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Hamstring autograft utilization in reconstructing anterior cruciate ligament: A review of harvesting techniques, graft preparation, and different fixation methods

Albishi W *et al*. Hamstring autograft

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Abstract

Rupture of the anterior cruciate ligament (ACL) is a common orthopedic injury. Various graft options are available for the reconstruction of ruptured ACL. Using the hamstring muscle as an autograft was first described in 1934, and it remains a commonly harvested graft for ACL reconstruction. Hamstring autografts can be harvested using the traditional anteromedial approach or the newer posteromedial technique. An isolated semitendinosus tendon can be used or combined with the gracilis tendon. There are numerous methods for graft fixation, such as intra-tunnel fixation or extra-tunnel fixation. This comprehensive review discusses the different hamstring muscle harvesting techniques and graft preparation options and fixation methods. It provides a comprehensive overview for choosing the optimal surgical technique when treating patients.

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Core Tip: The anterior cruciate ligament (ACL) rupture is a common orthopedic injury and various graft options are available for the reconstruction of a ruptured ACL. This comprehensive review discusses the different hamstring muscle harvesting techniques as well as graft preparation and fixation methods that can be used to guide clinicians in making evidence-based decisions when treating their patients.

INTRODUCTION

The knee is a weight-bearing mobile joint that gains stability through various supportive structures[1]. Limiting tibial translation, cruciate ligaments act as the greatest stabilizing force of the knee[2]. The anterior cruciate ligament (ACL) extends from the posteromedial aspect of the femoral lateral condyle to the tibial eminence in the anteromedial and posterolateral bundles. It functions by preventing anterior displacement of the tibia in the sagittal plane[1,2]. A common orthopedic complaint is the ACL injury. Sanders *et al*[3] reported in his 21-year population-based study that the annual incidence of ACL injury is 68.6 per 100000 person-years.

The ACL can be injured by either a direct contact force to the knee or a non-contact mechanism by landing or deceleration motion which represents 70% of ACL cases[4]. Boden *et al*[5] described the event as a combination of the misdirected kinetic energies that results in the "twisting event" of a valgus knee and tibial internal rotation in addition to the columnar buckling effect.

Patients usually describe an ACL injury with an audible loud pop followed by an immediately swollen painful knee. Later, incidents of giving way to pivot movements may also occur[6,7]. Examination of the affected extremity is an effective diagnostic tool, whereas magnetic resonance imaging is the main diagnostic confirmatory tool. Although multiple factors influence the management of a patient with a ruptured ACL, limited data support the choice of a purely conservative management[6,8]. Various graft options are available for the reconstruction of a ruptured ACL. The two main graft categories are allografts [bone-patellar tendon-bone (BTB), hamstring, tibialis anterior and posterior, peroneal, achilles] and autografts (BTB, quadriceps, and hamstring)[9]. The semitendinosus (ST) tendon, which is the hamstring tendon used for ACL rupture (ACLR), is found on the medial side of the knee between layer I (encompassing the sartorius muscle) and layer II (encompassing the superficial medial collateral ligament) as described by Warren *et al*[10] and Nichalas *et al*[11]. The insertion of the ST tendon is on the anteromedial aspect of the tibia on the conjoining structure of the pes anserinus together with the gracilis and sartorius tendons[12,13]. In general, better outcomes found

in the literature support the use of autografts than allografts. Moreover, hamstring tendon autograft is one of the optimal choices for reconstructing a ruptured ACL. This is because of the lower failure rates in comparison to that of allografts and avoidance of anterior knee pain found with BTB grafts[9]. In 1934, Galliazi was the first orthopedic surgeon to describe the use of the hamstring tendon as an autograft for ACLR[14]. The aim of this review is to discuss the different hamstring muscle harvesting techniques, graft preparation options, and fixation methods.

The reference numbers will be superscripted in square brackets at the end of the sentence with the citation content or after the cited author's name, with no spaces.

METHOD/LITERATURE SEARCH

We searched for the following keywords in the PubMed database: hamstring autograft, hamstring harvest, infrapatellar branch of the saphenous nerve (IPBSN) injury, saphenous nerve injury, posteromedial hamstring harvest, semitendinosus autograft, gracilis tendon autograft, ACL fixation, and suspensory interference screws. The main review question was "What are the strategies of hamstring autografts available for ACL reconstruction?" and "How are they harvested, prepared, and fixated?" The article collection was not limited to PubMed search of the previously mentioned terms, and further studies were identified and retrieved through citations. Articles were assessed for relevance for inclusion in this review based on the titles and abstracts. The database was searched up to August 22, 2021. Non-English papers and case reports were excluded.

