Review Article

Proprioception in anterior cruciate ligament deficient knees and its relevance in anterior cruciate ligament reconstruction

Mandeep S Dhillon, Kamal Bali, Sharad Prabhakar

Abstract

Injury to the anterior cruciate ligament (ACL) not only causes mechanical instability but also leads to a functional deficit in the form of diminished proprioception of the knee joint. "Functional" recovery is often incomplete even after "anatomic" arthroscopic ACL reconstruction, as some patients with a clinically satisfactory repair and good ligament tension continue to complain of a feeling of instability and giving way, although the knee does not sublux on clinical testing. Factors that may play a role could be proprioceptive elements, as the intact ACL has been shown to have significant receptors. Significant data have come to light demonstrating proprioceptive differences between normal and injured knees, and often between injured and reconstructed knees. ACL remnants have been shown to have proprioceptive fibers that could enhance functional recovery if they adhere to or grow into the reconstructed ligament. Conventionally the torn remnants are shaved off from the knee before graft insertion; modern surgical techniques, with remnant sparing methods have shown better outcomes and functional recovery, and this could be an avenue for future research and development. This article analyzes and reviews our understanding of the sensory element of ACL deficiency, with specific reference to proprioception as an important component of functional knee stability. The types of mechanoreceptors, their distribution and presence in ACL remnants is reviewed, and suggestions are made to minimize soft tissue shaving during ACL reconstruction to ensure a better functional outcome in the reconstructed knee.

Key words: Anterior cruciate ligament, reconstruction, mechanoreceptors, proprioception

Introduction

Despite a better understanding of the anatomic aspects, better instrumentation and perhaps better surgical techniques, the functional outcomes after anterior cruciate ligament (ACL) reconstruction are variable. The mechanical stability/tightness of the grafted ACL after reconstruction has correlated poorly with postoperative patient satisfaction and the functional outcome.[1] These varying results after ACL reconstruction have been previously attributed predominantly to anatomic factors. The functional issues like proprioception and compensatory mechanisms have only recently come to light, and their role in achieving post-operative stability is only now coming to the forefront. Many authors have shown that proprioceptive feedback might be an important factor relating to functional outcomes, as well as a subjective feeling of stability in ACL-reconstructed knees.[2,3]

Proprioception refers to the specialized variation of the sensory modality of touch that encompasses the sensation of joint movement and joint position. It has three components: a static awareness of joint position, awareness/detection of movement and acceleration, and a closed loop efferent activity which starts reflex response and regulates muscles. Proprioception is receptor and neural arc mediated; it has been demonstrated that a significant number of mechanoreceptors exist in the fibers of the ACL.[4-8] These receptors (along with the mechanoreceptors located in the PCL, the collateral ligaments and capsular fibers), play an important role in the complicated neural network of proprioception.[9,10] Mechanical stability of the knee, although the principal factor for a successful outcome, may not be sufficient in itself for a good outcome after ACL reconstruction; the evolution of our knowledge has now

Department of Orthopaedics, Post Graduate Institute of Medical Education and Research (PGIMER), Chandigarh, India

Address for correspondence: Dr. Kamal Bali,
Department of Orthopedic Surgery, Post Graduate Institute of Medical Education and Research (PGIMER), Chandigarh - 160 012, India. E-mail: kamalpgi@gmail.com

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shown that proprioception recovery also plays a significant role in the overall success of this reconstructive procedure.

Post injury proprioception loss is perhaps indirectly demonstrated by the altered gait patterns of the ACL-deficient knee; studies have demonstrated that these are probably altered due to changes in proprioception, and not principally due to the mechanical instability that ensues.[11-13] Altered gait patterns plus proprioceptive deficits significantly add to the mechanical instability in ACL-deficient knees, and can predispose to secondary injuries.[14] It thus becomes relevant to understand the importance of proprioception in stabilizing the knee joint, and also the fact that anatomic issues alone may not suffice to get back good function.

The authors searched MEDLINE, EMBASE, CINAHL, and Google Scholar using the keywords "proprioception", "ACL reconstruction", "knee sensation", "mechanoreceptors", and "nerve supply", without time limits or restriction to language. Based on our literature review, we present a discussion on the concept of functional stability of the knee joint. We also review in detail the current literature dealing with mechanoreceptors in both uninjured and injured ACL stumps; the decrease in proprioception following an ACL injury; the restoration of proprioception after ACL reconstruction; and the role of postoperative rehabilitation. The review also analyses the studies pertaining to remnant preservation during ACL reconstruction and discusses the current status of such remnant preserving surgeries.

