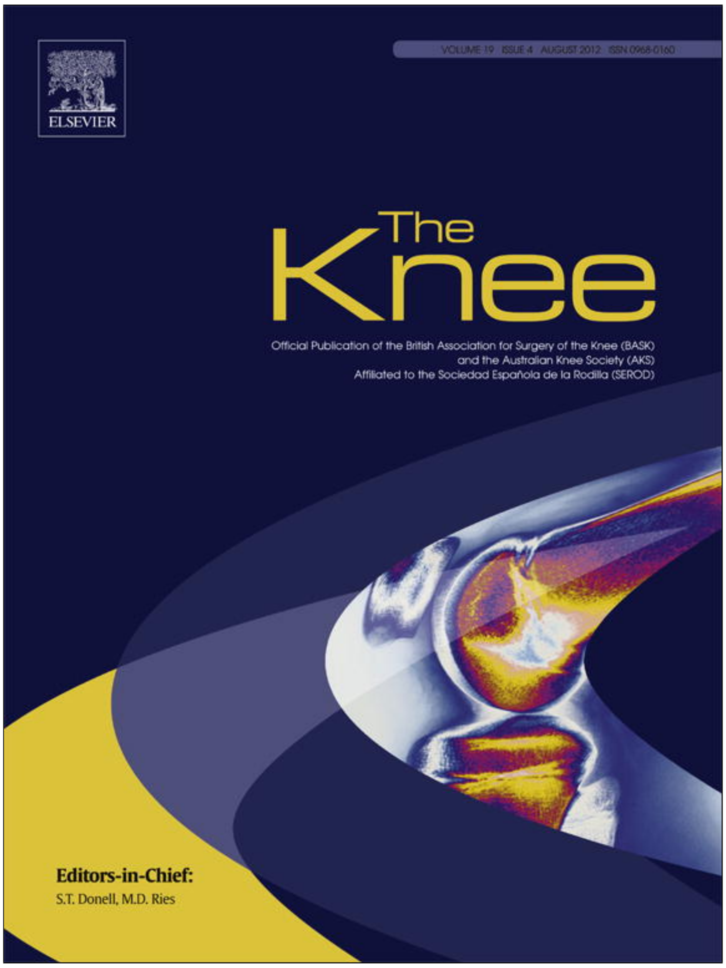
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Evaluation of a one-stage ACL revision Technique using bone void filler after cyclic loading ☆

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ABSTRACT

Background: Revision anterior cruciate ligament (ACL) reconstruction often requires a two-stage approach. This study analyzes the biomechanical properties after cyclic loading of a one-stage ACL revision technique using a calcium phosphate bone cement.
Methods: Arthroscopic reconstruction of the ACL was performed in 5 matched pairs of fresh–frozen cadaveric knees separated into two groups. The control group underwent a standard reconstruction with a bone-patellar tendon–bone autograft with bioabsorbable interference screw fixation. The experimental group simulated a failed reconstruction by drilling a 12 mm hole and underwent a revision after filling it with a bioabsorbable calcium phosphate bone cement. The specimens were dissected, scanned for bone mineral density, and cyclically loaded on a mechanical testing system (preload of 250 cycles of 5–75 N at 0.5 Hz followed by 10,000 cycles of 20–150 N at 1 Hz). Intact specifmens underwent a load-to-failure protocol of 50 mm/min. Ultimate load, stiffness, and modes of failure were recorded. Data was analyzed using paired t-tests.
Findings: All specimens completed the mechanical testing protocol. The control group had a mean maximum load of 471.33 N (SD 220.73 N) and the experimental group had 453.54 N (SD 152.36; $p = 0.84$). There were no statistically significant differences in maximum load or stiffness. No correlation between bone mineral density (BMD) and maximum load was found.
Interpretation: Using calcium phosphate filler in a single-stage ACL revision is biomechanically viable. Further testing of long-term incorporation of the ACL graft in an animal model, along with human clinical trials, should be performed before there is clinical acceptance of this technique.

