Review Article

Biomechanical comparison of anterior cruciate ligament reconstruction fixation methods and implications on clinical outcomes

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Abstract: Anterior cruciate ligament reconstruction (ACLR) is one of the more common surgeries encountered by orthopaedic surgeons, which has its inherent challenges due to the complex anatomy and biomechanical properties required to reproduce the function and stability of the native ACL. Multiple biomechanical factors from graft choice and tunnel placement to graft tensioning and fixation methods are vital in achieving a successful clinical outcome. Common methods of ACLR graft fixation in both the primary and revision setting are classified into compression/interference, suspensory, or hybrid fixation strategies with multiple adjunct methods of fixation. The individual biomechanical properties of these implants are crucial in facilitating early post-operative rehabilitation, while also withstanding the shear and tensile forces to avoid displacement and early graft failure during graft osseointegration. Implants within these categories include the use of interference screws (IFSs), as well as suspensory fixation with a button, posts, surgical staples, or suture anchors. Outcomes of comparative studies across the various fixation types demonstrate that compression fixation can decrease graft-tunnel motion, tunnel widening, and graft creep, at the risk of damage to the graft by IFSs and graft slippage. Suspensory fixation allows for a minimally invasive approach while allowing similar cortical apposition and biomechanical strength when compared to compression fixation. However, suspensory fixation is criticized for the risk of tunnel widening and increased graft-tunnel motion. Several adjunct fixation methods, including the use of posts, suture-anchors, and staples, offer biomechanical advantages over compression or suspensory fixation methods alone, through a second form of fixation in a second plane of motion. Regardless of the method or implant chosen for fixation, technically secure fixation is paramount to avoid displacement of the graft and allow for appropriate integration of the graft into the bone tunnel. While no single fixation technique has been established as the gold standard, a thorough understanding of the biomechanical advantages and disadvantages of each fixation method can be used to determine the optimal ACLR fixation method through an individualized patient approach.

Keywords: Anterior cruciate ligament (ACL); ACLR fixation; ACLR biomechanics; graft fixation

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Introduction

Anterior cruciate ligament (ACL) injury is one of the most common knee injuries encountered in orthopaedic surgery, typically occurring during non-contact sport participation, specifically with cutting and pivoting exercises (1). Therefore, ACL reconstruction (ACLR) is a common orthopaedic surgical procedure performed to restore the native function of the ACL and provide translational and rotatory stability of the knee (2,3). The incidence of primary and revision ACLR is increasing annually, with an estimated 80,000 to 100,000 people in the United States undergoing this procedure per year (1,4), with revision rates between 4.1% and 13.3% of all primary ACLRs (5,6).

There are multiple reconstruction techniques with the goal of restoring rotational and translational knee stability and function (2,7). There is a myriad of technical challenges to consider during ACLR that impact clinical outcomes including graft selection, tunnel positioning, graft tensioning, fixation methods, and healing properties (1,2,8,9). In addition to a wide array of fixation methods, several devices have also been developed for graft fixation (1). The different types of fixation methods in ACLR are typically categorized into compression, suspension, post, or hybrid fixation (10,11). Regardless of the implant chosen for fixation, secure fixation is paramount to avoid displacement of the graft and allow for graft integration into the bone tunnel, which typically occurs around three months after surgery (2). Therefore, the biomechanical properties of these implants are particularly important in facilitating early post-operative rehabilitation after ACLR that is necessary for a successful clinical outcome, while also withstanding the shear and tensile forces to avoid displacement and early graft failure during graft osseointegration (12).

The overall reported ACL graft rupture rate at longer than 10-year follow-up was 6.2%, with 10.3% clinical failure (13). While many different factors can lead to ACLR failure, graft fixation is one important factor. Currently, there is no consensus on the optimal graft fixation technique. The reasons for lack of consensus may be attributed to several factors including but not limited to different types of ACLR grafts used, surgeon preference, industry influence/competition, lack of evidence-based recommendations from clinical outcomes studies, and variations in the reported biomechanical effectiveness for different fixation types. Therefore, it is important for surgeons to understand the reported advantages and disadvantages of using different ACLR fixation types based on biomechanics and clinical outcomes. Therefore, the purpose of this review was to highlight the unique advantages and disadvantages of each type of graft fixation method and provide perspective on the role that the available biomechanical properties play in optimizing fixation strategies based on reported clinical outcomes.

