



Subcortical Backup Tibial Fixation in Anterior Cruciate Ligament Reconstruction Has Similar Maximal Strength to Current Techniques

Donald F. Colantonio, M.D., Rachel C. Kicklighter, B.S., Anthony H. Le, M.S., Margaret A. Nowicki, Ph.D., Matthew A. Posner, M.D., Liang F. Zhou, M.D., and Shawn M. Gee, M.D.

Purpose: To evaluate the biomechanical profile of subcortical backup fixation (subcortical button [SB]) in anterior cruciate ligament (ACL) reconstruction as compared with a bicortical post and washer (BP) and suture anchor (SA) when used with interference screw (IS) primary fixation and to evaluate the utility of backup fixation for tibial fixation with extramedullary cortical button primary fixation. **Methods:** Fifty composite tibias with polyester webbing—simulated graft were used to test constructs across 10 methods. Specimens were separated into the following groups ($n = 5$): 9-mm IS only, BP (with and without graft and IS), SB (with and without graft and IS), SA (with and without graft and IS), extramedullary suture button (with and without graft and IS), and extramedullary suture button with BP as backup fixation. Specimens were tested under cyclic loading and then loaded to failure. Maximal load at failure, displacement, and stiffness were compared. **Results:** Without a graft, the SB and BP had similar maximal loads (802.46 ± 185.18 N vs 785.67 ± 100.96 N, $P = .560$), and both were stronger than the SA (368.13 ± 77.26 N, $P < .001$). With graft and an IS, there was no significant difference in maximal load between the BP ($1,461.27 \pm 173.75$ N), SB ($1,362.46 \pm 80.47$ N), and SA ($1,334.52 \pm 195.80$ N). All backup fixation groups were stronger than the control group with IS fixation only (932.91 ± 99.86 N, $P < .001$). There was no significant difference in outcome measures between the extramedullary suture button groups with and without the BP (failure loads of 721.39 ± 103.32 N and 718.15 ± 108.61 N, respectively). **Conclusions:** Subcortical backup fixation in ACL reconstruction has similar biomechanical properties to current methods and is a viable backup fixation alternative. Backup fixation methods work synergistically with IS primary fixation to strengthen the construct. There is no advantage to adding backup fixation to extramedullary button (all-inside) primary fixation when all suture strands are secured to the extramedullary button. **Clinical Relevance:** This study provides evidence that subcortical backup fixation is a viable alternative for surgeons during ACL reconstruction.

From the Department of Orthopaedic Surgery, Walter Reed National Military Medical Center, Bethesda, Maryland, U.S.A. (D.F.C.); Uniformed Services University of the Health Sciences, Bethesda, Maryland, U.S.A. (D.F.C., M.A.P., S.M.G.); Department of Civil and Mechanical Engineering, United States Military Academy, West Point, New York, U.S.A. (R.K.K., M.A.N.); Extremity Trauma and Amputation Center of Excellence, Bethesda, Maryland, U.S.A. (A.H.L.); John A. Feagin Sports Medicine Fellowship, West Point, New York, U.S.A. (M.A.P., L.F.Z., S.M.G.); Department of Orthopaedic Surgery, Keller Army Community Hospital, West Point, New York, U.S.A. (M.A.P.); Department of Orthopaedic Surgery, Tripler Army Medical Center, Honolulu, Hawaii, U.S.A. (L.F.Z.); and Department of Orthopaedic Surgery, Fort Belvoir Community Hospital, Fort Belvoir, Virginia, U.S.A. (S.M.G.).

D.F.C. and R.K.K. contributed equally to this work and are co-first authors. The authors report the following potential conflicts of interest or sources of funding: This research was supported in part by an appointment to the Department of Defense (DoD) Research Participation Program administered by the Oak Ridge Institute for Science and Education through an interagency agreement between the U.S. Department of Energy and the DoD. The Oak Ridge Institute for Science and Education is managed by Oak Ridge Associated Universities under U.S. Department of Energy contract number DE-20

SC0014664. Additionally, funding was provided through the Stamps Charitable Foundation. The identification of specific products or scientific instrumentation is considered an integral part of the scientific endeavor and does not constitute endorsement or implied endorsement on the part of the authors, the DoD, or any component agency. The views expressed in this manuscript are those of the authors and do not necessarily reflect the official policy of the DoD or the U.S. Government. D.F.C. receives research support from Arthrex, outside the submitted work. Full ICMJE author disclosure forms are available for this article online, as *supplementary material*.

Received October 31, 2021; accepted October 10, 2022.

Address correspondence to Shawn M. Gee, M.D., Department of Orthopaedic Surgery, Fort Belvoir Community Hospital, 9300 DeWitt Loop, Fort Belvoir, VA 22060, U.S.A. E-mail: shawn.m.gee.mil@mail.mil

Published by Elsevier Inc. on behalf of the Arthroscopy Association of North America. This is an open access article under the CC BY-NC-ND license (<http://creativecommons.org/licenses/by-nc-nd/4.0/>).

