the minimum pitch diameter of the external thread (d_{2min}) (Equation 1). The diameter and pitch specifications are easily gathered from a table of thread dimension standards for each given thread size [14].

$$AS_s = \frac{\pi * LE * D_{1max}}{p}\left[\frac{p}{2} + 0.57735\left(d_{2min} - D_{1max}\right)\right] \quad (1)$$

Shear stress *V* can be calculated by dividing the thread shear area by the applied force *F* (Equation 2).

$$V = \frac{F}{AS_s} \tag{2}$$

The applied force F was estimated based on numerous assumptions of extreme loading circumstances. The graft was assumed to have been placed on the femoral condyle and sitting proud of the surface so that it bears the entirety of any tibiofemoral contact force. Such forces have been found to exceed 6.2 body-weights during large loading activities such as stair climbing [15]. Assuming the individual weighs 150-pounds (667 N), this corresponds to a simulated tibiofemoral contact force of over 4100 N.

Given that F = 4100 N, the shear stress V was calculated for numerous graft sizes from 10-25 mm encompassing the most common sizes of osteochondral allografts across typical graft insertion depths (represented by the length of engagement LE in the equation). The results were plotted in Figure 7.

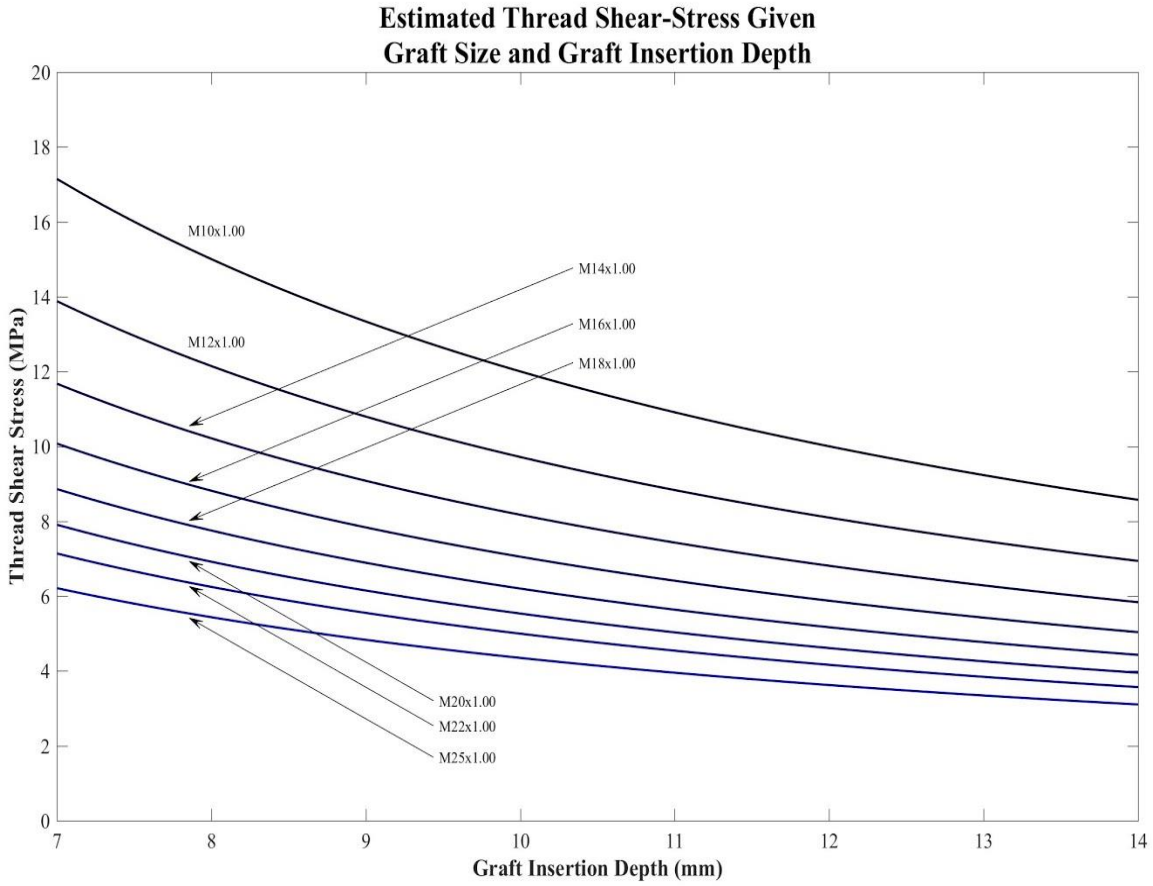


Figure 7: Plot of thread shear stress with various thread geometries varying with graft insertion depth. The simulated load comes from a 150-pound individual climbing stars generating a tibiofemoral contact force of 4100 N.

Cortical bone, such as that present surrounding the receiving hole for an osteochondral allograft, can support a shear stress of approximately 50 MPa [16]. Given the results of the simulation in Figure 7, shear stress in the smallest graft (a 10-mm graft with an M10x1.00 thread)

at the minimum insertion of 7-mm only experiences a shear stress of 17 MPa—this is well below the prescribed failure criterion of 50 MPa. Given the extreme (and very unlikely) loading parameters described in this simulation, the contact forces acting directly on the graft will result in shear stress far below the failure stress. Ultimately, these data indicate that the graft can readily support moderate loads until the donor bone can integrate with native bone and reform a solid foundation.