Compression fixation

One commonly used method of securing a graft both in the femur and tibia during ACLR is interference screw (IFS) fixation, which employs a compression technique. IFSs have a long history of successful outcomes with a reproducible technique that involves placing a screw in the tunnel to compress the graft against the cancellous tunnel wall (7,14,15). There are different types of IFS fixation to include metallic (often titanium), polyetheretherketone (PEEK), or bioabsorbable screws. Advantages and disadvantages of IFS types can be seen in *Table 1*. Historically, metal screws were used in up to 1 in 10 ACLR in adolescents and young adults (16), but they have decreased in popularity due to the higher rate of clinical sequalae, and consequence of projection artifact on magnetic resonance imaging (MRI). As such, newer bioabsorbable materials have been utilized to allow for superior post-operative MRI assessment and to allow for gradual resorption with bone replacement and less likelihood of graft injury during time of insertion (15). While bioabsorbable screws have demonstrated good clinical outcomes (17-22) and are MRI compatible, they are rarely completely replaced by bone or absorbed by the body, can cause hyperinflammation and cystic changes, and may be predisposed to breakage, migration and osteolysis (19,23). PEEK screws, on the other hand, are non-bioresorbable and MRI compatible. The product is biocompatible and demonstrates appropriate strength for ACLR (15).

In a randomized controlled trial, Shumborski *et al.* (15) compared PEEK and titanium IFS fixation among 133 adult patients who were randomized to either PEEK or titanium IFS fixation during primary ACLR with 4-strand hamstring tendon autograft. Authors reported no differences in ACLR re-rupture rate as well as subjective or objective clinical outcomes ($P>0.05$). The authors also noted that post-operative MRI evaluation of the ACLR graft was improved in the PEEK group due to less artifact than titanium IFS. The absence of metal artifact on MRI, modulus of elasticity similar to human bone, biological compatibility, and equivalent clinical outcomes suggest that PEEK implants may be an excellent choice of ACLR

Table 1 The advantages and disadvantages of the different types of interference screws used for anterior cruciate ligament reconstruction

Interference screw type	Advantages	Disadvantages
Metal	• No breakdown • Rigid fixation	• MRI artifact • Irrigation/need for removal
Biocomposite	• MRI compatible • ↓ Removal • ↓ Graft injury	• Tissue reaction • Breakage • Osteolysis
PEEK	• Biocompatible • Non-resorbable • MRI compatible	• Breakage

↓, decreased.

graft fixation. Shen *et al.* (19) compared bioabsorbable and metallic IFS fixation in a meta-analysis of 10 randomized controlled trials comprising 790 patients undergoing single-bundle ACLR. When tested biomechanically with a KT-1000/-2000 arthrometer, there were no statistically significant differences between bioabsorbable and metallic screw fixation (P>0.05). Also, there were no significant differences in infection or knee joint instability, which has been corroborated by other recent studies (24,25). Other biomechanical studies comparing metal and bioabsorbable IFS fixation of a soft tissue graft found no differences in ultimate load to failure or construct stiffness (17,18). Similarly, Drogset *et al.* (21) found no significant differences in functional outcomes between bioabsorbable and metal IFS fixation in their prospective randomized study utilizing bone-patellar tendon-bone (BTB) autograft for ACLR.

The utilization of compression fixation specifically in the setting of all-soft tissue grafts has become a point of concern as surgeons questioned whether IFSs would provide adequate fixation without risking injury to the graft at time of insertion. To further investigate this concern, Brand *et al.* (26) found that bioabsorbable screws were comparable or superior to titanium screws for IFS fixation with respect to load-to-failure for soft tissue grafts and that the bioabsorbable implant produced less screw thread-induced laceration of the soft tissue graft during testing. Another study also concluded that either screw could be used effectively (17). In another biomechanical study, Kruppa *et al.* (27) examined force exerted across soft tissue grafts that were secured with a tibial IFS. Authors reported that the graft force decreased substantially over the first twenty-four hours after fixation and that this diminished force was not affected by screw diameter or length. As a result, the authors concluded that IFS fixation for all-soft tissue grafts may lead to early postoperative laxity following ACLR in the clinical setting. This finding was confirmed in additional studies that demonstrated graft slippage and weakened biomechanical properties of the soft tissue graft after fixation of all-soft tissue grafts with IFS (11,28). Contrary to these findings, Micucci *et al.* (29) showed no significant differences in ultimate fixation strength or graft slippage of multiple tested IFSs of varying diameter in the fixation of soft tissue grafts for ACLR. Studies commenting on compression fixation can be seen in *Table 2*.