1. Introduction

There are over 100,000 anterior cruciate ligament (ACL) reconstructions performed yearly with a success rate of approximately 90% [1,11]. Despite the many advances in technique and technology, there are still a significant number of failures due to improper tunnel placement or tunnel widening [10,26]. Revisions typically require two surgical stages: one to fill the widened or misplaced tunnels with a bone graft and another to reinsert the ACL graft. The second stage must occur at least 4 months after the first stage in order for the bone graft to be fully incorporated into the knee. This delay leaves the knee vulnerable to instability and may be detrimental to the health of the menisci [2,7,8].

The use of a calcium phosphate bone void filler to fill the widened tunnels in the tibia or femur may allow ACL revisions to be successfully completed in one stage [24]. Vaughn et al. [24] found that the mean load-to-failure of ACL grafts was similar between the calcium phosphate bone void filler group (301 N, [SD 95 N]) and control group (312 N, [SD 127 N]). They concluded that there was no significant difference in the initial fixation strength between cadaveric knees that underwent the gold standard central-third bone-patellar tendon–bone ACL reconstruction and knees that underwent ACL revision after filling a simulated enlarged tunnel with the bone void filler.

However, before the clinical use of this technique is accepted, more rigorous testing of the bone filler, such as cyclic loading, must be conducted. The purpose of this study is to evaluate the fixation strength of calcium phosphate bone void filler for ACL revision surgery using a cyclic loading *in situ* human cadaveric knee model.

☆ All authors were fully involved in the study and preparation of the manuscript and that the material within has not been and will not be submitted for publication elsewhere.

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2. Methods

2.1. Surgical procedure

Five pairs of fresh–frozen cadaveric knees were obtained as matched pairs. The specimens had no history of knee surgery and had no evidence of severe osteoarthritis. Individual knees from each pair were randomized to either the control or experimental group. Four of the specimens were female, one was male, and the mean age was 54.6 years (range of 23–88 years). Specimens were thawed approximately 24 h before any use, and were otherwise stored at −20 °F.

From each specimen, autologous bone-patellar tendon–bone grafts were harvested from the central 10 mm of the patellar tendon with 10 mm by 30 mm bone blocks. The bone blocks were prepared with rongeurs without crimping, and standard transosseous sutures were placed through two drill holes for eventual graft passing.

Each specimen underwent a full arthroscopic evaluation and complete resection of the native ACL. The control group underwent a standard primary ACL reconstruction with bone-patellar tendon–bone autograft. The tibial tunnel was drilled with a 10 mm cannulated drill at the center of the anatomic ACL insertion. The knee was then hyperflexed and a 7 mm over-the-top-guide (Biomet, Warsaw, Indiana) was inserted through the anteromedial portal. After a transfemoral guide wire was drilled through the guide, a 10 mm diameter femoral tunnel was drilled at the corresponding 10 o'clock or 2 o'clock position with a 1 mm back wall. A notchplasty was performed when necessary to prevent graft impingement on the sidewall and roof. With the knee in hyperflexion, the graft was inserted in the femoral tunnel and fixed with an 8 × 25 mm Lactosorb Gentle Threads (Biomet, Warsaw, Indiana) bioabsorbable interference screw. The interference screw was superolaterally placed to the bone block, compressing the graft against the posterior aspect of the bone tunnel. Finally, all the soft tissue surrounding the femur was resected, leaving just the distal femur and graft connected to the free tibial bone block.

The calcium phosphate bone void filler treatment group was designed to simulate a failed ACL reconstruction scenario due to the two most common failure modes: 1) improperly placed tunnels or 2) widened tunnels due to a wind-shield wiper effect. The surgical procedure was completed in two main steps; the first simulated a failed reconstruction that was filled with Callos Impact (Skeletal Kinetics, Cupertino, CA) and the second step was a standard revision. Instead of a 7 mm over the top guide, a 12 mm guide (Biomet, Warsaw, Indiana) and guide pin were used to center a 12 mm drill to create a femoral bone void in each test specimen that would be of reproducible size and location. This oversized, anteriorly placed hole would overlap the anticipated site for the proper anatomic reconstruction (at the 10 o'clock or 2 o'clock position). The 12 mm hole was drilled to a depth of approximately 35 mm to create a large contained bone void that would interfere with fixation at the time of revision and simulate a previously mal-positioned tunnel, a void generated from removal of prior graft or fixation materials, or from a windshield wiper effect of the graft creating a widened tunnel.