FDA Manual Orthopedic Device Standards

The U.S. Food and Drug administration outlines medical device regulations in CFR Title 21- Subchapter H [17]. There are particular exemptions to the requirement of sending premarket notifications to the FDA, provided that the device has existing characteristics of commercially distributed devices of that generic type [18]. In the case of intention to use a device for a different purpose than that of pre-existing devices of the same type, notification is still required. In addition, a modified device operating on a different fundamental technology requires notification of the FDA. For the purposes of manual orthopedic surgical instruments, exemptions apply in the same manner, so long as they are classified within a particular group, as well as adhere to specific limitations [19]. A generic device, such as a bone tap with minor modifications, would likely necessitate little regulation, and perhaps qualify for exemption, in contrast to a novel instrument for threading donor tissue.

Surgical Instrument Material Standards

Various grades of stainless steel are used in biomedical applications. Corrosion resistance is an essential aspect of any surgical instrument. The International Organization for Standardization (ISO) specifies metals commonly used to manufacture standard surgical instruments [20]. There are many alloys of stainless steel available, however martensitic alloys are generally chosen for surgical instruments, due to its substantial hardness [21]. This grade of surgical steel meets the requirements of ISO product standards, passing corrosion tests based on the methods of sterilization normally encountered by these products (i.e. autoclaving) [22].

Client Information

Dr. Brian Walczak is a faculty member at the University of Wisconsin School of Medicine and Public Health. Dr. Walczak is an orthopedic surgeon specializing in sports medicine, pediatric sports medicine, and joint preservation. He is experienced with the OCA procedure and proposed the mechanism of a screw-in graft to address numerous shortcomings.

Design Specifications

A device will be developed for orthopedic surgeons performing osteochondral allograft transplantation and allow them to thread the donor graft and corresponding recipient site. The chief aim of the system is to improve chondrocyte viability (compared to current impaction methods) which has a positive relationship with procedure success. The procedure for threading the graft into the donor site should be easy for the surgeon and should integrate with the current surgical technique. Ideally, the system will require minimum skilled input from the surgeon to prevent avoidable errors. The entire system must be easily sterilizable, and operable in a surgical environment. For more detailed product specifications, refer to Appendix A.

Preliminary Designs

Suction Cup

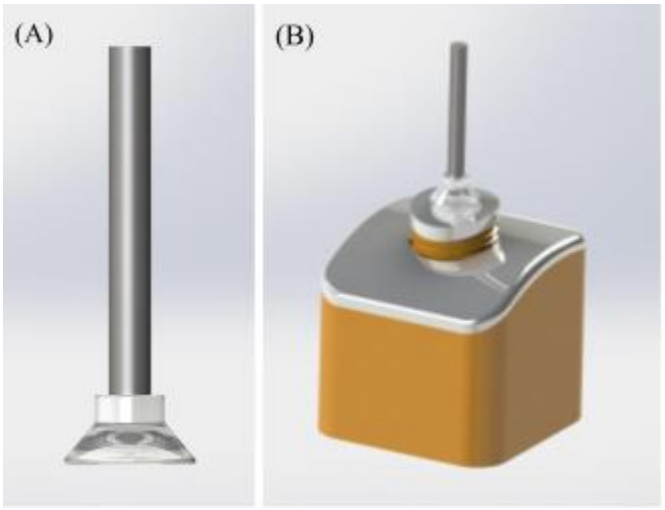


Figure 8: (A) Isometric view of the suction cup design; (B) Suction cup design interfaced with the graft as it is screwed into the recipient site.

A suction cup would permit graft insertion by attaching to the superficial surface of the allograft, directly on the cartilage, presumably without damage. Assuming the suction force was sufficient to screw the allograft into place, this would allow for an easy tightening of the allograft without physically damaging the cartilage. However, there are no studies relating the effects of a suction-force to chondrocyte viability, so outcomes are uncertain. Another major concern is the ability of the small suction cup to effectively grip the allograft and provide enough torque to insert the graft. These two major concerns led to this design scoring relatively poorly in the design matrix.

Trident

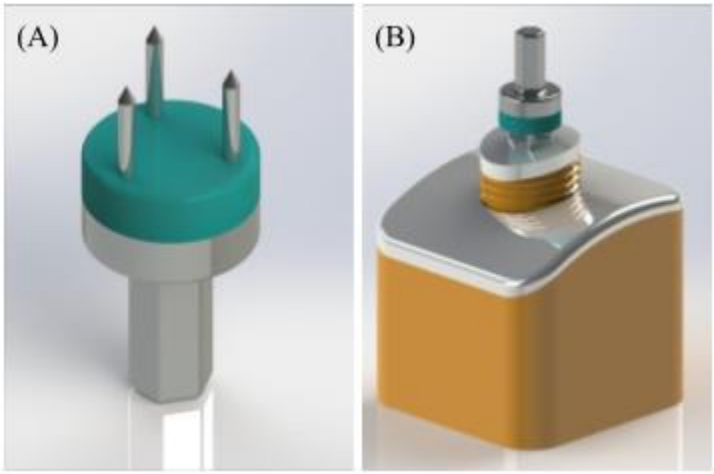


Figure 9: (A) Isometric view of the trident design; (B) Trident design interfaced with the graft as it is screwed into the recipient site.

The trident design—akin to a "specialized" screwdriver-- consists of three sharp tines that would be lightly tapped into the allograft until reaching bone. Between the metal plate at the cartilage surface is a disposable silicone cap which protects the cartilage from the metal back plate should the surgeon insert the tines too deep. Once inserted, it functions as any traditional screwdriver and inserts the allograft into place. Although this design does pierce the cartilage, the tines are extremely small and are comparable to wires used to secure large OCAs and can be viewed as an extension of a current technique [23]. Regardless, we believe that the tines will not affect the resulting chondrocyte viability. One concern with this design includes the fact that, the tines may have a chance of bending or breaking if a significant force is placed on them. Having few drawbacks, this design scored well in the design matrix.