GRAFT HARVESTING

Anteromedial technique

Typically, the hamstring tendon is harvested using the anteromedial approach. The incision is performed medial to the anterior tibial tuberosity and approximately 4-6 cm distal to the joint line. The direction and length of the incision differed based on the surgeon's preference. This is followed by dissection of the subcutaneous tissue until the

sartorial tendon in layer I is exposed. Beneath this layer, the semitendinosus and gracilis tendons are found. Once the tendons are identified, harvesting can be performed in two ways: (1) dissecting the tendons distally, stripping proximally with a closed stripper; and (2) using an open stripper proximally and then stripping distally with a closed stripper. In the first technique, a whip stitch is used for countertraction during harvest. Second, a right-angled retractor is used for countertraction while stripping the tendon[12,13,15,16].

Hamstring tendon harvest may be associated with complications including injury to the medial collateral ligament, premature amputation of the tendon, and injury to the infrapatellar saphenous nerve[12,13,17]. Several methods have been proposed to overcome these complications.

In dissecting through the sartorius tendon in layer I to reach the ST and GT, extreme caution in addition to adequate anatomical knowledge has been advocated to avoid injuring the superficial medial collateral ligament immediately below the two tendons in layer II[12,13]. Moreover, in the new OLIBAS harvesting technique recently published, Olivos-Meza *et al*[17] proposed the use of the tibial tubercle and medial border of the tibia as landmarks for an easier harvest with less complications. MCL injury is suggested to be reduced by a couple of maneuvers in the dissection technique. First, the superficial dissection of the subcutaneous tissue using a No. 15 blade with a vertical incision line, followed by blunt dissection medially and laterally with retractors, and further cleaning of any remnants with 360° motion using wet gauze. Second, direct, safe access to the tendons between the sartorius tendon and MCL by blunt introduction of Kelly forceps into the over-elevation landmark representing the gracilis as seen through the incision while the knee is in 90° flexion. The semitendinosus tendon contains multiple accessory bands. Meticulous dissection of such bands is crucial to prevent harvesting of a graft shorter than expected. Before advancement of the stripper, scissors can be used to release bands while the tendon is taut forcefully by a Penrose drain if the surgeon has chosen a proximal to distal grafting direction or by the whip stitch if a distal to proximal direction is preferred[12,13]. Olivos-Meza *et al*[17] urged manual

exploration of expansions by introducing the index finger along the tendon path and rotating it 360°. Any expansions felt should be exposed through the incision by a Kelly and cut. Colombet *et al*[18] described another approach in identifying all expansions. By pulling out expansions through the incision one by one using an alternative probe hook maneuver, more expansions are exposed. Moreover, the stripper could be easily advanced 10 cm without resistance, indicating that no expansions were left. Furthermore, the direction of the stripper has been proposed to reduce the risk of premature amputation when it is aimed at the origin of the ST, ischial tuberosity, or lesser trochanter when harvesting the GT[13]. Another issue that might require a surgeon to use another graft is retraction and loss of tendons during stripping. This complication is thought to be reduced in the OLIBAS technique by holding the tip of the tendon perpendicularly with strong forceps and rolling it multiple times until the knuckles of the surgeon's non-dominant hand rest on the operated knee while advancing the stripper firmly and gently with the dominant hand[17].

The saphenous nerve gives rise to two branches as it exits the adductor canal: the infrapatellar branch and sartorial branch[19]. The IPBSN is a small cutaneous nerve supplying the anterior aspect of the knee, anterolateral aspect of the leg, and anteroinferior aspect of the knee joint capsule[20]. The sartorial branch provides sensory innervation to the medial aspect of the leg and ankle[19].

Injury to the IPBSN is a common complication of the anteromedial approach for ACL reconstruction. The reported prevalence of IPBSN injury using the anteromedial approach ranges from 21.1% to 83%[15,19-29]. This injury can cause hypoesthesia, dysesthesia, painful neuroma, and reflex sympathetic dystrophy[28]. Pagnani *et al*[12] and Solman *et al*[13] implemented a figure of four position with the knee flexed and the hip abducted and externally rotated during harvest. This position allows the saphenous nerve located on top of the gracilis at the posteromedial joint line to relax, reducing the risk of injury. Pękala *et al*[30] also recommended the use of a figure of four position. Despite the use of this configuration, Figueroa *et al*[28] in their prospective study found 77% of patients to have clinical hypoesthesia and electrophysiological denervation of