2666-061X/211542

<https://doi.org/10.1016/j.asmr.2022.10.012>

Anterior cruciate ligament (ACL) rupture is among the most common injuries in active individuals, with roughly 250,000 injuries per year.¹ As a result, ACL reconstruction is one of the 10 most performed orthopaedic procedures annually.² Techniques and technology for ACL reconstruction continue to evolve, and minimizing soft-tissue graft slippage is a focus of recent advancements.^{3,4} The 2 fundamental forms of ACL graft fixation are interference fixation and suspensory fixation. In constructs that use a soft-tissue graft, tibial-sided interference screw (IS) fixation has been identified as the weak point, leading many surgeons to add a backup form of fixation.⁴⁻⁹

Although adding supplementary tibial fixation adds cost and time to the procedure, studies have found that backup fixation improves the ultimate failure load and decreases elongation of a reconstructed ACL through load sharing between the primary and backup fixation devices.^{3,9-17} There are many options for backup fixation, and 2 commonly used methods in current practice are a bicortical post and washer (BP) and a suture anchor (SA). Verioti et al.⁹ recently compared the displacement and ultimate strength of ACL grafts with a post and washer versus an SA for backup tibial fixation in a porcine study. Their study showed a higher maximal load to failure in the group with post-and-washer backup fixation compared with the SA group; however, there was no statistically significant difference between groups. Although a bicortical post offers stout suspensory fixation, it places a large washer on the medial cortex of the tibia and often leads to hardware irritation. Additionally, although a knotless SA provides low-profile fixation, it requires a large drill hole and relies on interference fixation.

Cortical suspensory buttons are another fixation option commonly used for soft-tissue fixation.¹⁸⁻²² Cortical buttons can be used in an intramedullary or extramedullary fashion through a small drill hole. In ACL reconstruction, cortical buttons are most commonly used in an extramedullary fashion on the femoral side and are becoming increasingly popular for tibial-sided fixation in all-inside constructs. Intramedullary subcortical buttons (SBs) have shown similar strength to ISs in subpectoral biceps tenodesis¹⁹ and may offer another low-profile backup fixation option in ACL reconstruction, as described by Gee et al.²³ (Fig 1).

The purposes of this study were to evaluate the biomechanical profile of subcortical backup fixation in ACL reconstruction as compared with a BP and SA when used with IS primary fixation and to evaluate the utility of backup fixation for tibial fixation with extra-medullary cortical button primary fixation. Our hypotheses were that intramedullary SB backup fixation would provide similar maximum strength and graft displacement to current techniques and that adding

supplementary fixation to an extramedullary cortical button suspensory construct would not increase the ultimate load to failure of the construct.

Methods

Specimens

Fifty composite tibia specimens (fourth-generation composite, model 3402; Sawbones, Pacific Research Laboratories, Vashon, WA) were used to test fixation techniques across 10 methods. All specimens were prepared with an anteromedial 9.5-mm drill tunnel by a single investigator (D.F.C.) using a custom 3-dimensionally printed jig for standardization. The tibias were then separated into groups according to which fixation device would be tested, with 10 groups of 5 specimens each: polyester graft with 9 × 28-mm metal IS alone (Arthrex, Naples, FL), BP alone (Bi-cortical Post and Washer; Arthrex), BP with graft and IS (IS-BP), SB alone (BicepsButton; Arthrex), intramedullary SB with graft and IS (IS-SB), 4.75-mm SA alone (SwiveLock; Arthrex), SA with graft and IS (IS-SA), extramedullary button alone (Attachable Button System [ABS]; Arthrex), extramedullary button with graft and IS (IS-ABS), and extramedullary button as primary fixation with bicortical post as backup fixation (ABS-BP). To test fixation devices without graft and an IS, two 15-cm strands of high-tensile strength suture were secured in the tibia with the fixation device of interest 2 cm distal to the tibial tunnel and were then routed through the tunnel. A 30-cm length of 2-cm-wide polyester webbing (Uline, Pleasant Prairie, WI) was used to simulate the graft. The polyester webbing was doubled over to form a loop, and the opposite end was secured with 2 strands of high-tensile strength suture (FiberWire; Arthrex) with 5 Krackow stitches each. The graft was fixed in the bone tunnel with a 9 × 28-mm cannulated metal IS except when used with the extramedullary button.

Specimens in each group were then placed in a custom 3-dimensionally printed jig, and a bicortical drill hole specific to each implant size was created in the same location, 2 cm distal to the anteromedial graft tunnel (Fig 2). In the SB group, the simulated cancellous material was removed from the anteromedial cortex with a curette to ensure that the suture button would seat appropriately.

Specimens were then mounted to the servohydraulic mechanical testing system (MTS) (858 Mini Bionix II; MTS Systems, Eden Prairie, MN) with the graft tunnel in line with the load cell and actuator. Specimens were fixed in place on the MTS to measure the initial fixation tension generated by the surgeon. A single, sports fellowship-trained investigator (XXX) assessed all tibias and performed all fixation procedures.