Suspensory fixation

Suspensory fixation of an ACLR graft is another commonly used technique that typically involves the use of an extra-cortical bone plug on the femur, tibia, or both that is connected to the graft by suture. Studies examining suspensory fixation are highlighted in *Table 3*. The development of suspensory fixation has led to a more minimally invasive approach such as utilizing an all-inside ACLR technique (21). In the realm of suspensory fixation, fixed-loop devices (FLDs) and adjustable-loop devices (ALDs) are both commercially available. In FLDs, the graft is attached to a suture loop that is connected to a button that is flipped against cortical bone. In ALDs, the graft is secured to an adjustable loop of suture and a button such that the tension in the construct can be set after flipping the button against the cortex (30). FLDs keep the graft on tension by connecting it at a constant length to the cortical button to maintain the interface between the graft and the bone for healing (31). Multiple studies have found that FLDs have been associated with a higher load-to-failure (30-32). The disadvantage of FLDs include the potential for inaccurate graft and tunnel measurements leading to graft laxity and poor osseointegration as FLDs are a set length and cannot be adjusted once implanted. Newer ALDs have

Table 2 Studies on compression fixation in anterior cruciate ligament reconstruction

Reference	Year	Study type	Study purpose	Conclusion
Scheffler (11)	2002	Biomechanical study	Evaluate tensile properties with incremental cyclic loading based on level and method of graft fixation	• Fixation with interference screws allows graft slippage • Can be limited by bone block or application of hybrid fixation, especially on tibial side
Shumborski (15)	2019	Randomized controlled trial	Compare the clinical performance of ACL reconstruction with PEEK and titanium interference screws at 2 years	• No significant differences in graft rerupture rate, contralateral ACL rupture rate, subjective outcomes, or objective outcomes.
Kramer (16)	2020	Retrospective review	Retrospectively analyze the complications associated with tibial bioabsorbable interference screw use in adolescents after ACLR	• Screw-site pain most common complication • Reoperation for screw-related symptoms was 5%
Laxdal (17)	2006	Randomized controlled trial	Compare the clinical/radiographic results in metal versus bioscrew IFS for ACLR	• No biomechanical significant differences on arthrometer • No differences in functional outcome
Kaeding (18)	2005	Prospective study	Compare bioscrew and metal IFS	• No functional/biomechanical differences between groups
Shen (19)	2010	Meta-analysis	Investigate the outcomes between bioabsorbable and metallic screw fixation in ACL reconstruction.	• No significant difference in knee joint stability or knee joint function outcome between bioabsorbable and metallic interference screws
Myers (20)	2008	Randomized controlled trial	Prospectively assess the outcome of ACLR by use of bioscrew and titanium IFS	• No differences in functional/radiographic outcomes
Drogset (21)	2011	Prospective study	Compare long-term clinical outcome after ACL-reconstructions with BPTB-grafts fixed with metal interference screws or bioabsorbable screws	• No significant differences between the groups in any parameter measured • Better Pivot shift results in the bioscrew group
Kousa (22)	2001	Biomechanical study	Evaluate initial fixation strength among hamstring tendon graft tibial fixation devices	• PEEK screw was the strongest in the single-cycle load-to-failure test
Xu (23)	2021	Meta-analysis	Compare metal and bioscrew IFS	• No difference between two in knee function or laxity • Metallic screws had fewer complications
Benedetto (24)	2000	Randomized controlled trial	Compare a bioabsorbable to a metal screw in anterior cruciate ligament reconstruction	• No significant functional or patient reported differences were found between the groups at 1 year
Arama (25)	2015	Randomized controlled trial	Compare clinical/radiologic outcomes of the PLLA-HA screw versus titanium screw for hamstring tendon ACLR	• No difference in any clinical outcome measure at 2- or 5-year follow-up between the 2 groups
Brand (26)	2005	Biomechanical study	Compare the biomechanical properties of eccentrically positioned bioabsorbable and titanium interference screws for hamstring tendon graft	• Bioscrew was similar in load-to-failure with metallic screw • Less graft thread-induced laceration in bioscrew