Tweezers

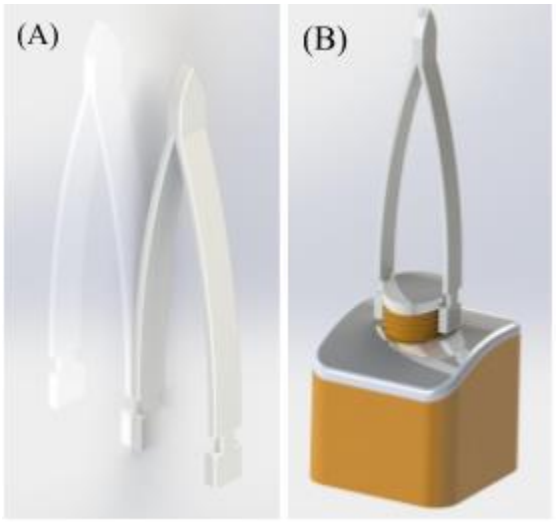


Figure 10: (A) Isometric view of the tweezers design; (B) Tweezers design interfaced with the graft as it is screwed into the recipient site.

An ideal design might be one that never contacts the delicate cartilage at all; thus, the tweezers were envisioned to grasp the subchondral bone without touching the articular cartilage. The tips of the tweezers are thin sheets consisting of many small pins. These pin-filled sheets will be made from a biocompatible polymer so that the tips would break off and be left attached to the bone to degrade into the body. This allows for the bulk of the tweezers to be detached and removed, leaving the allograft secured in place. A few daunting issues became evident: first, it would be very difficult to manufacture pins and their supporting sheet to be small enough to not significantly increase the graft's diameter, yet strong enough to not fracture under torsion. Furthermore, it was anticipated that a bioresorbable component would massively complicate the project. These concerns ultimately detracted from the tweezers' overall score in the design matrix.

Preliminary Design Evaluation

Graft Screwdriver Design Matrix

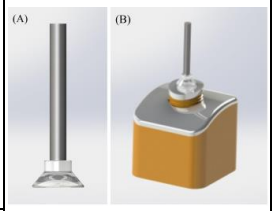
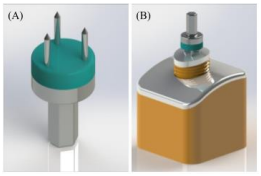
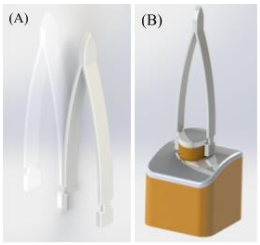
Design		Suction Cup 		Trident 		Tweezers 	
Criteria	**Weight**						
Tool Strength	20	2/5	8	5/5	20	3/5	12
Chondrocyte Viability Maintenance	20	4/5	16	4/5	16	5/5	20
Ease of Use	15	2/5	6	5/5	15	5/5	15
Procedure Time	15	3/5	9	4/5	12	3/5	9
Sterilizability	10	5/5	10	5/5	10	5/5	10
Safety	10	4/5	8	4/5	8	3/5	6
Manufacturing Time	5	4/5	4	3/5	3	2/5	2
Cost	5	4/5	4	4/5	4	4/5	4
Total	**100**		**65**		**88**		**78**

Table 1: Design matrix for the potential recipient site threading designs. Individual criteria scores are out of 5 and are weighted by each category. The highest possible score is 100. Red cells indicate the high score in each criteria category.

Design Matrix Criteria

Tool Strength (20)

The designs presented are intended to interface with a small cross section of the donor graft. Therefore, the actual interfacing mechanism must be inherently small, which increases the likelihood of premature failure. The device will experience torsional loading due to the friction of the bone threads during insertion. Therefore, the structural integrity of the device-graft interface must be maintained to properly insert the graft to the proper depth in the recipient site.

The Suction Cup design scores poorly in this category because it has an uncertain grip strength. The Suction Cup has a small profile, decreasing the potential vacuum force that is

available to grip the graft. Also, the wet surface may not produce enough friction to prevent slippage of the device as the torque is applied. The Trident device scores the best of the designs because it has rigid pins that could bend or break, but distributes the force across three pins which minimizes the possibility. The Tweezers design scored in between because the interface design offers a strong grip, but is quite thin and has a large potential to prematurely break during the procedure.

Chondrocyte Viability Maintenance (20)

Chondrocyte viability is crucial in OCA transplantation because it is a significant determinant of procedure success. Chondrocytes are sensitive to excessive loading and can be easily harmed if not handled properly. Thus, the graft screwdriver must minimize cell death and permit full graft insertion.

The Suction Cup design scores moderately well because, with initial estimations, the force applied on the graft is below typical levels seen in vivo, however, it is unknown how the suction method will affect the chondrocyte viability. The Trident method also scores moderately well because although the pins pierce the cartilage, the contact between the device and graft is small. The Tweezers design scores the best of the three designs because it interfaces with the bony portion of the graft, thus inherently protecting chondrocyte viability.

Ease of Use (15)

Surgeons have a well-established protocol for OCA transplantation. Therefore, creating a device that can easily interface with the existing procedure is ideal. This would increase surgeon comfort with the device and improve its marketability. Furthermore, a device used in the operating room must be easy to operate to decrease the risk for surgeon error when performing this surgery.

The Suction Cup design scores poorly in this category because there may be an issue with consistently applying suction. This concern is amplified if the graft has a convex shape that interferes with vacuum formation within the suction cup. The Trident design scores well because it mimics the current procedure in that it is tapped into the donor graft much like how the impacting rod inserts the graft into the patient. The Tweezers design also scores well because it is a simple tool whose function is analogous to that of a common pair of tweezers.