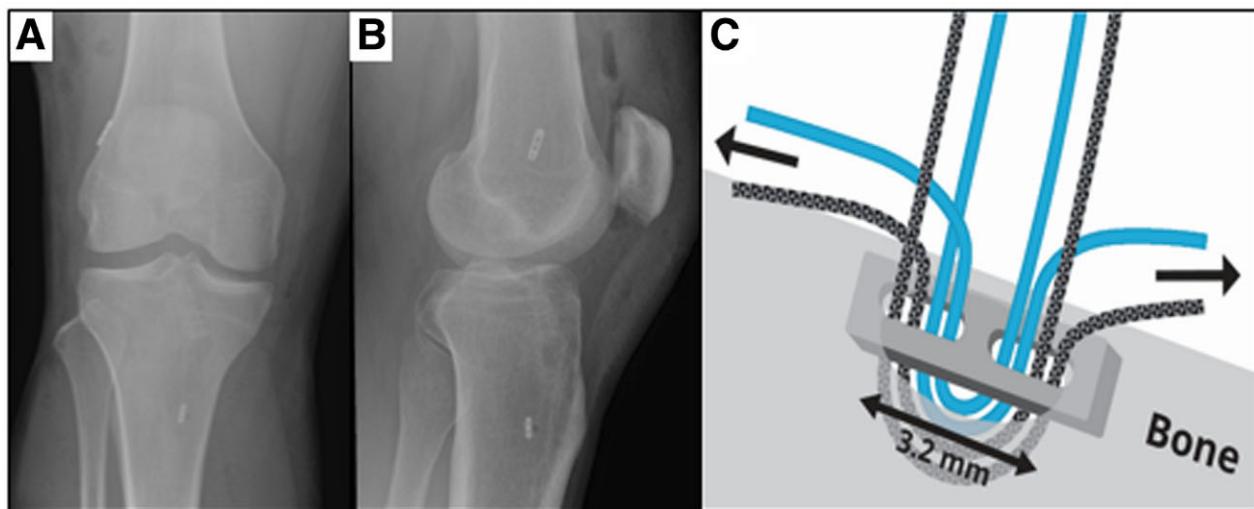


Fig 1. Anteroposterior (A) and lateral (B) radiographs of right knee after anterior cruciate ligament reconstruction with interference screw and subcortical backup fixation in tibia. (C) Subcortical backup fixation with suture strands looped through metal button and anchored to intramedullary cortex of tibia.

Biomechanical Testing

Specimens were affixed to the MTS actuator via a custom fixture and pins (Fig 3). The loose end of the graft was secured in a gripper mounted directly to the load cell in line with the MTS actuator. Specimens were preloaded at a constant 50 N in tension for 10 seconds and were then cyclically loaded from 50 to 250 N for 500 cycles at 1 Hz. After cyclic loading and a subsequent 10-second constant 50-N preload, specimens were loaded to failure at a constant longitudinal distraction rate of 5 mm/min until the load across the specimen failed to maintain 25% of the maximum load detected

throughout distraction or until the graft was completely pulled out of the tunnel. Force and displacement were continuously recorded at 102 Hz by the MTS actuator and in-line load cell throughout the cyclic loading and load-to-failure testing.

Data Reduction

Force and displacement data were filtered using a fourth-order zero-lag Butterworth filter (sampling frequency, 102 Hz; cutoff frequency, 1 Hz) and processed with custom MATLAB scripts (vR2020a; The MathWorks, Natick, MA). Cyclic displacement

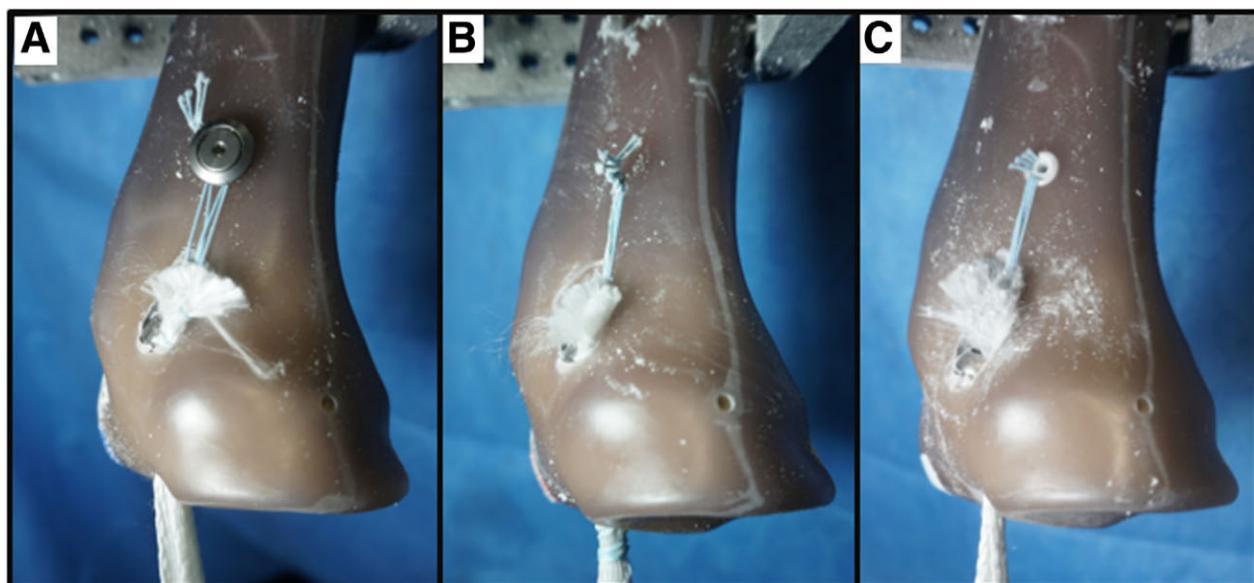


Fig 2. Examples of specimens in 3 backup fixation groups mounted to testing apparatus with tibial plateau oriented toward floor. (A) Interference screw primary fixation with bicortical post-and-washer backup. (B) Interference screw primary fixation with subcortical backup. (C) Interference screw primary fixation with suture anchor backup.

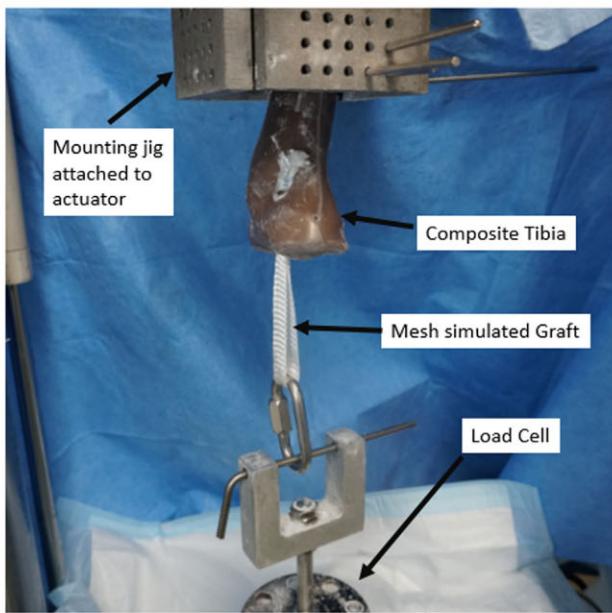


Fig 3. Biomechanical testing apparatus with composite tibia specimen mounted in custom jig. The simulated graft is secured into the bone tunnel with an interference screw and anchored to a mounting device attached to the load cell.