The Callos Impact (Skeletal Kinetics, Cupertino, CA) cement was prepared according to the manufacturer's recommendations for technique, timing, and insertion into the syringe. Within 1 min after mixing, the syringe was placed through the anteromedial portal with the knee in hyperflexion, and was visualized with the arthroscope. Once positioned over the void, approximately 3–5 cm^3 of filler was delivered directly into the bone void with the saline pump flow off. The filler was manually impacted into the bone void by holding pressure with a finger or bone tamp for approximately 2 min with the saline pump flow on. The knee was then placed into a plastic bag and submerged in a circulating 37 °C water bath to simulate normal body temperature for an additional 18 min for proper curing of the Callos.

The specimen was taken out of the bath after 18 min and was arthroscopically probed to demonstrate solidification. The mixing procedure, timing of incubation and method of application was determined in consultation with the manufacturer to optimize the functionality of the product. Any excess structural bone void filler was removed with a combination of simple egress of fluid through the widened portal site with 50 mmHg pump pressure inflow, minimal use of a 4.5 mm shaver with suction and arthroscopic graspers.

The next part of the procedure for the experimental specimens consisted of a revision reconstruction using the identical technique used in the primary bone-patellar tendon–bone autograft technique as described above using a 7 mm over the top guide and a 10 mm femoral tunnel. The new tunnel was placed in the correct anatomic position using a medial transportal technique through an approximate 50:50 composite of native cancellous bone and the newly implanted structural bone void filler. The graft was placed in the new tunnel with equal circumferential contact with native bone and structural filler, and then fixed with the identical 8 × 25 mm interference screw construct as in the control group. After the screw was inserted, all the soft tissue surrounding the femur was resected, leaving just the distal femur and a graft connected to the free tibial bone block. Finally, the specimens were incubated for 24 h in a circulating 37 °C water bath. All specimens were frozen again in a −20 °C freezer until mechanical testing.

2.2. Biomechanical testing

Biomechanical testing of the five pairs involved both cyclic loading and load-to-failure testing. A custom testing platform was manufactured to allow 2°. of motion along a 45° incline (Fig. 1). After thawing for 24 h, each sample was prepared by potting the specimen in a cylindrical block along the shaft with polymethylmethacrylate (PMMA) resin. The shaft of the femur had two short bicortical screws

Fig. 1. Side profile of the MTS test fixture with a potted specimen inside. The square cylinder can slide up and down the 45° incline, changing its height or depth.

placed transversely to interdigitate with the PMMA to prevent motion during testing. After each specimen block was mounted to the testing platform, the free end of the ACL graft with an intact tibial bone block was fixed to a corrugated metal clamp attached to the piston of a servohydraulic MTS Bionix 858 frame (MTS Systems, Eden Prairie, MN) (Fig. 2). The platform was carefully aligned so that the vector pull was in direct line with the femoral bone tunnel to simulate the greatest possible force on the graft [24,27]. Due to varying graft lengths for each specimen, all grafts were initially clamped with a clearance of 1 cm between the bottom of the clamp and the femoral condyle.

Each specimen was preconditioned by cyclically loading the graft under a sinusoidal load with 5 to75 N of force at 0.5 Hz for 250 cycles. This ensured stretching of the soft tissue of the graft, settling of the interference screw, and accounts for potential premature slippage [6]. If the preconditioning was successfully completed, the loading protocol shifted to a 1 Hz sinusoidal load of 20 to150 N for 10,000 cycles. To ensure the graft was hydrated, moist gauze was wrapped around the graft and was sprayed with phosphate buffered saline every 20 min.