Table 2 *(continued)*

Table 2 *(continued)*

Reference	Year	Study type	Study purpose	Conclusion
Kruppa (27)	2020	Biomechanical study	Investigate the force in soft tissue grafts secured with a tibial interference screw	• Graft force in soft tissue grafts secured with a tibial interference screw decreased substantially • Screw length/diameter had no affect
Sawyer (28)	2013	Biomechanical study	Investigate the biomechanics in soft tissue grafts secured with a tibial interference screw	• Single insertion of interference screws for soft tissue graft fixation weakens the biomechanical properties of the graft itself
Micucci (29)	2010	Biomechanical study	Evaluate the effect that interference screw diameter has on fixation strength of a soft-tissue ACL graft	• No statistically significant differences in ultimate strength and graft slippage between screws

ACLR, anterior cruciate ligament reconstruction; IFS, interference screw; bioscrew, bioabsorbable screw; ACL, anterior cruciate ligament; BPTB, bone-patellar tendon-bone; PLLA-HA, poly(L-lactic acid) and hydroxyapatie.

Table 3 Studies on suspensory fixation in anterior cruciate ligament reconstruction

Reference	Year	Study type	Study purpose	Conclusion
Houck (30)	2018	Meta-analysis	Compare the biomechanical results of fixed- versus adjustable-loop femoral cortical suspension devices in studies simulating ACLR	• Adjustable loop device had strongest "time zero" ultimate load to failure when compared to fixed loop device
Onggo (31)	2019	Systematic review	Compare biomechanical and clinical outcomes between ALD and FLD in the femoral fixation	• Superior biomechanical properties of FLDs • ALDs and FLDs yielded similar clinical outcome scores and graft rerupture rates
Eguchi (32)	2014	Biomechanical study	Evaluate the mechanical strength of two cortical suspension devices	• FLD greater mechanical strength than ALD • Increased cyclic displacement in ALD
Smith (33)	2020	Biomechanical study	Compare loop elongation and load at failure of ALDs/FLDs	• FLD had highest failure load • No differences in elongation between devices
Singh (34)	2018	Biomechanical study	Compare elongation of ALD/FLD	• No statistically significant differences among the devices for total or dynamic elongation
Johnson (35)	2015	Biomechanical study	Compare five femoral suspensory fixation devices	• Significant differences were observed between current fixed-loop and adjustable-loop cortical suspension devices for soft tissue femoral fixation when subjected to high loads experienced during rehabilitation
Petre (36)	2013	Biomechanical study	Compare four femoral suspensory fixation devices	• Each ALD/FLD had the necessary biomechanical properties with regard to ultimate failure strength, displacement, and stiffness for initial fixation of soft tissue grafts in the femoral tunnel
Barrow (37)	2014	Biomechanical study	Compare ALD/FLD to native knee physiologic loads	• The ultimate load of all graft-fixation devices exceeded the forces likely to be experienced in a patient's knee during the early postoperative rehabilitation period

ACLR, anterior cruciate ligament reconstruction; ALD, adjustable loop device; FLD, fixed loop device.

a one-way locking system that allows for customization of the tension in the construct, theoretically improving graft incorporation by minimizing micromotion (31).

In a systematic review comparing FLDs and ALDs, Onggo *et al.* (31) reported superior biomechanical graft properties in FLDs including higher graft stiffness and higher ultimate load-to-failure. It is important to note that the authors found biomechanical improvement with re-tensioning of ALDs after tibial fixation as per manufacturer instructions and that both constructs possessed the necessary biomechanical strength of a native ACL. Despite the differences in biomechanical properties, there were no significant differences in clinical outcomes, ACLR re-rupture rates, or radiographic evaluation between the two implants. Other biomechanical studies comparing ALDs and FLDs demonstrated no differences in device elongation when cycled on an Instron machine. This is clinically relevant as graft/construct elongation will produce laxity and resultant clinical failure (33,34).

While suspensory fixation can be used with either bony or all-soft tissue grafts, biomechanical comparison of femoral cortical suspension in all-soft tissue grafts noted significant differences between FLDs and ALDs (33-36). FLDs had less cyclic displacement when compared with ALDs (35,36). Petre *et al.* (36) also biomechanically compared suspension devices in soft tissue grafts in a porcine model looking at ultimate load to failure, stiffness, and displacement. They found that all devices tested had the necessary physiologic biomechanical properties with regard to displacement, failure strength, and stiffness for initial fixation in ACLR when compared to the native ACL. This study did note that FLDs allowed less initial and cyclic displacement but attributed this difference in initial displacement to the critical step of re-tensioning the ALDs after cycling the knee and fixing the tibial side. ALDs have been shown to possess the physiologic strength necessary to be used in ACLR when cyclically tested *in vitro* and compared to the native knee (36,37).