the IPBSN post-operatively using a vertical incision. They concluded that this nerve injury must have occurred during the harvest since the saphenous nerve is far from the incision and would only be at risk during stripping where a sharp instrument is near. Mahmood et al[21] have conducted a similar study using an oblique anteromedial incision. They found that 24% of patients complained of hypoesthesia, and the same patients were found to have IPBSN injury on electrophysiological study. Sanders et al[15] performed a survey-based study of patients who underwent ACL reconstruction through a vertical anteromedial incision while also utilizing the figure of four position. Among the participants, 74% reported disturbed sensation. In their anatomical analysis, Sanders et al[15] concluded that injury to the SBSN and IPBSN can occur during tendon stripping, especially when using a mini-incision that obligates the surgeon to blindly harvest the tendons. Furthermore, an anatomical study aimed at describing the IPBSN course with regard to surgery around the knee was also conducted. The IPBSN was found to have a highly variable coarse, the most common variant being the posterior pathway in 56% of the knees (arising along the inferior posterior border of the sartorius muscle), found alone in 28%, and in association with the intramuscular (piercing through the sartorius muscle) and/or the anterior pathway (anterior border of the sartorius muscle) in 28%. Accordingly, Walshaw et al[31] also concluded that the IPBSN is mostly damaged during tendon harvesting with the stripper owing to its close proximity to the ST and GT.

The lower prevalence of injury observed in the study by Mahmood et al[21] in comparison to Figueroa et al[28] and Sanders et al[15] can be attributed to the orientation of the incision. This may be attributed to the subcutaneous oblique course of the infrapatellar nerve inferior to the patella that occupies the anteromedial region of the knee with its multiple branches as reported by Hunter et al[32]. Two meta-analyses have found that the risk of IPBSN injury during ACL reconstruction is significantly higher with vertical incisions than with oblique incisions[30,33]. Pękala et al[34], by simulating differently directed incisions in an ultrasound study on healthy knees, have also documented a similar risk reduction for oblique incision over the vertical incision.

Multiple randomized controlled trials have studied the effect of incision direction on this complication. Keyhani *et al*[25], Mousavi *et al*[27], Sabat *et al*[22], Joshi *et al*[23], and Luo *et al*[19] found a decreased risk of IPBSN injury using the oblique incision compared to that with a vertical traditional incision (Table 1).

In contrast, Chen *et al*[29] and Leiter *et al*[35] found no relationship between the incision direction and IPBSN injury. The larger incision length in these two studies may be the reason, as Luo *et al*[19] found that the average distance between the upper edge of pes anserinus and IPBSN was 0.6 cm. Mahmood *et al*[21] found a significant association between incision length and risk of IPBSN injury. Moreover, the use of a shorter incision was strongly supported in the meta-analysis by Pękala *et al*[30] and Henry *et al*[20] in an anatomical study where they measured the safe distance between an incision and a nerve to be 0.82-0.87 cm (Table 1).

Shorter incisions with adequate access to the hamstring tendons have been proposed. In 2016, Colombet *et al*[18] suggested the use of a small 2-cm vertical incision over the palpable pes anserinus. This incision is intended to decrease the incidence of IPBSN injury and is the cosmetically preferred option. Direct access to the tendons can be achieved by a 3-cm horizontal incision over the fascia following careful soft tissue dissection using Metzenbaum scissors. In the OLIBAS technique, the unique anatomic landmark used for incision placement has also played a role in the use of a smaller vertical/oblique incision (1.5 cm) that allows for cosmetic benefit with direct access to the tendons. The incision is located on a horizontal line drawn between the two landmarks (tibial tubercle and medial border of the tibia) and divided into thirds, and a vertical or oblique incision is made in the second third. The risk of nerve injury is further reduced during subcutaneous tissue dissection, as sharp dissection is only performed in a proximal-distal direction, while further medial-lateral dissection is performed bluntly with two Farabeuf retractors[17]. A unique inverted L-shaped incision of the sartorial fascia has been used by multiple surgeons to allow direct access to the hamstring tendons and reduce the risk of nerve injury[15,17,23]. In a cadaveric study, Tillett *et al*[36] proposed a uniquely placed incision, which is claimed to be located in a

safe zone where neurological injury is prevented and direct access to tendons is achieved. This incision is inclined approximately 30º from the vertical, starting at a point 3 cm medial to the apex of the tibial tuberosity and ending 5 cm medial to it. The authors used this incision in 45 patients with no complications.

Ultrasound (US) was found to readily visualize the IPBSN and its main trunks over the pes anserinus, which are at risk during skin incision. Therefore, pre-operative identification of the anatomical distribution of the IPBSN by US is recommended to reduce the incidence of iatrogenic nerve injury by finding a safe area for the incision. However, smaller branches were not detected[30,34]. Regardless of the orientation of the incision, IPBSN iatrogenic injury remains an unavoidable complication of hamstring tendon harvesting using an anteromedial approach. The previous statement was supported by Leiter et al[35] since a safe zone to prevent IPBSN injury could not be found and nerve distribution is highly variable regarding the number and orientation of branches. Accordingly, an incision that is as small as possible and preferably oblique should always be the goal to limit the number of possibly injured branches[30,34,35]. Furthermore, multiple studies have demonstrated smaller areas of hypoesthesia in patients with oblique incisions than in those with vertical incision[19,22,35](Table 1).