Procedure Time (15)

The length of the OCA procedure tends to be correlated with its overall success due to the need to maintain chondrocyte viability of the donor graft. The longer a procedure takes, which means the longer the donor graft is removed from the 37 °C storage condition to be manipulated for grafting. the lower the likelihood of a successful outcome due to diminishing chondrocyte viability [24]. Thus, it is critical to develop a device and associated procedure that will effectively screw the donor graft without a dramatic increase in procedure length. This aspect of the device is not as critical as maintaining chondrocyte viability, or easily and accurately preparing and placing the graft, and it was weighted accordingly.

The Suction Cup and Tweezers designs scored mid-tier in this category because they add additional tools to the procedure that will require a certain level of training to integrate the new method into the current procedure. The Trident design replaces the impacting rod with a three-pronged screwdriver that is interfaced in a similar way to the current method with the addition of

a screwdriver motion. Therefore, it scores the best of the three designs. However, none of these designs are expected to greatly increase the overall length of the procedure.

Serializability (10)

All tools used in a surgical setting must be sterilized. Therefore, it is necessary for the product to be sterilized for repeated use. Since sterilization is a common practice with surgical tools, it did not receive as high of a weight as some of the considerations that are more specific to this device.

All tools scored equally well in this category because the main components are made of stainless steel or aluminum, which can be easily autoclaved before each procedure. All other components are made to be disposable and will come in a sterilized container.

Safety (10)

The tools must minimize risk to both the operator and the patients. For the patient, the device should not produce damage to the area surrounding the procedure. This category was not considered to be a major factor in the design matrix because the device would be primarily a modification of current orthopedic technologies that are also subject to these guidelines. Medical devices inherently require a high level of safety and should automatically be considered with the design.

The Suction Cup design scores well in this category because although it incorporates an untested technology, the device poses little concern of stabbing, scraping or other mechanical degradation of the bone or chondral tissue. On the other hand, the Trident design does contain sharp points that could stab the patient or operator, and potentially damage the transplanted cartilage. However, it still scores well due to the small and localized characteristics of the pins. The Tweezers does not score as well as the other two designs because it involves the insertion of an additional biomaterial into the body, which would require fine tuning so that the body does not reject it. Also, there is a greater potential for the device to break during the procedure prematurely for which there is no simple way to salvage the graft.

Manufacturing Time (5)

The device must be constructible within the means of tools accessible in the COE student shop. Additionally, the team's ability to use such tools proficiently will determine the degree of manufacturability pertaining to the design. The materials chosen must be easy to work with while compatible with other requirements of our design.

The Suction Cup device scores the best of the three designs because it is made from simple plastic components that are readily available and easily assembled. The Trident design is similar, but scores slightly worse because it is made up of several small components that will require some easy, slight modification before assembly into the final prototype. The Tweezers however, scores poorly because the process of creating the miniature grappling spikes will be a long process that will require a significant time filled with trial and error.

Cost (5)

Cost does not represent a significant design constraint given that the team will only be producing a single prototype to demonstrate a *proof-of-concept.* Furthermore, this device will ultimately be used in an extremely well-funded medical field so producing an inexpensive device is not of utmost concern.

The Suction Cup and Trident devices scored equally well in this category. Both designs use simple tools that are made from cheap materials. However, in each design, there is a disposable component that requires a recurrent cost throughout the lifetime of the device. The Tweezers design scores similarly for a similar reason of a simple device made from inexpensive materials, but the startup cost of making the polymer grip pads is high, decreasing its cost effectiveness.

Proposed Final Design

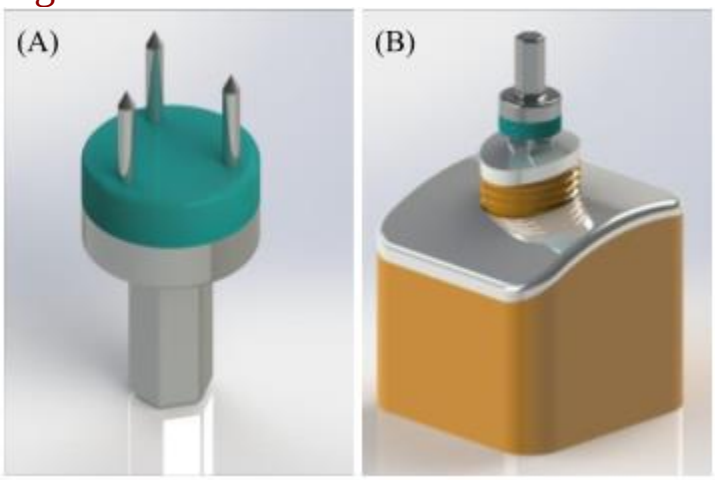


Figure 11: Proposed final design: The Trident. (A) Isometric view of the tweezers design; (B) Tweezers design interfaced with the graft as it is screwed into the recipient site.

The proposed final design for the graft screwdriver is the Trident design. Out of the three designs presented, this design has the strongest interface with the donor graft and will thus be the easiest to insert. This design can easily integrate into the current procedure because it functions similarly to the impaction rod, and it is easy to use because it attaches to a standard screwdriver handle. The additional time added to the procedure will be kept to a minimum due to the tool's easy procedure integration. Although the points are sharp and may present a small hazard, it has no more risk than other sharps found throughout an operating room. The device is made from two easily sterilizable materials: stainless steel and silicone. The stainless-steel portion lends itself to autoclaving, and the silicone is disposable and will come in pre-sterilized packages. Due to the small size of the pins, we hypothesize that there will only be localized areas of chondral damage that do not affect gross graft viability.