Post fixation

Post fixation is another method of ACLR, which is usually a metal screw, with or without a washer, or a cross pin that acts as a stable, inflexible point of fixation in the bone separate from the tunnel aperture that acts as a point of fixation for the graft. Post methods of fixation allow for cortical fixation of the graft to the bone often through the use of sutures as an intermediary (12). *Table 4* depicts the studies that include post fixation. When analyzing tibial sided graft fixation techniques, Weiss *et al.* (12) compared IFS fixation, screw-post and washer fixation, and screw-post and washer fixation with an additional IFS in an ACLR animal model. In their analysis, the hybrid fixation of a post and IFS yielded significantly higher final stiffness and higher yield load than the other fixation methods. In addition, the post only group was found to be biomechanically superior to the IFS cohort. Another comparison study on cross-pin fixation, IFS, and suspensory fixation found the cross-pin to have optimal stability regarding stress and strain at the femoral fixation site (38). In a systematic review on the effect of fixation methods on clinical outcomes, Speziali *et al.* (39) reported a failure rate of 17.3% when a cross-pin was used on the femoral side, which is in contrast to 5.8% with suspensory fixation (39). Suture anchors have also been used as a post fixation, with one cadaveric study demonstrating that suture anchor fixation with suture tape augmentation restored normal knee kinematics (40). There were no significant differences when compared to traditional BTB reconstruction and suspensory fixation alone.

Hybrid/adjunct fixation

A combination of fixation techniques, or hybrid fixation, is another method of securing a graft during ACLR (*Table 5*). Throughout the evolution of ACLR, hybrid fixation techniques have gained popularity, specifically when considering IFS fixation in isolation with concern of graft slippage with parallel fixation in a different plane (2). As such, hybrid fixation methods have been explored to determine if adjunct fixation improves graft stiffness and increase the fixation strength of the construct. Specifically, hybrid fixation has been used to address concerns with tibial fixation, as the tibia has lower bone density than the femur, and the graft is subject to slippage with parallel fixation (2,7,12). Multiple studies have found that suspensory fixation combined with an IFS fixation is biomechanically superior to suspensory fixation alone (41,42). In a porcine model, Walsh *et al.* (42) demonstrated that soft tissue grafts fixed with an IFS and suspensory cortical button were able to withstand higher initial and ultimate loads to failure. Similarly, hybrid fixation of an IFS with a post has also been shown to be biomechanically superior (12).

Suture anchors are reliable backup fixation in the tibia as well. Biomechanical analysis of these implants reveals that they possess equivalent pull out strength when compared

Table 4 Studies on post fixation in anterior cruciate ligament reconstruction

Reference	Year	Study type	Study purpose	Conclusion
Weiss (12)	2019	Biomechanical study	Comparative biomechanical analysis of tibial fixation strength for ACLR with interference screw compared with screw post and washer, and compared with the associated fixation of both methods (hybrid fixation)	• Hybrid fixation group presented a significantly higher final stiffness in comparison • Higher yield load compared to the interference screw group
Zainal Abidin (38)	2021	Biomechanical study	Analyze the biomechanical effects of different types of fixators (cross-pin, interference screw, and cortical button) towards stability after ACLR	• Cross-pin was found to have optimum stability in terms of stress and strain at the femoral fixation site
Speziali (39)	2014	Systematic review	Systematically review the fixation techniques for the ACL reconstruction and associated clinical outcomes at the early follow-up	• Femoral side cross-pin, metallic interference screw, bioabsorbable interference screw, and suspensory device were used in 32.3%, 27.3%, 24.8%, 15.5% of patients, respectively • Tibial side fixation was achieved with metallic interference screw, bioabsorbable interference screw, screw and plastic sheath, screw post and cross-pin in 38.7%, 31%, 15.7%, 12.8%, and 1.7% of patients, respectively
Muench (40)	2022	Biomechanical study	Compare knee kinematics in a cadaveric model of ACL repair using an ALD or suture anchor fixation with suture tape augmentation	• No significant differences between the three techniques

ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; ALD, adjustable loop device, FLD, fixed loop device.

to a traditional bicortical post implant and are a viable option for ACLR tibial hybrid fixation (43). Cyclic testing of suture anchors demonstrates that the tension set with these anchors at the time of insertion remains constant (44). Transosseous tunnels using only suture have also been described as a backup tibial fixation combined with IFSs, as have staple fixation (45-47).