(in millimeters), cyclic stiffness (in newtons per millimeter), failure load (in newtons), pullout displacement (in millimeters), pullout stiffness (in newtons per millimeter), and load at 5 mm of displacement (in newtons) were determined for each specimen and then for each of the 10 groups. To calculate these metrics, initial displacement (D_0), displacement at the beginning of cyclic loading (after 1 cycle) (D_1), displacement at the end of cyclic loading (after 500 cycles) (D_{500}), and displacement at the beginning of the load-to-failure test (D_{2F}) were manually selected for each specimen (Fig 2). Maximum load at failure was extracted from the load-to-failure testing after cyclic loading. Maximum displacement was calculated from the final displacement measurement at failure and the initial displacement measurement during the brief 50-N preload that followed cyclic loading. Load at 5 mm of displacement was recorded as a second method of measuring strength at failure, where failure was defined as 5 mm of displacement. Stiffness was calculated as the slope of the linear portion (approximately one-third) of the load-displacement curve produced during load-to-failure testing. Descriptive statistics (mean \pm standard deviation) were calculated for each metric. Modes of failure included (1) suture rupture, (2) suture slippage in backup fixation, and (3) graft pullout.

Statistical Analysis

Mean failure load, displacement, and stiffness values were compared between backup fixation groups without primary fixation (no simulated graft and IS)

and those with primary fixation (with simulated graft and IS) using 1-way analysis of variance followed by Bonferroni-adjusted post hoc pair-wise comparisons. The significance level was set a priori at $\alpha = .05$. A power analysis was performed and the available sample was determined to be adequate to detect a difference of 100-N force in failure load at a power of 86%. All statistical analyses were performed with the rstatix package using R (version 4.0.2; R Foundation for Statistical Computing, Vienna, Austria) in the RStudio program (version 1.3; RStudio, Boston, MA).

Results

Backup Fixation Only

When specimens were tested without a simulated graft and IS to isolate the supplementary fixation, the SB group had a greater failure load than the SA group (Table 1). There was no significant difference in maximum failure load between the SB group and the BP or ABS group ($P > .100$). The BP construct withstood a significantly greater failure load than the ABS construct. The ABS group had a greater failure load than the SA group. Similarly, the SB construct withstood a greater force at 5 mm of displacement than the SA construct (Table 1) and was not different from the BP and ABS constructs ($P > .100$). There were no significant differences in load at failure in all other comparisons ($P > .05$).

The SA and ABS groups displayed less pullout displacement than the SB group (Table 1). There was no difference in pullout displacement between the SB and BP groups, nor was there any difference in cyclic displacement among all 4 groups ($P > .05$).

The shapes of the total force-displacement curves of the SB, BP, and ABS groups were similar; the fixation constructs behaved like brittle materials, whereas the SA behaved more like a ductile material (Fig 4). Compared with the SB group, the ABS group had greater pullout stiffness (Table 1). The ABS group had the greatest pullout stiffness of the 4 groups. There were no other significant differences in pullout stiffness values. Compared with the SB group, the BP group showed greater cyclic stiffness. The BP group also showed greater cyclic stiffness than the SA group. There was no significant difference in cyclic stiffness in the other comparisons (Table 1).

Primary and Backup Fixation

The control group with graft and an IS only as the primary fixation had a mean maximum load to failure of 932.91 ± 99.86 N. When specimens were tested with a graft, IS, and backup fixation, the SB, BP, and SA groups showed greater failure loads than the control group (IS) ($P < .001$, Table 2). There was no statistically significant difference between the IS-SB group and the

Table 1. Biomechanical Testing Results of Fixation Groups Tested Without Graft

Group	Cyclic Displacement, mm	Cyclic Stiffness, N/mm	Failure Load, N	Pullout Displacement, mm	Pullout Stiffness, N/mm	Force at 5 mm of Displacement, N
BP	4.61 ± 1.13	38.36 ± 16.86*	785.67 ± 100.95†	11.55 ± 2.87	60.49 ± 3.20†	438.78 ± 20.26
SB	6.89 ± 1.99	15.31 ± 4.43	802.46 ± 185.18	9.44 ± 2.34	60.26 ± 11.34	433.29 ± 57.73
SA	9.40 ± 5.23	13.27 ± 7.87	368.13 ± 77.26*†	5.59 ± 1.51*	45.58 ± 18.38†	337.79 ± 49.60*
Extramedullary button (ABS)	5.36 ± 1.20	20.95 ± 5.24	587.42 ± 100.39	4.96 ± 1.75*	78.38 ± 9.93*	452.90 ± 45.83

NOTE. Biomechanical outcome measures for each backup fixation device tested without simulated interference screw primary fixation are presented as mean ± standard deviation.

ABS, Attachable Button System; BP, bicortical post; SA, suture anchor; SB, subcortical button.

*Significantly different from SB group at 5% level of significance. The *P* values for comparison to the SB group were as follows: *P* = .003 for failure load, *P* = .025 for pullout displacement, and *P* = .035 for force at 5 mm of displacement in SA group; *P* = .028 for pullout displacement and *P* = .028 for pullout stiffness in ABS group; and *P* < .001 for stiffness in BP group.

†Significantly different from ABS group at 5% level of significance, with *P* = .014 for failure load in BP group, *P* = .009 for failure load in SA group, *P* = .005 for pullout stiffness in BP group, and *P* = .011 for pullout stiffness in SA group.