Functional Stability of the Knee Joint

The major mechanical function of the ACL is to prevent excessive anterior tibial translation in various degrees of flexion. A complete failure of the human ACL occurs at stress levels of about 1725 Newtons, while bone avulsions and ligamentous micro-failures occur at lower stress levels.[2] It has also been demonstrated *in vitro* that the load on the knee joint and its ligaments during strenuous activities such as downhill skiing substantially exceeds potential injury levels;[15] thus the knee joint must rely on mechanisms other than the mechanical properties of its ligaments to maintain joint stability during strenuous physical activities. This may be a form of "functional stability" which is brought about by the muscle contractions, which is aided by sensations transmitted through mechanoreceptors present in the ligaments to the brain.

After an ACL injury, it has been observed that the relationship between passive stability and the functional stability of the knee joint is often vague.[16,17] Borsa[11] proposed that the functional instability that occurs after an injury to the ACL is due to the combined effects of excessive tibial translation and a lack of "coordinated muscle activity" to stabilize the knee joint. This lack of coordinated muscle stabilization of the knee joint is thought to be due to diminished or absent sensory feedback from the ACL to the neuromuscular system.

Mechanoreceptors in Intact ACL

Histologically it has been demonstrated that the uninjured human ACL contains mechanoreceptors that can detect changes in tension, speed, acceleration, direction of movement, and the position of the knee joint.[4-9,17] Various authors have demonstrated mechanoreceptors by different methods [Table 1].

The first histological demonstration of mechanoreceptors in the human ACL was done by Schultz, *et al.*[5] in 1984. They obtained human cruciate ligaments at the time of total knee replacement, from autopsy and amputation specimens, and examined histological sections of the ligaments for the presence of mechanoreceptors using the Bodian, Bielschowsky, and Ranvier gold-chloride stains for axons and nerve-endings. The cruciate ligaments obtained at the time of total knee replacement were found to be too distorted by disease processes to provide sufficient evidence. The autopsy and amputation specimens, however, contained fusiform mechanoreceptor structures measuring 200 by 75 μm, with a single axon exiting from the capsule of the receptor. One to three receptors were found at the surface of each ligament beneath the synovial membrane, but were absent from the joint capsules and menisci. Morphologically the receptors resembled Golgi tendon organs, and it seemed likely that they provided proprioceptive information and contributed to reflexes inhibiting injurious movements of the knee. Subsequent studies have demonstrated a higher concentration of mechanoreceptors near ACL attachments to bone.[4-6]

Direct stress applied to ACL has also been shown to cause reflex hamstring activity (mediated at the spinal cord level), which contributes to the maintenance of joint integrity.[18] Damaged mechanoreceptors would alter neuromuscular

Table 1: Mechanoceptors in an intact ACL

Author	Type of receptor	Method used
Schultz, *et al.*[5]	Golgi tendon organs	Bodian, Bielschowsky, Ranvier gold chloride
Zimny *et al.*[4]	Ruffini end organs and Pacinian corpuscles	Modified gold-chloride
Schutte *et al.*[6]	Slow-adapting Ruffini type and rapidly adapting Pacinian corpuscle	Gairns gold chloride
Halata *et al.*[7]	Ruffini corpuscles, and lamellated corpuscles	H and E electron microscopy
Fromm *et al.*[8]	Ruffini corpuscles	Immuno-histology

ACL - Anterior cruciate ligament

functions secondary to diminished somato-sensory information (proprioception and kinesthesia); this is becoming a key factor in understanding functional instability after ACL injuries.[19,20]

Importance of Proprioception

Roberts *et al.*[21] analyzed proprioception of knee joint and its relation to activity level, laxity, meniscal injuries, collateral ligament injuries, cartilage injuries, age and subjective function in patients with ACL-deficient knees. The threshold to detection of slow passive movement was taken as a measure of proprioception of the knee. These authors found that lateral cartilage lesions, increased laxity, and older age were the factors associated with poorer proprioception, while a higher activity level prior to injury co-related with better proprioception after injury. They also found that subjective knee function was directly related to knee proprioception.