Posteromedial technique
To avoid some of the aforementioned complications, Franz et al[37] pioneered a new approach in harvesting the hamstring tendon from the popliteal fossa. Franz's technique starts with the leg in a figure of four position, with the knee in 60º flexion, allowing for relaxation and protection of the saphenous nerve. The incision is made horizontally on the popliteal crease on top of the semitendinosus tendon, which is palpable in the posteromedial aspect of the popliteal fossa. A visible anatomical landmark to help locate the incision is the Jobert's groove, which is described by Prenkopf, representing the space between the adductor muscle group from the ST. Vertical dissection of the fascia follows. A FiberTape® suture is then looped around the tendon. The tendon is then pulled out through the incision while the knee is flexed to

90°, permitting visualization and dissection of the distal accessory insertions, and avoiding premature graft amputation. Distal-to-proximal harvesting is carried out with an open stripper first to release proximally. Afterwards, a closed tendon stripper is advanced to release the tendon from its insertion distally while palpating the stripper on the anteromedial aspect of the tibia with caution not to perforate the skin. The same incision can be used to harvest the gracilis if the surgeon chooses to follow the same procedure[37].

Kodkani et al[38] implemented a posteromedial technique with some modifications. A small incision (~1–1.5 cm) is made horizontally at the same location as described by Franz. To grant better access to the tendons, the knee is flexed at 30° and externally rotated. Moreover, knee flexion is increased for optimal identification and cutting of distal fibrous bands. After freeing the tendon proximally, the distal insertion is released while the knee is completely flexed and internally rotated. In a review of eight cases, Kodkani et al[38] reported zero intraoperative and post-operative complications, and all patients had very satisfactory cosmetic results. Letartre et al[39] further modified this technique. During the procedure, the surgeon conveniently faced the posterior aspect of the knee. This view is achieved while the hip is flexed, and the knee is flexed at 20°. An assistant holds the limb up by the foot and applies external rotation. A 3-4 cm horizontal incision over the palpable ST is then made. Proximally, the tendon is harvested at 120° flexion. Distal harvesting is performed using a closed, short stripper. In an evaluation of 90 patients prospectively, a complete failure of harvest was reported during their first attempt for the posteromedial approach that required conversion to the anterior approach. In another case, the gracilis was harvested mistakenly instead of the semitendinosus, while in two cases, the ST alone resulted in a weak graft that was reinforced by the gracilis. In addition, no premature ambulation of the graft or sensory deficit occurred in any of the patients.

Wilson et al[40] have described a vertical posteromedial incision. This incision is made while the leg is in a figure of four position, starting from the popliteal crease where the ST is palpable and extending 2-3 cm proximally. The longitudinal orientation of the

incision is thought to improve wound healing, prevent wound complications, and provide a cosmetically appealing option. The tendon is then extracted from the wound, and fibrous extensions are dissected until no calf pinching is visible, which indicates missed bands. Proximal to distal stripping is then performed.

A double incision technique using both an anterior and a posterior incision was described by Prodromos et al[41] with a posterior 2-cm incision while the knee is in 30º flexion in a figure of four position. The incision could be performed vertically or horizontally using the ST as a starting point. Both the ST and GR are pulled out through the wound and held by Penrose drains. The anterior 2-cm incision is made at the ST insertion, as guided by the surgeon's index finger, following the course of the tendon from the posterior, and tenting the skin which marks the location. The incision is obliquely inclined at 45° in relation to the tibia and perpendicular to the pes anserinus. The tendon is harvested proximally with an open stripper from the anterior incision and passed through the posterior incision. At this point, the tendon can be delivered through an anterior incision, and distal release is initiated by cutting the periosteum along the superior and inferior edges of the pes anserinus with a scalpel. Strong pulling of the tendons results in periosteal elevation of 1 cm approximately along with the tendon. The attached part of the periosteum is then incised sharply. This is thought to increase the length of the tendon by adding 1 cm of periosteum and approximately 2 cm of pes anserinus. Accessory tendons are cut with a no. 15 blade or Metzenbaum scissors as they obscure the advancement of the stripper. In a chart review of 175 patients who underwent this technique, no intraoperative difficulties or complications were encountered. The wounds healed without further complications except for one incidence of anterior cellulitis which was managed conservatively with antibiotics. Wound healing and cosmesis were thought to be superior in the posterior incision. In fact, 80% of patients thought they had a better scar appearance compared to that of others who underwent ACL reconstruction[41].