IS-BP or IS-SA group. The failure loads of the IS-BP and IS-SA groups were also greater than those of the IS, ABS, and ABS-BP groups (*P* = .006 for IS-SA vs. IS and *P* < .001 for all other comparisons). The control group (IS) had a higher failure load than the ABS and ABS-BP groups (Table 2). There was no significant difference between the ABS and ABS-BP groups.

The IS and IS-SA groups displayed less pullout displacement than the IS-SB and IS-BP groups (Table 2). There was no difference in displacement between the IS-SB and IS-BP groups (*P* > .05). The IS group displayed less pullout displacement than the ABS and ABS-BP groups. Cyclic displacement in the IS-SB group was lower than that in the ABS and ABS-BP groups (Table 2). The cyclic displacement values in the IS, IS-BP, IS-SB, and IS-SA groups were all lower than those in the ABS and ABS-BP groups (*P* < .05) but were not significantly different from each other.

Unlike the shape of the total force-displacement curves in the isolated SB and BP groups, the IS-SB and IS-BP constructs behaved more like ductile materials. The ABS and ABS-BP constructs still behaved as brittle materials (Fig 4). Unlike the isolated groups, the ABS and ABS-BP groups had lower pullout stiffness values than the IS-SB group whereas the IS-SA group had greater pullout stiffness. The ABS and ABS-BP groups had lower pullout stiffness values than all other groups (*P* < .001), and the ABS group had lower pullout stiffness than the ABS-BP group (*P* < .001). The IS, IS-BP, and IS-SA groups had greater cyclic stiffness values than the ABS and ABS-BP groups (*P* < .001, Table 2). There were no significant differences in any other comparisons (*P* > .05).

Modes of Failure

In 1 specimen in the SA group, failure occurred during initial cyclic loading; this specimen was excluded from the results. In addition, 1 specimen in the IS-SA group was excluded as an outlier. The most common

mode of failure was suture rupture (36 of 48 specimens) or suture slippage (8 of 48). The mode of failure for the specimens in the SA and IS-SA groups was suture slippage. The mode of failure for all specimens in the BP, IS-BP, SB, IS-SB, ABS, and ABS-BP groups was suture rupture.

Discussion

The results indicate that a subcortical suture button provides similar maximal strength to other methods of supplementary tibial fixation during ACL reconstruction. The maximum load at failure was greater than that of the isolated SA and was not significantly different from that of the bicortical post or the extramedullary button. The results indicate that the isolated SB and BP constructs have the greatest maximum failure loads, the isolated ABS construct is the next strongest, and the SA construct is the weakest. When primary fixation with a graft and IS were incorporated into the construct, the SB group again showed maximal strength similar to the BP and SA groups.

In a similar study, Veriotti et al.⁹ compared the biomechanical properties of an SA versus a bicortical post for backup ACL graft fixation with an IS in porcine tibias. They found a maximal load to failure of 1,148 ± 186 N using a bicortical post and a maximal load of 1,007 ± 176 N using the same 4.75-mm SA as in our study. These results were significantly greater than the maximal load using an IS in isolation (778 ± 139 N). Although these loads are lower than those found in our study, the trends in differences are similar in that the bicortical post and SB showed the highest failure loads and all 3 supplementary devices yielded a higher maximal load than the IS alone. In another porcine study, Kim et al.¹⁷ showed similar performance between backup fixation with a 3.5-mm screw and that with a 6-mm SA. Similarly, Walsh et al.²⁴ found that tibial ACL graft fixation with a retrograde IS was

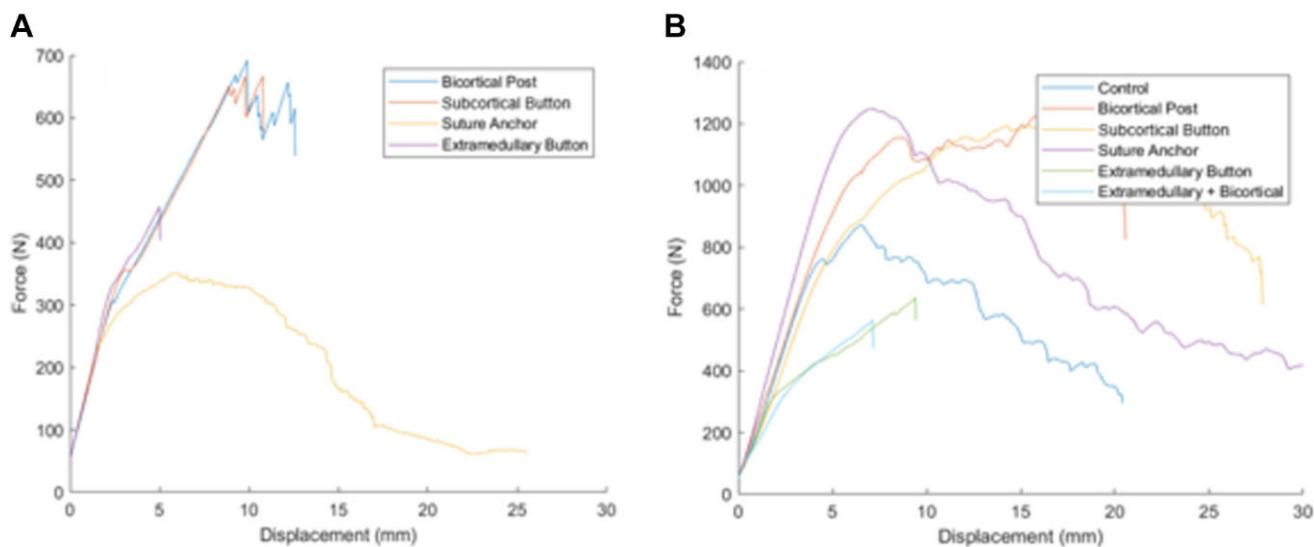


Fig 4. Force displacement curves of each backup fixation construct when tested without (A) and with (B) simulated graft and interference screw primary fixation.

strongest when used in conjunction with an extra-medullary suture button as supplementary fixation compared with the screw or button in isolation. The failure loads for all fixation methods measured in our study were most similar to those in the study of Verioti et al.⁹; however, they were greater than those reported in all 3 similar studies. The greater loads measured in our study may be attributable to using composite tibias rather than porcine specimens.