Staple fixation has more recently been described as an adjuvant to another method of fixation through cortical anchoring of the graft loop parallel to the tibial tunnel in the longitudinal position. This method is indicated for patients with good cortical bone stock and is often reserved for patients with open physes (48). Gerich *et al.* (49) described its use in cases where a bone block protrudes out of the tibial tunnel. Stiffness of the construct was significantly higher with the use of a surgical staple than with an IFS and they concluded that staple fixation is comparable. Contrary to these finding, Teo *et al.* (47) compared solitary IFS with an IFS and backup surgical staple and found that there was no biomechanical advantage and that the supplementary fixation may not benefit the construct.

Comparison of fixation methods

Due to the high technical demands of ACLR with significant clinical implications for graft failure, the biomechanical properties of overall graft fixation by compression, suspensory, post and hybrid fixation techniques have been compared throughout the literature. The major biomechanical advantages and disadvantages of these fixation methods are highlighted in *Table 6*. While each method of graft fixation possesses its own advantages and disadvantages, there is no clear superior fixation technique from a biomechanical perspective when performed technically correct. However, one study suggests that graft tension levels close to 90 N and graft fixation at a 30-degree knee-flexion angle are recommended to achieving overall satisfactory clinical outcomes (2).

Comparison of IFS compression fixation and suspensory fixation techniques have been evaluated extensively

Table 5 Studies on hybrid fixation in ACLR

Reference	Year	Study type	Study purpose	Conclusion
Pereira (2)	2021	Systematic review	Review the current evidence on tibial-graft fixation	• No consensus on the best method for tibial fixation of the grafts in ACL reconstructions regarding tension
Brand (7)	2000	Review	Review of literature on graft fixation devices	• Fixation should be done at normal anatomic attachment • No consensus on best device
Weiss (12)	2019	Biomechanical study	Comparative biomechanical analysis of tibial fixation strength for ACLR with interference screw compared with screw post and washer, and compared with the associated fixation of both methods (hybrid fixation)	• Hybrid fixation group presented a significantly higher final stiffness • Also had a higher yield load compared to the interference screw group
Oh (41)	2006	Biomechanical study	Evaluate the effect of hybrid femoral fixation with bioabsorbable interference screws	• Hybrid femoral fixation with suspensory fixation and a bioabsorbable interference screw is stronger than interference or suspensory fixation alone with respect to ultimate tensile strength, stiffness, and slippage
Walsh (42)	2009	Biomechanical study	Compare biomechanical screw/suspensory fixation versus either alone	• Combined screw/suspensory had higher load-to-failure • Combined yield stiffer construct
Verioti (43)	2015	Biomechanical study	Compare three methods of tibial-sided fixation	• No significant difference between IFS, IFS + post, or IFS + suture anchor
Athiviraham (44)	2021	Biomechanical study	Determine whether initial tensioning of suture tape before fixation with a knotless suture anchor significantly affects final tension of the suture tape	• Final tension of the suture tape construct appears to be reproducible and consistent, independent of the initial tension introduced with suture anchor placement
Eisen (45)	2008	Technique article	Describes transosseous backup suture fixation for ACLR	• Technique for backup tibial fixation precludes the need for external hardware
Carulli (46)	2017	Randomized controlled trial	Compare the clinical/radiological outcomes of patients with tibial fixation by a centrally placed resorbable screw/sheath to a resorbable interference screw/staple fixation	• No significant differences between groups
Teo (47)	2017	Retrospective review	Determine whether supplementary tibial graft fixation with a staple is routinely necessary for ACLR	• No significant difference in the objective and subjective outcome assessments between staple/no staple
Diego (48)	2017	Technique article	Describe femoral fixation with a combined metal IFS and staple	• Technique for combined IFS/staple femoral fixation
Gerich (49)	1997	Biomechanical study	Evaluate the primary biomechanical parameters of this technique compared with a standard IFS fixation	• Staple fixation resulted in comparable max load to failure, graft slippage, and stiffness to IFS