Khanna et al[42] recently described a posterior hamstring harvesting technique for pediatric and adolescent subjects. The incision was made horizontally 2-3 cm in length

over the palpable ST, while the leg was abducted, and externally rotated. A proximal-to-distal harvest was then adopted. The semitendinosus accessory band was excised and the gracilis was harvested in a similar manner. A total of 214 patients were followed up for a minimum of 6 mo for complication analysis. In all cases, the tendons were identified intraoperatively, and no incidence of premature graft transection was reported. No wound healing issues, painful scars, restriction of knee motion due to incision location, or neurovascular injuries were observed. The patient also reported no cosmetic concerns.

Anteromedial vs posteromedial technique

The traditional anteromedial hamstring harvest was compared with the posteromedial approach as described by Franz *et al*[37]. They conducted an randomised controlled trial (RCT) with 100 patients and found that the average ST harvest time was significantly lower in the posteromedial group. Although the harvested graft was sufficient in length for both groups, the average length was significantly longer in the anteromedial group with a 2 cm difference. Fourteen percent of patients in the anteromedial group reported sensory deficits along the distribution of the saphenous nerve, compared to zero sensory issues in the posteromedial group. Pain scores using the visual analog scale were similar in both groups. No wound complications were found in the posteromedial group, whereas one case in the anteromedial group had a superficial wound infection which was treated conservatively with oral antibiotics. Patients who underwent a posteromedial incision had a significantly smaller incision than those who underwent a vertical anteromedial incision.

Shu *et al*[43] retrospectively reviewed 29 patients who underwent a posteromedial harvest as described by Wilson *et al*[40]. Among these patients, 22 underwent an anteromedial harvest. Operative and tourniquet times were significantly lower in the posteromedial group. This could be explained by the ease of tendon and accessory band identification using the posteromedial approach. The posteromedial group also had a reduced risk of unintentionally harvesting the gracilis. Both groups had no incidences

of premature tendon amputation or IPBSN injury. The patients were then contacted for subjective knee scores, including Knee Osteoarthritis and Outcomes Score, Western Ontario and McMaster Universities Osteoarthritis Index, and International Knee Documentation Committee score (IKDC). All scores showed no significant differences between the two groups.

In the posteromedial incision, tendons are readily identified, and adequate exposure of all extensions and accessory insertions can be achieved[38,40]. Specifically, the most important ST accessory insertion found in 90% of patients is attached to the medial head of gastrocnemius. This band is found 2.6 cm below the posterior incision and 7.6 cm away from the anterior approach[44]. Posterior direct access to the tendon can be achieved even in obese patients, as the tendons are palpable posteriorly and have little subcutaneous tissue coverage[37]. Moreover, Roussignol et al[44] found that a 3 cm posterior incision is sufficient in both identifying tendons and cutting accessory insertions with the complete avoidance of premature transection of the graft.

Neurological injury of the saphenous nerve and its branches is avoided in a posterior approach, as the nerve is protected from the sharp stripper by the sartorial fascia that is left intact in this technique[38,44]. Therefore, none of the studies included in this review reported such complications following the posteromedial approach (Table 2).

In a prospective clinical study, Ochiai et al[24] reported a low IPBSN injury rate of 21.1% following an anteromedial approach using a vertical incision. This may be explained by the long follow up of 24 mo compared with the 77% at 3 wk post reconstruction in the study by Figueroa et al[28]. Furthermore, Luo et al[19], Sabat et al[22], Leiter et al[35], and Chen et al[29] reported that the area of sensory disturbances heals over time. Similarly, Joshi et al[23] reported gradual improvement in paresthesia within a year. Recovery was also noted to be faster with the oblique incision than with vertical incision. A hypothesis generated to support the difference was that in the oblique incision, IPBSN injury results in neuropraxia, while the vertical incision results in a neurotmesis injury[23]. Sabat et al[22] and Mousavi et al[27] reported higher satisfaction rates in patients who underwent oblique incision than in those who underwent vertical

incision. In contrast, Grassi et al[33] reported that the incision orientation had no impact on the Lysholm score or patient subjective satisfaction. Moreover, Ochiai et al[24] reported no significant difference in Lysholm score, visual analog scale pain score, patient-based SF-36, and presence of anterior knee pain in relation to IPBSN injury. However, patients with IPBSN were found to be significantly less satisfied than patients without this complication[21]. Apart from the above-mentioned studies, Sanders et al[15], Keyhani et al[25], Figueroa et al[28], and Sabat et al[22] reported that the majority of patients with a neurological injury post-operatively thought that it had no significant effect on their daily activities.