If the graft did not fail during the cyclic loading testing, load-to-failure testing was initiated. This was similar to the protocol used in Vaughn et al. [24]. Using the same MTS setup, each sample underwent displacement-controlled loading at 50 mm/min until failure. Failure was defined as loss of fixation including pullout of the graft or interference screw, fracture of femur, or rupture of the graft. It can also be observed visually and reflected by an abrupt change in continuous force measurements from the MTS mechanical data. During the cyclic loading portion, failure was defined as greater than 4 mm translation of the graft [19].

The MTS recorded the displacement and force for various cycles during the cyclic loading portion and recorded the displacement and force at a rate of 20 Hz during the load to failure test. The force and displacement of the graft were plotted at cycle 1, 10, 100, 1000 and 10,000 as well as during the load to failure cycle.

2.3. DEXA scanning

The specimens were DEXA scanned with a Hologic QDR series scanner (Hologic, Bedford MA) in a 15 cm water bath. The specimens were scanned with the anterior side of the femur facing up and were then analyzed using a 35 × 25 pixel box that was positioned in the metaphyseal flare with the top corners of the pixel box touching cortical bone. The box enclosed the metaphyseal bone, excluding any cortical bone, and was placed to not include the femoral tunnel with the implanted graft and/or Callos. The bone mineral density (BMD) inside this box was calculated using Hologic software.

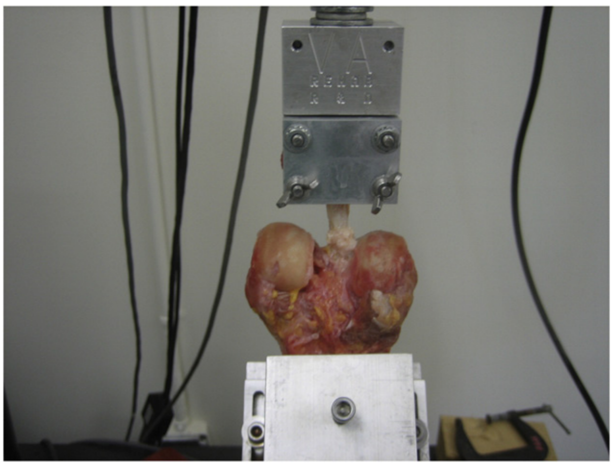

Fig. 2. Test specimen loaded onto MTS with the graft clamped to the piston.

2.4. Statistical analysis

An *a priori* power analysis based on a non-inferiority study design was conducted, using the data from Vaughn et al. [24]. Initial estimates required a sample size of 220 specimens for each group to achieve a statistical power of 80%, given an equivalence definition of 10%. With an equivalence definition of 20%, 60 specimens for each group were required. These sample sizes were not feasible due to tissue procurement issues. Though adequate power was not possible, biomechanical assessment of this technique is necessary as 1) it is important to analyze this technique, which may substantially improve current treatment strategies for ACL revision, 2) to elucidate whether additional animal studies should be performed to evaluate long-term incorporation of the bone plug–cement interface.

After the data was collected, a mixed-effects regression model was run for each cycle, comparing the stiffness calculations between the groups, which control for BMD. Furthermore, a paired t-test analyzed the difference in maximum loads between the two groups. The graft stiffness was calculated by finding a line of best fit with a R^2 value of at least 0.990 (Table 1). Significance was defined as $p \leq 0.05$. Statistical consultation was obtained through the VA Medical Center.

3. Results

All five pairs of specimen completed the entire cyclic loading protocol. The mean load-to-failure strength in the control group (471.3 N, [SD 220.7 N]) was not significantly different than the Callos experimental group (453.5 N, [SD 152.4 N]; $p = 0.85$) (Table 2). The mean difference of the maximum load was 17.8 N. Furthermore, in a head to head comparison between each pair, the experimental specimens had the higher maximum load in 2 of the 5 pairs.