Composite bones have been used to simulate human bone in a variety of biomechanical studies.²⁵⁻³² Although some studies have shown stronger biomechanical properties of composite bones as compared with osteoporotic human cadaveric specimens,²⁵ fourth-generation composite tibias, as used in this study, have similar material properties to young human cadaveric bone.^{28,30} Fourth-generation composite tibias and femurs have also been used in ACL-related research to evaluate for fracture risk around femoral and tibial drill tunnels.^{26,29} Although these models may approximate young human cadaveric bone, it is difficult to directly compare our results with those of previously published porcine studies. When this study was performed, our facility did not have the capacity to accommodate animal or human cadaveric specimens and, therefore, composite bones were used.

When supplementary fixation devices were tested in isolation, both the bicortical post and the suture button were significantly stronger than the SA. This is likely because of the suspensory nature of the post and suture button, conferring strength through high-tensile strength sutures, versus the SA, which relies on friction between the screw-suture-bone interface. This mechanistic difference is reflected in the differing failure modes between groups, given that the SA

constructs failed by suture slipping out from the anchor-bone interface whereas the suspensory devices failed by the sutures rupturing. Although the differences were not statistically significant between the suspensory devices and the SA when the graft was incorporated, the data trended toward the suture button and the post providing higher maximal loads.

There was no difference in isolated cyclic displacement, but the ABS and ABS-BP groups showed more cyclic displacement than the other groups. Cyclic displacement is permanent elongation that occurs after the first cycle meant to replicate normal loading conditions. The results of this study indicate that an extramedullary suture button construct, such as that used in an all-inside technique, sees more displacement under normal loading conditions than constructs with IS fixation. As such, these constructs may be at greater risk of elongation or loosening during the initial rehabilitation phases before the graft heals into the bone tunnel.

When used with the IS and under load-sharing conditions, the SA showed one of the greatest failure loads, the greatest load at 5 mm of displacement, and one of the lowest pullout and cyclic displacement values. However, the SA was inferior to other fixation methods in isolation and therefore may be more likely to fail as a backup device if the IS were to fail. The SB and BP also showed strong maximum loads, as well as loads at 5 mm of displacement, and low cyclic displacement values, and they performed well in isolation, meaning that they would secure the graft if the IS failed. The ABS performed well in isolation, but it did not perform well in conjunction with the IS under load-sharing conditions. Additionally, the SA, IS, and ABS groups showed less pullout displacement than the BP and SB

Table 2. Biomechanical Testing Results of 6 Fixation Groups Tested With Graft

Group	Cyclic Displacement (mm)	Cyclic Stiffness (N/mm)	Failure Load (N)	Pullout Displacement (mm)	Pullout Stiffness (N/mm)	Force at 5 mm of Displacement (N)
Control (IS only)	3.64 ± 0.94	29.85 ± 5.03	932.91 ± 99.86*	4.58 ± 2.34*	171.66 ± 23.76	760.05 ± 146.08
BP	3.45 ± 0.60	30.26 ± 4.26	1,461.27 ± 173.75	14.33 ± 4.92	161.57 ± 39.94	908.64 ± 267.58
SB	3.20 ± 0.97	35.61 ± 13.34	1,362.45 ± 80.46	15.16 ± 4.09	137.56 ± 32.30	787.36 ± 219.77
SA	3.14 ± 1.15	35.08 ± 13.11	1,275.03 ± 165.89	5.93 ± 1.16*	189.07 ± 25.15*	1,093.76 ± 97.20*
Extramedullary button (ABS)	7.43 ± 1.70*	14.03 ± 2.51*	721.39 ± 103.32*†	8.50 ± 1.84*†	51.82 ± 5.46*	450.61 ± 34.01*
ABS-BP	7.58 ± 1.28*	14.20 ± 1.88*	718.15 ± 108.61*†	8.48 ± 2.38*†	67.38 ± 0.85*	464.26 ± 14.16*

NOTE. Biomechanical outcome measures for each backup fixation device tested with simulated IS primary fixation are presented as mean ± standard deviation.

ABS, Attachable Button System; BP, bicortical post; IS, interference screw; SA, suture anchor; SB, subcortical button.

*Significantly different from SB group at 5% level of significance. The P values for comparison to the SB group were as follows: $P < .001$ for failure load and $P < .001$ for pullout displacement in the IS group; $P = .004$ for pullout displacement, $P < .001$ for pullout stiffness, and $P = .037$ for force at 5 mm of displacement in the SA group; $P = .008$ for cyclic displacement, $P < .001$ for cyclic stiffness, $P < .001$ for failure load, $P = .011$ for pullout displacement, $P = .008$ for pullout stiffness, and $P = .010$ for force at 5 mm of displacement in the ABS group; and $P = .008$ for cyclic displacement, $P < .001$ for cyclic stiffness, $P < .001$ for failure load, $P = .013$ for pullout displacement, $P = .008$ for pullout stiffness, and $P = .011$ for force at 5 mm of displacement in the ABS-BP group.