GRAFT PREPARATION

Once the hamstring tendons were completely harvested, muscular remnants were removed. Based on the choice to harvest the semitendinosus alone or together with the gracilis, the preparation differs. For a four-strand (quadrupled) semitendinosus graft (4-ST), the ST is folded with a non-absorbable suture in the middle, and the two ends are stitched with a nona-bsorbable suture. The graft was folded again with a non-absorbable suture in the middle, held on a suspensory device, and whipstitched from proximal to distal. In case both semitendinosus and gracilis (2ST-2GT) are harvested, a four-strand graft is created with both tendons folded and loaded on a suspensory device. A non-absorbable suture is passed twice around the free ends, and the tendons are whipstitched with a non-absorbable suture once from distal to proximal, and again from proximal to distal[45]. These graft options are most commonly used when hamstring autografts are preferred[46].

4ST vs 2ST-2GT hamstring autograft

To guide the choice between 4ST and 2ST-2GT autograft, multiple investigators have compared patient-reported outcomes as well as hamstring muscle strength following ACL reconstruction. Ardern et al[47] stated that harvesting the gracilis along with the semitendinosus results in a deficit in isometric strength at deep knee flexion angles.

Furthermore, Sharma *et al*[46] also found a large difference between ST autograft subjects and STGT autograft subjects in isometric strength at deep flexion angles in a meta-analysis. A significant decrease in active knee flexion angle after STGT harvesting has been reported[46,47]. Similar with isometric strength, active knee flexion is evaluated while the hip is in relative extension, aiding in demonstrating hamstring muscle insufficiency. A significant difference in isokinetic peak torque was found by Chin *et al*[48]. This deficit is rarely found in the literature because the isokinetic flexion peak torque is generated at shallow angles that are produced by the contraction of the biceps femoris rather than the semitendinosus and/or gracilis. Additionally, the peak torque is measured while the hip is flexed to 90°, a suboptimal position for the hamstring to flex the knee[47].

In a randomized control study, Tashiro *et al*[49] evaluated hamstring muscle strength and compared the results between patients who had both tendons harvested and patients with isolated ST harvest. The STGT group had significantly weaker isometric and isokinetic hamstring strength than the group with preserved gracilis. Moreover, both groups were found to have significantly weaker hamstrings at angles of 70° and deeper in isokinetic and isometric evaluations compared to the pre-operative status. Similarly, Nakamura *et al*[50] found a significant hamstring strength deficit identified using isokinetic testing at 90° in both groups. However, noifferrence was observed between the STGT and ST groups. A significantly lower active knee flexion angle in the STGT group was found. Hu *et al*[51] reported a significantly higher strength deficit in the STGT group during isometric flexion at 90°. A trend of increasing deficit with increasing angle was also noted[49,51]. A loss in active knee flexion angle was significantly higher in the STGT group than in the ST group in a prospective review by Adachi *et al*[52]. However, no significant difference was reported in hamstring isokinetic strength evaluation[52]. Yosmaoglu *et al*[53] in another prospective review reported a significantly higher hamstring isokinetic deficit in flexion at 60° in subjects post-STGT autograft harvest than in subjects post-ST autograft harvest. Three RCTs by Carter *et al*[54], Karimi-Mobarakeh *et al*[55], and Gobbi *et al*[56]; two prospective cohort studies by Inagaki *et al*[57]

and Segawa *et al*[58]; and three retrospective studies by Ardern *et al*[59], Barenius *et al*[60], and Lipscomb *et al*[61] found no difference in flexion hamstring strength deficit after ACL reconstruction with an isolated ST harvest or a combined ST and GT harvest. Of the studies included in this review, only two investigated rotational muscle strength and compared patients after STGT autograft and ST autograft. Segawa *et al*[58] in their prospective review have reported a significantly higher deficit of internal rotation at 30° and 120° in the STGT group. This same strength deficit was found to be significantly more common in females than in males. Additionally, Gobbi *et al*[56] found a significantly greater deficit in isokinetic internal and external rotation at 60°.

The large number of articles with different study designs that reported no difference in hamstring strength between the two groups could be attributed to the method of strength evaluation used[47]. Most articles assessed the strength deficit with isokinetic testing which are done in a sitting position while the hip is 90° flexed, a position that doesn't allow the ST and GT muscles to contract concentrically to produce knee flexion were a deficit could be spotted. Another explanation is that the isokinetic peak torque is usually measured at shallow angles. Here, knee flexion is elicited mostly by biceps femoris contraction, while the semitendinosus and gracilis muscle function is best evaluated at deeper angles[47]. In contrast, a reported strength deficit was elicited by Ardern *et al*[59] as a result of poor rehabilitation or early assessment, where the muscles have not recovered fully.