During the load to failure testing protocol, eight of the ten individual specimens failed on the femoral bone block insertion side and two failed at the free tibial bone block end (Table 1). In six out of the eight femoral side failures, the femoral bone block cracked or fractured under tension, causing part of the bone block to shear past the fixation without dislodging the interference screw or damaging the implanted Callos material. During the other two failures on the femoral side, the bone block completely pulled out of the tunnel. One of these grafts pulled out the interference screw as well. Finally, the two specimens that failed at the tibial side had bone blocks that fractured inside the MTS clamp under tension. These fractures left only the soft tissue of the graft remaining, which could not be re-clamped even though the graft was still completely intact on the femoral end.

Table 2 provides demographic information, bone mineral density, and the stiffness calculations at cycles 1, 10, 100, 1000 and 10,000. The stiffness of the graft for each specimen, calculated from the slope of the Force/Displacement graph during various cycles, generally increased as the number of cycles increased. The average stiffness for the control group was 105.5, 113.6, 115.8, 124.1, and 121.9 N/mm whereas the control group had values of 96.8, 105.6, 105.8, 112.1, 120.3, and 134.5 for cycles 1, 10, 100,

Table 1
Failure mode and maximum load data for all specimens.

Specimen number	Side	Group	Failure mode	Failure cycle number	Highest load reached
1	Right	Control	Femoral bone block fracture	–	285.96 N
1	Left	Callos	Femoral bone block fracture	–	460.07 N
2	Left	Control	Femoral bone block and screw pullout		– 326.46 N
2	Right	Callos	Femoral bone block fracture	–	491.8 N
3	Right	Control	Femoral bone block fracture	–	705.59 N
3	Left	Callos	Femoral bone block fracture	–	683.07 N
4	Left	Control	Tibial bone block fracture	–	319.24 N
4	Right	Callos	Femoral bone block pullout	–	291.00 N
5	Right	Control	Tibial bone block fracture	–	719.37 N
5	Left	Callos	Femoral bone block pullout	–	342.59 N

Table 2
Demographic data and stiffness calculations for all specimens.

	Side	Age	Gender	BMD g/cm²	Stiffness (N/mm) Cycle 1	Cycle 10	Cycle 100	Cycle 1000	Cycle 10,000	Failure cycle	Maximum load recorded (N)
Control specimen #											
1	Right	54	M	0.798	94.06	101.39	102.13	108.87	102.44	135.34	285.96
2	Left	23	F	0.635	72.32	87.65	82.38	90.82	92.37	81.70	326.46
3	Right	57	F	0.714	131.26	137.53	143.64	149.34	156.67	136.52	705.59
4	Left	88	F	0.601	81.09	92.66	95.82	103.82	99.56	134.17	319.24
5	Right	51	F	0.54	148.68	148.52	154.86	167.39	158.53	170.39	719.37
Average	–	54.6	–	0.66	105.48	113.55	115.77	124.05	121.91	131.62	471.33
Callos specimen #											
1	Left	54	M	0.77	103.31	110.21	102.68	107.56	110.93	146.09	460.07
2	Right	23	F	0.617	88.57	96.17	100.79	110.61	116.15	106.80	490.99
3	Left	57	F	0.856	100.45	109.94	104.66	107.03	113.57	117.32	683.07
4	Right	88	F	0.569	101.86	114.02	115.31	121.98	134.46	164.03	291.00
5	Left	51	F	0.544	89.60	97.74	105.49	113.10	126.19	138.07	342.59
Average	–	54.6	–	0.67	96.76	105.62	105.79	112.06	120.26	134.46	453.54

1000, and 10,000, respectively. When comparing the mean stiffness calculations between the groups for each cycle, we failed to detect a statistical difference between the two groups for each cycle (Fig. 3). There was also no significant correlation between bone mineral density and stiffness or maximum load (Fig. 4).

4. Discussion

This study further augments the conclusions reached in the previous Vaughn et al. study, that the utilization of a specific calcium phosphate cement to fill defects in the femur after failed ACL reconstructions, can allow for a single stage revision reconstruction [24]. This technique allows for anatomic placement of the revision graft without sacrificing tunnel position to obtain adequate fixation. This study further demonstrates that this is accomplished without a statistically significant loss in immediate fixation strength.