ACLR, anterior cruciate ligament reconstruction; IFS, interference screw.

in the biomechanical and clinical literature. Overall, biomechanical implications on clinical decision making for ACLR soft tissue graft fixation has remained a challenge, and biomechanical studies have yet to account for the "windshield-wiper" effect leading to higher risk of tunnel widening observed for suspensory devices. Prior research has

Table 6 The advantages and disadvantages of various anterior cruciate ligament reconstruction graft fixation methods

Fixation method	Advantages	Disadvantages
Compression	• ↓ Graft-tunnel micromotion • ↓ Tunnel widening • ↓ Graft creep	• Risk of screw-tunnel divergence • Graft damage • Cancellous fixation • Graft slippage
Suspensory	• Minimally invasive • ↑ Tension between graft/bone interface • Cortical fixation • Similar biomechanics to compression	• ↑ Graft-tunnel motion • "Windshield wiper phenomenon" • Tunnel widening
Suture anchor	• Maintenance of tension	• Anchor pull-out
Post/staple	• Useful in open physes • Useful in graft-tunnel mismatch • Stable, inflexible fixation	• Hardware irritation • More invasive

↓, decreased; ↑, increased.

demonstrated that tunnel osteolysis or widening occurs no matter what graft type (i.e., bone or soft tissue) or fixation method is used and is a reported natural phenomenon. However, there is higher risk of tunnel osteolysis due to this windshield-wiper effect when using soft-tissue grafts and suspensory fixation devices where the graft is not fixed directly in the closed socket tunnel (50). Furthermore, heterogenous suspensory devices have been compared to IFS fixation which has led to inconsistent conclusions in the literature. Mayr *et al.* (51) noted that grafts fixed with tibial ALDs resulted in higher graft elongation but had higher ultimate failure loads in comparison with those fixed with IFSs at time zero. In contrast, a recent biomechanical study reported that tibial and femoral fixation with three unique adjustable-loop suspensory devices demonstrated higher ultimate failure loads and lower graft elongation when compared to a construct with femoral fixed-loop suspensory fixation and tibial IFS fixation (52). Contrary to these findings, other studies have found that the fixation method biomechanical properties are similar between groups with no definitive clinical impact (53,54).

Studies have also compared IFS, suspensory, post, and cross-pin fixation for ACLR. Ma *et al.* (55) compared the three modes of fixation with a hamstring ACLR and found no significant differences in clinical outcomes among IFS, suspensory, or post fixation with at least 2 years of follow-up. Cyclic load testing showed similar amounts of graft displacement across all tested types of femoral fixation (56). Specifically examining femoral-sided fixation, one study found that cross-pin was found to have optimum stability with regard to stress and strain (38). This is in contrast to another study that found it to be biomechanically inferior to suspensory fixation (57).

Strengths and limitations

This review provides the most comprehensive and thorough presentation of the available literature in terms of available ACLR fixation methods based on known biomechanical properties and related clinical outcomes. This review gives surgeons a comprehensive presentation of the advantages and disadvantages of the various fixation methods necessary to provide a patient-specific approach to ACLR, though it was not without limitations. This review was limited by the heterogeneity of the current available literature. Comparison studies combined different methods of fixation and with inconsistent reporting of similar outcomes. Biomechanical testing, when performed, was not performed in the same manner across all studies and different outcome measures were used across these models to assess graft success (i.e., load to failure, cyclic loading, graft stiffness, etc.) Because an ACL graft can be successfully secured with any of the above listed categories of fixation or a combination of methods, it is difficult to provide consistent and direct comparisons. Finally, there was a paucity of studies with high-level evidence, thus lowering the overall level of evidence presented.

Conclusions

There remains no clear consensus on the optimal ACLR graft fixation technique or implants when comparing compression, suspensory, post and hybrid fixation methods. The lack of consensus suggests that the ideal fixation method should likely be individualized based on patient-specific factors and demands, patient expectations and desired outcomes, as well as surgeon experience with the goal of restoring anatomic ACL position and function. By having a thorough understanding of the biomechanical properties and associated clinical outcomes of the various described ACLR fixation methods, the advantages and disadvantages of each fixation method can be used to determine the optimal ACLR fixation method based on an individualized approach.

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