Despite the statistical significance in hamstring strength, the previously mentioned articles reported no difference in subjective patient-reported outcome scores[46-49,55-60]. In addition, Hu *et al*[51] found a significant difference in the pain section of the knee injury and osteoarthritis outcome score. This can be attributed to the fact that the strength deficit is only observed in such deep angles and is not utilized by most people in their daily activities and is specifically used by athletes in gymnastics, judo, and wrestling (Table 3)[46,47,52].

GRAFT FIXATION

Currently, there are many methods for femoral-sided graft fixation in ACL reconstruction. They can be categorized into two main types: intra-tunnel fixation (interference screw) and extra tunnel fixation (cortical fixation devices or femoral loops). Fixation of soft tissue grafts is generally considered a weak point early in the post-operative course after ACL reconstruction[62]. Therefore, many different devices have been developed for soft-tissue femoral fixation[63]. Despite numerous options, the gold standard for femoral fixation has not yet been identified[63].

Suspensory fixation

Fixation methods can be categorized into compression, expansion, and suspension. Suspensory devices can be subdivided into cortical (metal plates with or without suture loops), cancellous, and cortico-cancellous devices[64]. Suspensory fixation devices can maximize the amount of graft in the femoral tunnel, thereby improving the outcomes of ACL reconstruction. Suspensory devices commonly feature a button that rests on the cortex of the femur and a loop that holds the folded soft tissue ACL graft in position until healing can occur[65-68]. This technique can avoid common problems that occur with interference screw fixation, such as divergent screw placement, laceration of sutures or grafts by screw threads, and increasing difficulty of revision surgery in the presence of screws[69].

Interference screw fixation

Because of its capacity to resist cyclic movements, one of the most efficient fixation devices are interference screws. The interference screw is a conical threaded device inserted into the bone tunnel, compressing the graft against the tunnel walls, and fixing it in the desired position. Although it is more commonly used on the tibial side; this screw can also be used for femoral fixation. Interference screws may be composed of metals or bioabsorbable materials[70]. A review article by Debieux *et al*[70] showed no difference in self-reported knee function and patients' post-operative activity levels when comparing bioabsorbable interference screws with metallic interference screws.

However, bioabsorbable screws may be associated with overall treatment failures, including implant breakage during surgery.

Suspensory fixation vs interference screw fixation

There is no consensus on the best method to achieve hamstring autograft fixation during ACL reconstruction. Intra-tunnel fixation methods predominantly rely on the use of metal or bioresorbable interference screws. Extratunnel fixation methods generally rely on buttons, staples, or washer-post combinations placed outside the tunnel over the adjacent cortical bone surface[71]. Based on the literature review, each fixation has its own advantages and disadvantages for achieving early and long-term successful ACL reconstruction. Regarding the incidence of graft lengthening under cyclical loads after ACL reconstruction, Boutsiadis *et al*[72] assessed anterior knee laxity following primary ACLR. They found that the use of an adjustable loop suspensory fixation device for femoral fixation is associated with non-inferior post-operative anterior knee laxity results compared with interference screw fixation at a minimum 2-year follow-up. The operative pivot shift is the only significant risk factor for post-operative residual anterior knee laxity > 3 mm.

Regarding tunnel widening, a meta-analysis comparing the clinical results of the all-inside (ACLR) technique using suspensory cortical button fixation to a whole tibial tunnel drilling technique with interference screw fixation has shown that all-inside ACLR with suspensory cortical button fixation was not clinically superior in terms of functional outcomes, knee laxity measured with an arthrometer, or rerupture rate. However, the advantage of using suspensory cortical button fixation is the ability to utilize a thicker graft and a lower rate of tibial tunnel widening[73]. In addition, Baumfeld *et al*[74] found significantly more femoral tunnel widening associated with the endobutton suspensory fixation system compared to double cross-pin fixation in the tunnel. However, they found significant difference in the amount of tibial tunnel widening between the groups in this study[74]. Furthermore, a prospective comparative study by Sabat *et al*[75] compared the incidence of tunnel widening in patients who

underwent ACL reconstruction with a quadrupled hamstring graft using either endobutton CL (Smith & Nephew Endoscopy, Andover, MA) or Transfix (Arthrex, Naples, FL) on the femoral tunnel side and bioabsorbable interference screws in the tibial tunnel using computed tomography scans. Femoral tunnel widening was significantly lower in the Transfix group than in the EndoButton group. Regarding tunnel drilling techniques, Saygi *et al*[76] investigated the effect of tunnel undersizing (tight fit ACL reconstruction technique) on tunnel widening and overall clinical outcomes compared with conventional ACL reconstruction techniques. They concluded that undersized drilling might be preferred when using button fixation to reduce tunnel widening and improve clinical satisfaction.