Development Process

Fabrication

Materials

The key material constraints in this prototype were driven by the fact that they must comply with a surgical environment. Traditionally, these include 400-series martensitic stainless steels which offer excellent strength and corrosion resistance [21]. While these alloys are the standard in surgical applications, they tend to be more expensive, harder to machine, and are more challenging to locate in appropriate sizes. Given that the team was simply making a prototype to demonstrate a proof-of-concept, scrupulous adherence to these standards was not necessary. The team decided to use 300-series stainless steel alloys which are less expensive, easier to machine, and more readily available, but still offer sufficient strength and corrosion resistance.

Methods

The prototype consists of three components: the main driver body, the stainless-steel pins, and the protective silicone cap. The stainless-steel pins were purchased pre-fabricated at an appropriate length and diameter (15.875 mm long; 1.5875 mm diameter). The pins will be sharpened on a lathe to allow them to pierce the tissue during insertion and minimize local damage.

The protective silicone cap will be made using a custom mold. The silicone comes as two liquid parts that solidify after mixing. The liquid silicone will be poured into a custom 3D printed mold that exactly matches the final dimensions of the protective cap. After pouring, the silicone and mold will be placed in a vacuum chamber to remove residual air pockets from the liquid silicone ensuring a uniform part.

The driver body will be fabricated from 303 stainless-steel rod turned to a diameter of 10 mm and a length of 20 mm on the lathe. A 15 mm portion of this 10 mm blank will be further turned down to 6.35 mm in diameter, and 15 mm in length to rough out what will become the hex-driver portion of the driver (this will allow it to be used in any standard screwdriver).

After the driver profile is roughed out on the lathe, it will be placed in a collet block to secure it in the mill. A 3/16-inch ball end-mill will be used in the CNC mill to define the standard 1/4-inch hex profile on the back of the driver. A 1.5875 mm drill bit will be used to create holes for the sharpened pins to be press-fit into the driver body. The molded silicone will then be slid over the sharpened pins, and the graft screwdriver is complete.

Testing

To test the efficacy of our prototype, we will conduct a series of comparative surgeries in porcine models obtained from the Clinical Sciences Center at the University of Wisconsin-Madison. Surgeries will be performed following the standard impaction protocol outlined above and a different set of surgeries will be performed using our new threading protocol.

A single biopsy of cartilage will be taken from the center of each impacted allograft. These biopsies are intended to be a relative sample of the gross tissue viability of impacted grafts. Two biopsies will be taken from the cartilage of the threaded graft. One will be taken from a location on the graft relatively far from where the pins were inserted. The other will be taken from a location on the graft beginning where the pins were inserted and extending radially outward. The purpose of the first biopsy is to assess the relative viability chondrocytes that were implanted by

threading. The of the second biopsy is for us to understand the profile of chondrocyte viability surrounding the pins. An additional biopsy of cartilage that has not been implanted will be taken from each of the knees. This biopsy will be used to normalize the initial tissue viability of each sample.

All biopsies will be stained with Calcein AM and Ethidium Homodimer-1. This stain is a form of a live/dead assay which is intended to characterize tissue viability. Calcein AM is a green fluorochrome that binds to the membrane of living cells and will fluoresce green when excited using confocal microscopy. Ethidium Homodimer-1 is a red fluorochrome that integrates into dead cells and will fluoresce red when excited using confocal microscopy.

All samples will then be imaged using an A1RS confocal microscope at the Wisconsin Institute for Medical Research Imaging Core. Analysis of cell viability in from these images will then be performed using ImageJ.

The motivations for our testing are two-fold. The intention of first analysis is to compare the relative viability of impacted cartilage with cartilage that was implanted using our threading protocol. We hypothesize that there will be a significant increase in the chondrocyte viability of grafts that were implanted using our threading protocol over grafts that were implanted using the standard impaction protocol. The second motivation for our testing is to understand the profile of chondrocyte viability surrounding the locations were pins that were inserted into the threaded grafts. Our hypothesis is that there will be a small layer of dead chondrocytes immediately surrounding these locations, but that chondrocyte viability will dramatically increase proportionally with respect to the radial distance from these locations.

Power stats

To calculate the significance of the testing results, a two-sided paired t-test with a significance level of $\alpha = 0.05$ will be used. The number of samples necessary to achieve significance was calculated from Equation 3.

$$n = \left(\frac{t_{\alpha/2,n-1} * \sigma}{\bar{x}}\right)^2 \quad (3)$$

In this equation, n is the number of samples, t is a test statistic obtained from a standard T-table, x is expected mean of the difference between the two groups, and σ is the standard deviation of the expected difference between the groups. From the data obtained last semester,

$x = 41.75$ and $\sigma = 3.66$. From here, a T-table can be used to find an appropriate n. Because x is large and σ is small in the previous semester data, a minimum sample size of 3 was calculated. However, considering the ease of access to viable tissue and the desire to increase confidence in our analysis, the team decided to use 6 samples in each of the four test conditions for a total of 24 samples.

Conclusion

OCA transplantation is an increasingly common procedure, particularly with the young and athletic demographics. Due to the relatively high failure rate, our client, Dr. Walczak, proposed an alternative surgical method. Our previous work was to create a threading tool system for the graft so that the surgeon could simply screw the graft into the patient. This would eliminate the force applied on the graft by the current impaction method and preserve chondrocyte viability and improving procedure success. Initial testing showed that the chondrocyte viability of our samples markedly increased over impaction; however, complete insertion of the graft into the recipient site was not attained. Therefore, a specialized screwdriver, the Trident, was designed to aid in the insertion process. This design incorporates three tines that will insert into the graft and provide torque to graft with minimal cartilage damage. The Trident is designed to interface with a standard screwdriver to provide a familiar method of screw insertion.