Recent literature has addressed the need for alternative grafting options during revision ACL reconstructions to avoid staging this procedure. Prior studies have suggested the use of pre-formed allograft or even synthetic bone dowels to fill such bone voids [3,4]. The successful use of these strategies become limited when the bone void is large or cannot be effectively made to a cylinder shape to adequately accept the graft. However, the calcium phosphate cements, by their moldable properties, would be more amenable to filling the variably sized or shaped defects and allow for consistent anatomic tunnel placement. Ultimately, the goal is to avoid a staged reconstruction and the sequelae of continued knee instability, such as the risk of meniscal tears and pain [5,18].

This study tests the hypothesis that a single-single stage revision ACL reconstruction can be performed with the use of certain types of biocompatible bone void fillers. The calcium phosphate cements were chosen based on their demonstrated ability to remodel in a similar fashion in both cortical and cancellous bone, via an osteoclastic cell-mediated process, such that stability is not compromised during the remodeling phase [13]. Orthopaedic trauma literature has also shown the utility of this form of graft, including the augmentation of fixation in tibial plateau fractures, peritrochanteric fractures and distal radius fractures [17,23]. Animal studies have demonstrated the remodeling phase with no evidence of structural integrity loss as the graft is incorporated into the surrounding host bone [9]. While this has not yet been formally evaluated in humans, these features would make this the ideal compound for both initial and long term stability for this application.

Our described procedure is relatively straightforward and reproducible for a trained arthroscopist with proper surgical planning and adherence to the manufacturer's recommendations. This study focused its evaluation on a single form of calcium phosphate cement and as the physical and chemical properties of the various manufacturer's products vary extensively; caution should be exercised when using other compounds [13].

Our cyclic loading protocol was not identical to any protocol found in literature. We chose a load-controlled (constant force) protocol because it is more rigorous and realistic than displacement-controlled loading and controls for any elongation of the graft. A loading frequency of 1 Hz was chosen to simulate the frequency of normal

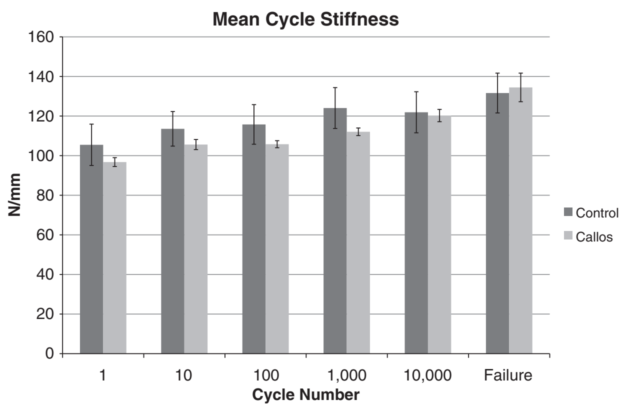

Fig. 3. Comparison of the mean stiffness calculations (in Newtons/mm) at various cycles. Error bar corresponds to standard error.

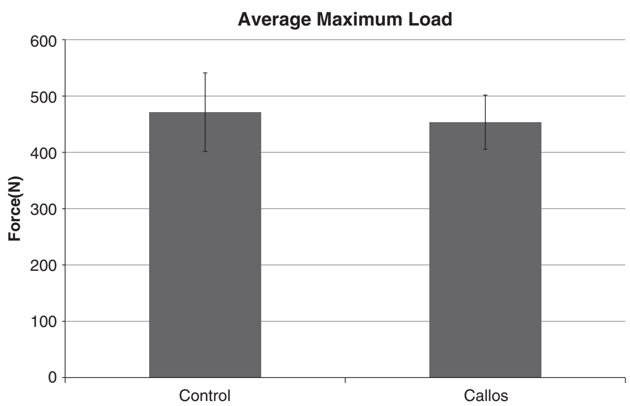

Fig. 4. Comparison of mean maximum load (in Newtons) for both groups. Error bar corresponds to standard error.

walking [14]. A lower bound of 20 N was chosen to represent a reasonable level of minimum force in the graft after pre-tensioning based on the recommendation of [20]. The upper load of 150 N was within the range of forces reported in previously published studies that cyclically loaded the ACL [12,19,25]. This magnitude was also in the range of physiologic *in situ* forces that the ACL experiences during normal walking [15,19,21,22]. Since the testing of Callos simulates the rehabilitation stage immediately after surgery before any incorporation and remodeling of the material, the force is sufficiently rigorous.