In general, each fixation device has biomechanical properties that have been demonstrated in several publications. Shen *et al*[77] compared cross-pin to endobutton-CL femoral fixation and found that they are equally strong and safe fixation options for ACL reconstruction. However, cross-pin fixation has significantly less displacement of the femur-graft-tibia complex than endobutton-CL fixation in response to the cyclic loading test. Thus, it could be considered when early aggressive rehabilitation following ACL reconstruction is required. Milano *et al*[64] found that corticocancellous suspension fixation obtained with transcondylar devices offers the best results in terms of graft elongation, fixation strength, and stiffness. On the other hand, cancellous suspension fixation was homogeneous with other suspension fixation mechanisms but is significantly weaker. Interference screws, both metallic and absorbable, showed a low failure load but the greatest graft elongation. They concluded that the mechanical behavior of cortical suspension fixation is strictly correlated with the area of the contact surface between the hardware and cortical bone and the structural properties of the implant. Vertullo *et al*[78] conducted a biomechanical study comparing quadrupled tendon graft constructs with adjustable loop suspensory fixation to four-strand graft constructs secured with screws and a femoral fixed-loop device. They found small, yet statistically significant, biomechanical differences between the different techniques. In addition, they found that tibial screw fixation resulted in a lower ultimate failure load

and higher total graft elongation. Another study compared the different fixation techniques for ACLR. On the femoral side, a cross-pin, a metallic interference screw, a bioabsorbable interference screw, and a suspensory device were used in 32.3%, 27.3%, 24.8%, 15.5% of the patients, respectively. On the tibial side, a metallic interference screw, a bioabsorbable interference screw, a screw and plastic sheath, a screw post, and a cross-pin were used in 38.7%, 31%, 15.7%, 12.8%, and 1.7% of the patients, respectively. The side-to-side anterior-posterior tibial translation was 1.9 ± 0.9, 1.5 ± 0.9, 1.5 ± 0.8, and 2.2 ± 0.4 mm for metallic interference screw, bioabsorbable screw, cross-pin, and suspensory device, respectively. The rate of failure was 6.1%, 3.3%, 1.7%, and 1.2% for the bioabsorbable interference screw, metallic interference screw, cross-pin, and suspensory device, respectively. Two-thirds of the patients achieved good-to-excellent clinical outcomes. Several pitfalls that affect current fixation techniques, such as graft tensioning and graft tunnel motion, remain unaddressed[79]. Moreover, Saccomanno et al[63] compared the cortical button with transfemoral suspensory fixation. They suggested that there were no short- to medium-term differences in the knee-specific outcome measures. In contrast, a meta-analysis by Hu et al[80] found a decrease in instrumented side-to-side anteroposterior laxity when cross-pin transfixation was used. However, the difference appears to have limited clinical significance compared with interference screw fixation. In addition, a two-year clinical outcome study found that patients who underwent ACL reconstruction with intra-tunnel or extratunnel fixation had comparable results based on objective IKDC, Lysholm knee scale, Tegner activity level survey, anterior knee joint laxity measurements, and time to resume sports. Patients who received intra-tunnel fixation began full weight-bearing, jogging, and running earlier than patients who received extra-tunnel fixation[62]. Finally, a meta-analysis showed that the overall graft failure and revision rates with press-fit fixation for ACLR were low. There were no significant differences in the complication rates between patients who underwent femoral press-fit or femoral metal interference screw fixation. Patients who underwent press-fit fixation for ACLR had significant improvements in functional outcome scores post-operatively and significantly lower

post-operative bone tunnel enlargement than patients who underwent bioabsorbable fixation. Thus, early evidence suggests that press-fit fixation is a good option for patients undergoing ACLR (Table 4)[81].

CONCLUSION

Multiple surgical maneuvers and approaches have been reported to avoid complications when reconstructing a ruptured ACL. For a hamstring tendon autograft, a shorter oblique anteromedial incision has been suggested to reduce the incidence of local neurological injuries compared to that with a longer vertical incision. Moreover, the posteromedial harvesting approach has been reported to be associated with fewer complications and better cosmetic outcomes. Sparing the gracilis tendon when harvesting the hamstring tendon can reduce the strength deficit post-operatively at deeper angles utilized by athletes. Several hamstring autograft fixation methods are available, but the optimum method is yet to be determined. Further studies are required to establish a safer surgical approach.

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