The efficacy of our prototype will be assessed in porcine models. There will be four sample groups of which we will test: a gross threaded group, a gross impaction group, a sample of the profile surrounding the tine insertion, and a control group for each. The chondrocyte viability of each sample will then be assayed via a live/dead stain using confocal microscopy. The aim with this testing is to gather chondrocyte viability evidence suggesting that a threading/screwing method is a viable alternative to the current OCA transplant procedure.

References

[1] S. L. Sherman, J. Garrity, K. Bauer, J. Cook, J. Stannard, and W. Bugbee, "Fresh osteochondral allograft transplantation for the knee: Current concepts," *Journal of the American Academy of Orthopaedic Surgeons*, vol. 22, no. 2. pp. 121–133, 2014.

[2] A. M. Torrie, W. W. Kesler, J. Elkin, and R. A. Gallo, "Osteochondral allograft.," *Curr. Rev. Musculoskelet. Med.*, vol. 8, no. 4, pp. 413–22, Dec. 2015.

[3] A. L. Pallante *et al.*, "Treatment of Articular Cartilage Defects in the Goat with Frozen Versus Fresh Osteochondral Allografts: Effects on Cartilage Stiffness, Zonal Composition, and Structure at Six Months," *J. Bone Jt. Surg.*, vol. 94, pp. 1984–1995, 2012.

[4] W. J. Long, J. W. Greene, and F. D. Cushner, "Early Clinical Outcomes Associated with a Novel Osteochondral Allograft Transplantation System in the Knee," *Adv. Orthop. Surg.*, vol. 2016, pp. 1–6, Mar. 2016.

[5] W. Bugbee, "Osteochondral Allograft Transplantation: Clinical Outcome and Return to Sport," *Aspetar Sport. Med. J.*, pp. 246–251, 2016.

[6] Zimmer Inc., "Zimmer Chondrofix Osteochondral Allograft: Surgical Technique," 2011.

[7] DePuy Synthese Mitek Sports Medicine, "COR ® PRECISION TARGETING SYSTEM Repair of Osteochondral Defects in Canines."

[8] W. D. Bugbee, A. L. Pallante-Kichura, S. Görtz, D. Amiel, and R. Sah, "Osteochondral allograft transplantation in cartilage repair: Graft storage paradigm, translational models, and clinical applications," *J. Orthop. Res.*, vol. 34, no. 1, pp. 31–38, Jan. 2016.

[9] G. I. Drosos and J. L. Pozo, "The causes and mechanisms of meniscal injuries in the sporting and non-sporting environment in an unselected population," *Knee*, vol. 11, pp. 143–149, 2004.

[10] J. C. Garrett, "Allograft OATS ® Resurfacing Technique for Articular Cartilage Restoration," Atlanta, 2016.

[11] B. H. Borazjani *et al.*, "Effect of Impact on Chondrocyte Viability During Insertion of Human Osteochondral Grafts," *J. Bone Jt. Surg.*, vol. 88, no. 9, p. 1934, Sep. 2006.

[12] R. W. Kang, N. A. Friel, J. M. Williams, B. J. Cole, and M. A. Wimmer, "Effect of Impaction Sequence on Osteochondral Graft Damage: The Role of Repeated and Varying Loads," *Am. J. Sports Med.*, vol. 38, no. 1, 2010.

[13] J. Bickford and S. Nassar, *Handbook of Bolts and Bolted Joints*. New York: Marcel Dekker, Inc., 1998.

[14] Maryland Metrics, "Maryland Metrics Thread Data Charts," 2014. [Online]. Available: http://burovik.biz/Metricthread.pdf. [Accessed: 05-Oct-2017].

[15] W. R. Taylor, M. O. Heller, G. Bergmann, and G. N. Duda, "Tibio-femoral loading during human gait and stair climbing," *J. Orthop. Res.*, vol. 22, no. 3, pp. 625–632, May 2004.

[16] C. H. Turner, T. Wang, and D. B. Burr, “Shear strength and fatigue properties of human cortical bone determined from pure shear tests.,” *Calcif. Tissue Int.*, vol. 69, no. 6, pp. 373–8, Dec. 2001.

[17] U.S. Food & Drug Administration, *Part 888 Orthopedic Devices*. 2017.

[18] *Limitations of exemptions from section 510(k) of the Federal Food, Drug, and Cosmetic Act (the act)*. Silver Spring, 2017, p. Part 888; Subpart A; Sec. 888.9.

[19] *Orthopedic manual surgical instrument*. 2017, p. Part 888; Subpart E; Sec. 888.4540.

[20] International Organization for Standardization, “ISO 7153-1:2016(en), Surgical instruments — Materials — Part 1: Metals,” 2016. [Online]. Available: https://www.iso.org/obp/ui/#iso:std:iso:7153:-1:ed-3:v1:en. [Accessed: 10-Oct-2017].

[21] KCI Publishing, “Stainless Steel and its Families,” 2017. [Online]. Available: http://www.stainless-steel-world.net/basicfacts/stainless-steel-and-its-families.html. [Accessed: 10-Oct-2017].

[22] T. Newson, “Selection of stainless steels for surgical instruments,” *2017*. [Online]. Available: https://www.bssa.org.uk/topics.php?article=132. [Accessed: 10-Oct-2017].

[23] G. C. Gracitelli, G. MMeric, P. A. Pulido, J. C. McCauley, and W. D. Bugbee, “Osteochondral Allograft Transplantation for Knee Lesions after Failure of Cartilage Repair Surgery,” *Cartilage*, vol. 6, no. 2, pp. 98–105, 2015.