†Significantly different from IS group at 5% level of significance, with $P = .011$ for failure load in ABS group, $P = .012$ for failure load in ABS-BP group, $P = .019$ for pullout displacement in ABS group, and $P = .031$ for pullout displacement in ABS-BP group.

groups. This is likely because of the stronger fixation at the anchor point in the SB and BP groups, allowing for elongation through the graft at maximal loads, whereas in the IS and SA groups, the construct fails as the sutures slip through the interference fit between the device and the bone. Finally, the isolated SB was less stiff under cyclic loading conditions than the BP, but *in vivo* testing is necessary to determine the impact this may have on healing.

Limitations

This study has several limitations. First, this was a biomechanical study using synthetic graft and bone substitutes rather than human or animal tissue. The composite tibias ensure consistent biomechanical properties between groups and specimens and have been found to adequately replicate the physiological values for mechanical properties and cancellous screw pullout.^{27,28-33} Although the results of this study may not be directly comparable to those of previous porcine models, the consistency of the manufactured tibias and comparability to young human cadaveric bone^{28,30} likely contribute to a consistent model that accurately compares fixation device biomechanical properties. To make this experiment more realistic, one possible change to the procedures would be to soak the composite tibias in body-temperature water before preparation and testing to better simulate *in vivo* conditions.²⁷ Similarly, this study used polyester webbing to simulate a soft-tissue ACL graft. Historically, synthetic grafts have been studied as potential substitutes for autograft or allograft tissue but have had a multitude of issues *in vivo*, largely owing to leaching effects and third-body particle wear.³⁴⁻³⁶ Some early outcome studies of polyester and other synthetic ACL grafts showed good outcomes regarding knee stability,

but immunologic responses over time led to graft failure.^{37,38} Although the synthetic graft used in this study may make the results difficult to relate to similar porcine studies, our control group with just graft and an IS had a similar failure load to that reported by Veriotti et al.,⁹ suggesting that the synthetic graft is an adequate substitute at time 0. Another limitation of this study is the small sample size. Although our ad hoc power analysis showed 86% power for a sample size of 5, a post hoc analysis showed that 13 specimens would be required to determine a difference between fixation groups. Post hoc power analysis showed that 5 specimens was adequate to determine a 100-N difference in maximal load between the fixation groups and the control group, however.

Conclusions

Subcortical backup fixation in ACL reconstruction has similar biomechanical properties to current methods and is a viable backup fixation alternative. Backup fixation methods work synergistically with IS primary fixation to strengthen the construct. There is no advantage to adding backup fixation to extramedullary button (all-inside) primary fixation when all suture strands are secured to the extramedullary button.

References

1. Filbay SR, Grindem H. Evidence-based recommendations for the management of anterior cruciate ligament (ACL) rupture. *Best Pract Res Clin Rheumatol* 2019;33:33-47.
2. Widner M, Dunleavy M, Lynch S. Outcomes following ACL reconstruction based on graft type: Are all grafts equivalent? *Curr Rev Musculoskelet Med* 2019;12:460-465.
3. Lee JJ, Otarodifard K, Jun BJ, McGarry MH, Hatch GF III, Lee TQ. Is supplementary fixation necessary in anterior