Most previous cyclic loading experiments of cruciate ligament grafts have subjected the grafts to a significantly lower number of loads [12,16,19,25,28,29]. One thousand cycles approximates one week of flexion–extension loading after an ACL reconstruction, therefore, our protocol of 10,000 cycles is a rigorous test that will be sufficient to simulate at least 2 months of walking [12,19,25].

The main limitation of our study is the inability to test more specimens, making the statistical analysis underpowered. The *a priori* power analysis conducted before the experiment using data from literature required 220 specimens for each group for 80% power, given an equivalence definition of 10%. This was not possible due to budgetary and procedural constraints and therefore a designation of equivalence between groups cannot be made. However, we did not find a statistical difference between the maximum loads or stiffness between the two groups in either the direct load to failure or cyclic load testing. Another limitation is that our experiment only tests the initial strength of the calcium phosphate filler. The key ability of the cement to be naturally reabsorbed is untested and would require a live animal model. Further studies need to be performed to evaluate the long-term incorporation of the implanted graft before clinical use.

5. Conclusion

No statistical difference was found between the single-stage ACL revision group using calcium phosphate bone void filler and the control group after cyclic loading of the ACL grafts. Further testing of long-term incorporation of the ACL graft in an animal model, along with human clinical trials, should be performed before there is clinical acceptance of this technique.

6. Conflicts of interest

No conflicts of interest are present with any of the above authors.