[24] J. Chahal *et al.*, “Outcomes of Osteochondral Allograft Transplantation in the Knee,” *Arthrosc. J. Arthrosc. Relat. Surg.*, vol. 29, pp. 575–588, 2013.

Appendix

Appendix A: Product Design Specifications

Osteochondral Graft Threading System
Product Design Specifications

Team: Alex Teague
Mark Austin
David Fiflis
Zach Wodushek

Function: Osteochondral allografts (OCAs) are used to repair chondral defects in young, active patients. The current procedure involves cutting the graft from cadaveric tissue, then using impaction to drive the graft into a low-clearance receiving hole drilled over the defect. The large impulse associated with graft impaction often leads to decreases in grafted chondrocyte viability, and negatively affects procedure outcomes [1]. To avoid deleterious impaction, we created a screw-in system which taps the patient receiving site and threads the donor graft allowing the graft to be screwed into the patient. Initial testing revealed that this new system has significantly higher implanted chondrocyte viability when compared to the impaction protocol. While this method increases chondrocyte viability, it is challenging to screw the graft flush with the native host tissue. Thus, the aim is to develop an OCA screwdriver that allows the surgeon to fully insert the graft and align it with the native tissue.

Client Requirements

1. The tool must allow graft insertion and removal from the recipient site so graft depth can be adjusted.
2. The tool must permit a graft height offset from native tissue of no more than ±1.0mm.
3. After graft preparation and insertion, chondrocyte viability must be consistently greater than 70%, which has been shown to be a threshold to successful graft integration [1].
4. The entire system must be sterilized before use in surgery.
5. The tool must be quick to use, and easy to learn so as not to drastically alter the current surgical practice.
6. Damage to the chondral surface must be no greater than what presently occurs during OCA transplantation.

Design Requirements

1. **Physical and Operational Characteristics**
    1. **Performance Requirements**
        1. Threading the graft and receiving site should not damage the articular cartilage
            1. It should limit gouging, scratching, and other mechanical alterations to the native, or graft cartilage.
            2. It should not result in significant chondrocyte death after use

2. Insertion of the graft must be easily executed to minimize the risk of tissue damage.
3. During the procedure, the graft should be easy to insert and remove allowing the surgeon to adjust the graft depth.
4. The tool must be easy to secure to and remove from the graft.

2. **Safety**
    1. The delivery system should not increase the chances of postoperative complications, including (but not limited to) infection, tissue death, or graft dislocation.
    2. Long term, the graft must not lead to an associated cartilage disorder, significant fissuring or fibrous tissue infiltration, or improper tissue integration.
3. **Accuracy and Reliability**
    1. The device should allow for successful graft integration into the recipient site. This means that the procedure should maintain at least 70% chondrocyte viability after implantation.
    2. The device should include a protocol to match the contour of the donor plug and recipient site that results in a height differential no greater than ±1.0 mm.
4. **Life in Service**
    1. Non-disposable components must be serializable to allow for repeated use
    2. Life of device materials will vary depending on chosen stainless steel alloy.
    3. Disposable components should be minimized in the design to prevent excessive recurring costs.
5. **Shelf Life**
    1. Capable of storage at room temperature.
    2. Must be compliant with hospital regulations of storage.
    3. Shelf life is not likely to present as a significant design consideration.
6. **Operating Environment**
    1. Tool use must not compromise sterility of the device or surgical field.
    2. Must function within range of operating room temperatures, in addition to *in vivo* conditions.
    3. Must be usable in concurrence with all other orthopedic tools and materials.
7. **Ergonomics**
    1. The device must be designed for comfortable handheld use by the orthopedic surgeon during the procedure.
    2. To promote easy rotation, the tool must be easy to locate over the central-axis of the graft.
8. **Size**
    1. Tools will be appropriately sized for handheld usage by orthopedic surgeon.
    2. The device should accommodate bone graft sizes must range between 10 mm - 25 mm in diameter and 7 mm - 12 mm deep.
9. **Weight**
    1. Since the device will be hand-held, its ultimate weight should not be so heavy that it is cumbersome, nor should it fatigue the surgeon during use.

10. **Materials**
    1. All materials must pass ISO regulations to corrosion resistance and excessive wear from use [2]–[4].
    2. Tools involved in the procedure must be sterilizable or disposable.
11. **Aesthetics**
    1. Aesthetics will serve as a secondary initiative to the function of the final product.

1. **Production Characteristics**
    1. **Quantity**
        1. One prototype capable of inserting the graft into the patient.
            1. The prototype may have more than one component.
    2. **Components**
        1. The final product must consist of a mechanism for inserting the graft into the recipient hole.
            1. The tool must interface with the graft to prevent slip during rotation for insertion.
            2. Must have a handle for the surgeon to grasp during use.
2. **Miscellaneous**
    1. **Standards and Specifications**
        1. The final product must comply with the FDA standard for manual surgical instruments as stated by CFR 21 - Subchapter H - Medical Devices [5]
    2. **Customer**
        1. Orthopedic surgeons implanting an osteochondral allograft
    3. **Patient Related Concerns**
        1. Decreasing chondrocytes cell viability leads to diminished graft integrity.
        2. Unwanted debris and fragments of the graft may be released into the synovial fluid environment and cause other complications.
    4. **Current Systems**
        1. Arthrex Osteochondral Allograft Transfer System (OATS). This system is the prototypical system used in osteochondral transplant procedures (and is most like the system Dr. Walczak uses). It uses a sizing guide, guide wire, and cannulating reamer to size, locate, and ream the chondral defect. The allograft is prepared using the hole saw which is guided by a manually held ring. The impaction rods forces the graft into the receiving hole [6].
        2. Zimmer Chondrofix Osteochondral Allograft. This system uses a hollow punch hammered into the bone to guide the drill bit during receiving site preparation. There is no need to prepare an allograft since it comes with a pre-made, decellularized allograft that fits precisely in the hole created by the punch and drill bit. The graft is inserted most of the way using the insertion tool and is pounded in the reminder of the way using an impaction rod [7].
        3. COR Precision Targeting System. This is the only surgical system that claims to address chondrocyte viability concerns associated with OCA transplantation. The tool encloses the graft during harvesting and insertion to protect it from mishandling. The surgical guide also claims to use “low

impaction insertion" but does not describe how impaction forces are minimized relative to traditional tools. Despite the promise with the system, it is not currently in use in human OCA transplantation. [8]