- cruciate ligament reconstructions? *Am J Sports Med* 2011;39:360-365.
4. Stadelmaier DM, Lowe WR, Ilahi OA, Noble PC, Kohl HW III. Cyclic pull-out strength of hamstring tendon graft fixation with soft tissue interference screws. Influence of screw length. *Am J Sports Med* 1999;27:778-783.
 5. Aga C, Rasmussen MT, Smith SD, et al. Biomechanical comparison of interference screws and combination screw and sheath devices for soft tissue anterior cruciate ligament reconstruction on the tibial side. *Am J Sports Med* 2013;41:841-848.
 6. Brand JC Jr, Pienkowski D, Steenlage E, Hamilton D, Johnson DL, Caborn DN. Interference screw fixation strength of a quadrupled hamstring tendon graft is directly related to bone mineral density and insertion torque. *Am J Sports Med* 2000;28:705-710.
 7. Balazs GC, Brelin AM, Grimm PD, Dickens JF, Keblish DJ, Rue JH. Hybrid tibia fixation of soft tissue grafts in anterior cruciate ligament reconstruction: A systematic review. *Am J Sports Med* 2016;44:2724-2732.
 8. De Wall M, Scholes CJ, Patel S, Coolican MR, Parker DA. Tibial fixation in anterior cruciate ligament reconstruction: A prospective randomized study comparing metal interference screw and staples with a centrally placed polyethylene screw and sheath. *Am J Sports Med* 2011;39:1858-1864.
 9. Veriotti CA, Sardelli MC, Nguyen T. Evaluation of 3 fixation devices for tibial-sided anterior cruciate ligament graft backup fixation. *Am J Orthop* 2015;44:E225-E230.
 10. Yoo JC, Ahn JH, Kim JH, et al. Biomechanical testing of hybrid hamstring graft tibial fixation in anterior cruciate ligament reconstruction. *Knee* 2006;13:455-459.
 11. Fabbriciani C, Mulas PD, Ziranu F, Deriu L, Zarelli D, Milano G. Mechanical analysis of fixation methods for anterior cruciate ligament reconstruction with hamstring tendon graft. An experimental study in sheep knees. *Knee* 2005;12:135-138.
 12. Vopat B, Paller D, Machan JT, et al. Effectiveness of low-profile supplemental fixation in anterior cruciate ligament reconstructions with decreased bone mineral density. *Arthroscopy* 2013;29:1540-1545.
 13. Barrera CM, Ennis H, Delcroix GJ, et al. Supplemental fixation of inner graft limbs in all-inside, quadrupled, single-tendon anterior cruciate ligament reconstruction graft construct yields improved biomechanical properties. *Arthroscopy* 2019;35:909-918.
 14. Klein SA, Nyland J, Kocabey Y, Wozniak T, Nawab A, Caborn DN. Tendon graft fixation in ACL reconstruction: In vitro evaluation of bioabsorbable tenodesis screw. *Acta Orthop Scand* 2004;75:84-88.
 15. Tetsumura S, Fujita A, Nakajima M, Abe M. Biomechanical comparison of different fixation methods on the tibial side in anterior cruciate ligament reconstruction: A biomechanical study in porcine tibial bone. *J Orthop Sci* 2006;11:278-282.
 16. JU Buelow, Siebold R, Ellermann A. A new bicortical tibial fixation technique in anterior cruciate ligament reconstruction with quadruple hamstring graft. *Knee Surg Sports Traumatol Arthrosc* 2000;8:218-225.
 17. Kim MK, Na SI, Lee JM, Park JY. Comparison of bioabsorbable suture anchor fixation on the tibial side for anterior cruciate ligament reconstruction using free soft tissue graft: Experimental laboratory study on porcine bone. *Yonsei Med J* 2014;55:760-765.
 18. Colantonio DF, Le AH, Keeling LE, et al. Intramedullary unicortical button and all-suture anchors provide similar maximum strength for onlay distal biceps tendon repair. *Arthroscopy* 2022;38:287-294.
 19. Buchholz A, Martetschläger F, Siebenlist S, et al. Biomechanical comparison of intramedullary cortical button fixation and interference screw technique for subpectoral biceps tenodesis. *Arthroscopy* 2013;29:845-853.
 20. Buchholz A, Siebenlist S. The intramedullary cortical button technique for distal biceps tendon repair. *Oper Tech Sports Med* 2018;26:126-129.
 21. Siebenlist S, Lenich A, Buchholz A, et al. Biomechanical in vitro validation of intramedullary cortical button fixation for distal biceps tendon repair: A new technique. *Am J Sports Med* 2011;39:1762-1768.
 22. Arora AS, Singh A, Koonce RC. Biomechanical evaluation of a unicortical button versus interference screw for subpectoral biceps tenodesis. *Arthroscopy* 2013;29:638-644.
 23. Gee SM, Zhou L, Donohue MA, Posner MA. Subcortical backup fixation in ACL reconstruction. *Arthros Tech* 2022;11:e171-e176.
 24. Walsh MP, Wijdicks CA, Parker JB, Hapa O, LaPrade RF. A comparison between a retrograde interference screw, suture button, and combined fixation on the tibial side in an all-inside anterior cruciate ligament reconstruction: A biomechanical study in a porcine model. *Am J Sports Med* 2009;37:160-167.
 25. Basso T, Klaksvik J, Syversen U, Foss OA. A biomechanical comparison of composite femurs and cadaver femurs used in experiments on operated hip fractures. *J Biomech* 2014;47:3898-3902.
 26. Aldebeyan W, Liddell A, Steffen T, Beckman L, Martineau PA. Proximal tibial fracture following anterior cruciate ligament reconstruction surgery: A biomechanical analysis of the tibial tunnel as a stress riser. *Knee Surg Sports Traumatol Arthrosc* 2017;25:2397-2404.
 27. Elfar J, Menorca RM, Reed JD, Stanbury S. Composite bone models in orthopaedic surgery research and education. *J Am Acad Orthop Surg* 2014;22:111-120.
 28. Gardner MP, Chong AC, Pollock AG, Wooley PH. Mechanical evaluation of large-size fourth-generation composite femur and tibia models. *Ann Biomed Eng* 2010;38:613-620.
 29. Han Y, Sardar Z, McGrail S, Steffen T, Martineau PA. Peri-anterior cruciate ligament reconstruction femur fracture: A biomechanical analysis of the femoral tunnel as a stress riser. *Knee Surg Sports Traumatol Arthrosc* 2011;19:S77-S85 (suppl 1).
 30. Heiner AD. Structural properties of fourth-generation composite femurs and tibias. *J Biomech* 2008;41:3282-3284.
 31. Zdero R, Olsen M, Bougheara H, Schemitsch EH. Cancellous bone screw purchase: A comparison of synthetic femurs, human femurs, and finite element analysis. *Proc Inst Mech Eng H* 2008;222:1175-1183.
 32. Zdero R, Rose S, Schemitsch EH, Papini M. Cortical screw pullout strength and effective shear stress in synthetic third generation composite femurs. *J Biomed Eng* 2007;129:289-293.

33. Welsh E, Daigle K. Comparison of mechanical strains in composite tibias versus human cadaver tibias. *Proc South Biomed Eng Conf* 1993;202-204.
34. Legnani C, Ventura A, Terzaghi C, Borgo E, Albisetti W. Anterior cruciate ligament reconstruction with synthetic grafts. A review of literature. *Int Orthop* 2010;34:465-471.
35. Sun J, Wei XC, Li L, et al. Autografts vs synthetics for cruciate ligament reconstruction: A systematic review and meta-analysis. *Orthop Surg* 2020;12:378-387.
36. Marieswaran M, Jain I, Garg B, Sharma V, Kalyanasundaram D. A review on biomechanics of anterior cruciate ligament and materials for reconstruction. *Appl Bionics Biomech* 2018;2018:4657824.
37. Letsch R. Comparative evaluation of different anchoring techniques for synthetic cruciate ligaments. A biomechanical and animal investigation. *Knee Surg Sports Traumatol Arthrosc* 1994;2:107-117.
38. Andersen HN, Bruun C, Søndergård-Petersen PE. Reconstruction of chronic insufficient anterior cruciate ligament in the knee using a synthetic Dacron prosthesis. A prospective study of 57 cases. *Am J Sports Med* 1992;20: 20-23.