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References

[1] Allen CR, Giffin JR, Harner CD. Revision anterior cruciate ligament reconstruction. Orthop Clin N Am 2003;34:79–98.
[2] Anderson C, Odensten M, Good L, Gillquist J. Surgical or nonsurgical treatment of acute rupture of the anterior cruciate ligament: a randomized study with long-term follow-up. J Bone Joint Surg Am 1989;71:965–74.
[3] Barrett GR, Broan TD. Femoral tunnel defect filled with a synthetic dowel graft for a single-staged revision anterior cruciate ligament reconstruction. Arthroscopy 2007;23:796.e1–4.
[4] Battaglia TC, Miller MD. Management of bony deficiency in revision anterior cruciate ligament reconstruction using allo- graft bone dowels: surgical technique. Arthroscopy 2005;21:767.e1–5.
[5] Brown CH, Carson EW. Revision anterior cruciate ligament surgery. Clin Sports Med 1999;18:109–71.
[6] Brown CH, Sklar JH. Endoscopic anterior cruciate ligament reconstruction using quadrupled hamstring tendons and endobutton femoral fixation. Tech Orthop 1998;13:281–98.
[7] Daniel DM, Stone ML, Dobson BE, Fithian DC, Rossman DJ, Kaufman KR. Fate of the ACL-injured patient: a prospective outcome study. Am J Sports Med 1994;22: 632–44.
[8] Fetto JF, Marshall JL. The natural history and diagnosis of anterior cruciate ligament insufficiency. Clin Orthop Relat Res 1980;147:29–38.
[9] Frankenburg EP, Goldstein SA, Bauer TW, Harris SA, Poser RD. Biomechanical and histological evaluation of a calcium phosphate cement. J Bone Joint Surg Am 1998;80:1112–24.
[10] George MS, Dunn WR, Spindler KP. Current concepts review: revision anterior cruciate ligament reconstruction. Am J Sports Med 2006;34:2026–38.
[11] Getelman MH, Friedman MJ. Revision anterior cruciate ligament reconstruction surgery. J Am Acad Orthop Surg 1999;7:189–98.
[12] Giurea M, Zorilla P, Amis A, Aichroth P. Comparative pull-out and cyclic-loading strength tests of anchorage of hamstring tendon grafts in anterior cruciate ligament reconstruction. Am J Sports Med 1999;27(5):621–5.
[13] Hak DJ. The use of osteoconductive bone graft substitutes in orthopaedic trauma. J Am Acad Orthop Surg 2007;15:525–36.
[14] Honl M, Carrero V, Hille E, Schneider E, Morlock MM. Bone–patellar tendon–bone grafts for anterior cruciate ligament reconstruction. An in vitro comparison of mechanical behavior under failure tensile loading and cyclic submaximal tensile loading. Am J Sports Med 2002;30:549–57.
[15] Markolf KL, Wascher DC, Finerman GA. Direct in vitro measurement of forces in the cruciate ligaments. Part II: The effect section of the posterolateral structures. J Bone Joint Surg Am 1993;75:387–94.
[16] Markolf K, Zemanovic J, McAllister D. Cyclic loading of posterior cruciate ligament replacements fixed with tibial tunnel and tibial inlay methods. J Bone Joint Surg Am 2002;84:518–24.
[17] Moore DC, Frakenburg EP, Goulet JA, Goldstein SA. Hip screw augmentation with an in situ-setting calcium phosphate cement: an in vitro biomechanical analysis. J Orthop Trauma 1997;11:577–83.
[18] Muller W. Kinematics. In: Muller W, editor. The knee: form, function, and ligament reconstruction. New York: Springer-Verlag; 1983. p. 17–29.
[19] Nagarkatti DG, McKeon BP, Donahue BS, Fulkerson JP. Mechanical evaluation of a soft tissue interference screw in free tendon anterior cruciate ligament graft fixation. Am J Sports Med 2001;29:67–71.
[20] Numazaki H, Tohyama H, Nakano H, Kikuchi S, Yasuda K. The effect of initial graft tension in anterior cruciate ligament reconstruction on the mechanical behaviors of the femur-graft-tibia complex during cyclic loading. Am J Sports Med 2002;30: 800–5.
[21] Rupp S, Hopf T, Hess T, Seil R, Kohn DM. Resulting tensile forces in the human bone–patellar tendon–bone graft: direct force measurement in vitro. Arthroscopy 1999;15:179–84.
[22] Sakane M, Fox RJ, Woo SL, Livesay GA, Li G, Fu FH. In situ forces in the anterior cruciate ligament and its bundles in response to anterior tibial loads. J Orthop Res 1997;15:285–93.
[23] Trenholm A, Landry S, McLaughlin K, Deluzio KJ, Leighton J, Trask K, et al. Comparative fixation of tibial plateau fractures using alpha-BSM, a calcium phosphate cement, versus cancellous bone graft. J Orthop Trauma 2005;19: 698–702.
[24] Vaughn ZD, Schmidt J, Lindsey DP, Dragoo JL. Biomechanical evaluation of a one-stage ACL revision technique using a structural bone void filler for femoral fixation. Arthroscopy 2009;25:1011–8.
[25] Weiss JA, Paulos LE. Mechanical testing of ligament fixation devices. Tech Orthop 1999;14:14–21.
[26] Wetzler MJ, Bartolozzi AR, Gillespie MJ, Rubenstein DL, Ciccotti MG, Miller LS. Revision anterior cruciate ligament reconstruction. Oper Tech Orthop 1996;6: 181–9.
[27] Woo SL, Hollis JM, Adams DJ, Lyons RM, Takai S. Tensile properties of the human femur anterior cruciate ligament tibia complex. The effects of specimen age and orientation. Am J Sports Med 1991;19:217–25.
[28] Yamanaka M, Yasuda K, Tohyama H, Nakano H, Wada T. The effect of cyclic displacement on the biomechanical characteristics of anterior cruciate ligament reconstructions. Am J Sports Med 1999;27:772–7.
[29] Zantop T, Reummler M, Welbers B, Langer M, Weimann A, Petersen W. Cyclic loading comparison between biodegradable interference screw fixation and biodegradable double cross-pin fixation of human bone–patellar tendon–bone grafts. Arthroscopy 2005;21:934–41.