4. There are no direct competitors, and of the ones currently in use, all rely on graft impaction.

References

[1] B. H. Borazjani *et al.*, "Effect of Impact on Chondrocyte Viability During Insertion of Human Osteochondral Grafts," *J. Bone Jt. Surg.*, vol. 88, no. 9, p. 1934, Sep. 2006.

[2] International Organization for Standardization, "ISO 7153-1:2016(en), Surgical instruments — Materials — Part 1: Metals," 2016. [Online]. Available: https://www.iso.org/obp/ui/#iso:std:iso:7153:-1:ed-3:v1:en. [Accessed: 10-Oct-2017].

[3] T. Newson, "Selection of stainless steels for surgical instruments," *2017*. [Online]. Available: https://www.bssa.org.uk/topics.php?article=132. [Accessed: 10-Oct-2017].

[4] KCI Publishing, "Stainless Steel and its Families," 2017. [Online]. Available: http://www.stainless-steel-world.net/basicfacts/stainless-steel-and-its-families.html. [Accessed: 10-Oct-2017].

[5] U.S. Food & Drug Administration, "CFR - Code of Federal Regulations Title 21," 2017. [Online]. Available: https://www.accessdata.fda.gov/scripts/cdrh/cfdocs/cfcfr/CFRSearch.cfm?CFRPart=888. [Accessed: 17-Oct-2017].

[6] W. Bugbee, "Osteochondral Allograft Transplantation: Clinical Outcome and Return to Sport," *Aspetar Sport. Med. J.*, pp. 246–251, 2016.

[7] Zimmer Inc., "Zimmer Chondrofix Osteochondral Allograft: Surgical Technique," 2011.

[8] DePuy Synthese Mitek Sports Medicine, "COR ® PRECISION TARGETING SYSTEM Repair of Osteochondral Defects in Canines."

Appendix B: Fabrication and Testing Material Expenses

Use	Product	Part Number	Supplier	Link	Quantity	Unit Price	Total Price
Die Platform Support Rods	1/4" Pin Diam, 3" Pin Length, Grade 416, Precision Dowel Pin	88231923	MSC Industrial Direct Co., Inc.	https://www.mscdirect.com/product/details/88231923	5	$ 2.86	**$ 14.30**
Threaded Tap	Rod,SS,303, 3/4 In Dia x 1 Ft L	2EWZ5	Grainger	https://www.grainger.com/product/GRAINGER-APPROVED-Rod-2EWZ5?breadcrumbCatId=17071&s_pp=false&picUrl=//static.grainger.com/rp/s/is/image/Grainger/2EWZ4_AS01?$smthumb$	1	$ 9.80	**$ 9.80**
Tap/Die Handle	Rod Stock,SS, 1 ft. L,3/8 in. dia.	48KU26	Grainger	https://www.grainger.com/product/GRAINGER-APPROVED-Rod-Stock-48KU26?breadcrumbCatId=17071&s_pp=false&picUrl=//static.grainger.com/rp/s/is/image/Grainger/2EYA2_AS01?$smthumb$	1	$ 4.05	**$ 4.05**
Die Tube	Rod,SS,304, 1 In Dia x 1 Ft L	2EXG5	Grainger	https://www.grainger.com/product/GRAINGER-APPROVED-Rod-2EXG5?breadcrumbCatId=17071&s_pp=false&picUrl=//static.grainger.com/rp/s/is/image/Grainger/2EWZ4_AS01?$smthumb$	1	$ 17.15	**$ 17.15**

Die Base	3/4" {T} x 3-1/2" {W} x 18" {L} 6061-T6511 Aluminum Flat, Extruded	N/A	Speedy Metals	https://www.speedymetals.com/pc-2307-8351-34-x-3-12-6061-t6511-aluminum-extruded.aspx	1	$ 24.45	**$ 24.45**
Trident pins	Unhardened Ground Stainless Steel Dowel Pin, Passivated Finish, 5/8" L, 0.0311 to 0.0313" Pin Dia.	5EDX8	Grainger	https://www.grainger.com/product/GRAINGER-APPROVED-Unhardened-Ground-Stainless-5EDX8	5	$ 0.74	**$ 3.70**
Pins	Unhardened Ground Stainless Steel Dowel Pin, Passivated Finish, 5/8" L, 0.0623 to 0.0625" Pin Dia.	5EDZ1	Grainger	https://www.grainger.com/product/GRAINGER-APPROVED-Unhardened-Ground-Stainless-5EDZ1	5	$ 0.73	**$ 3.65**
Graft Secure tool	Thumb Screw, Knurled, 10-32 x 1 1/2 L	5RA86	Grainger	https://www.grainger.com/product/GRAINGER-APPROVED-Thumb-Screw-5RA86	2	$ 5.60	**$ 11.20**
					Material Total:		**$ 88.30**
					Tax:		**$ 6.88**

					S & H		**$ 39.35**
					Total Expense:		**$ 134.53**

Table 1: Complete list of all materials used to make the prototype. Total project expenses are $134.53.