Other authors[22-24] have also commented on the poor correlation between the clinical signs, knee assessment scores and the patient satisfaction, and functional abilities following ACL reconstruction. Barrett[16] evaluated 45 patients of ACL-deficient knees who had undergone subsequent ACL reconstruction. Clinical ligament testing was done, along with subjective stability assessment, functional scores, and propriception evaluation. He noted that the clinical ligament stability levels correlated poorly with the patient's satisfaction and the overall functional outcome. However, it was the proprioception of the knee that actually correlated with both function ($r = 0.84$) and with patient satisfaction ($r = 0.9$). Barrett thus proposed that good postoperative proprioception, rather than the mechanical ligament stability, was the major factor that determined satisfactory functional outcome after ACL reconstruction.

Bonfim *et al.*[25] assessed proprioceptive function in patients after unilateral ACL reconstruction. The study included 10 participants each in an ACL reconstruction group and a control group without knee injury. Evaluation was based on knee position perception at predetermined angles, threshold for detection of passive knee movement at various angles, hamstring muscles latency, and postural control on single and double leg stance. Individuals with a reconstructed knee were found to have inferior results based on these evaluations. The authors thus concluded that after ACL reconstruction, some sensory and motor deficits in the knee still persisted, which could be due to the lack of proprioceptive feedback.

Beard *et al.*[26] proposed that measurement of proprioception in the ACL-deficient knees might be a useful guide to provide an objective assessment of efficacy of conservative treatment and the need for surgery in such patients. They studied 30 patients with unilateral ACL deficiency and found that the mean latency of reflex hamstring contraction in the injured leg was nearly twice that in the unaffected limb (99 ms and 53 ms respectively). A significant correlation was found between the differential latency and the frequency of episodes of "giving way" in the patients. The authors thus concluded that functional instability might be due, in part, to loss of proprioception and decreased proprioception might be an indicator of need for surgery.

Proprioception in ACL-deficient Knees

Many authors have demonstrated significant proprioceptive deficits in ACL-deficient knees.[12,27-30] The clinical methods of measuring proprioception in ACL-deficient knees have ranged from detection of passive change in motion, detection of threshold of movement, to active and visual reproduction of a fixed degree of passive angle change. Barrack *et al.*[12] evaluated 11 ACL-deficient knees where proprioception was measured using threshold to detection of passive change in knee position. Identical testing was carried out in an age-matched group with intact ACLs. The authors did a multivariate analysis and included potentially significant variables such as age, time from injury, and degree of rehabilitation in the patients. The authors found that proprioception was virtually identical in the two knees of the control group. The test group, however, showed a significantly lower proprioceptive activity in injured knees as compared to the uninjured knees. Upon multivariate analysis, ACL deficiency was found to be primarily responsible for the diminished proprioception of the injured knees; they thus concluded that complete ACL tears lead to a decline in proprioceptive function of injured knees.

A similar study was conducted by Corrigan *et al.*[27] who measured proprioception in 20 knees with ACL instability and compared it with 17 age-matched controls. These authors noted diminished proprioception in injured knees as compared to uninjured knees. An important finding noted was a significant correlation of the proprioceptive deficit of the injured knee with the hamstring/quadriceps power ratio recorded from the same limb. Subjects with greater power in hamstrings compared to the quadriceps showed better proprioceptive performance. However no such correlation was found in the control group with uninjured knees. The authors thus concluded that the quadriceps atrophy might be reflexly induced in ACL-deficient knees, and this may actually improve proprioception in injured knees.

A detailed analysis of proprioception in normal and ACL-deficient knees was also done by Pap *et al.*[28] Proprioception

was assessed using detection of knee movement in 20 patients with unilateral ACL deficient knees and 15 age-matched control subjects. These authors also found diminished proprioception in knees with ACL tears as compared to the uninjured knees of patients and the control group.

Effects of ACL Reconstruction and Postoperative Rehabilitation on Knee Proprioception

ACL reconstruction alters proprioception of the knee to a certain extent; some authors have demonstrated that reconstruction of ACL restores proprioception and kinesthesia equivalent to that of ACL intact knees.[31-36] Others have found that kinesthesia is better in ACL-reconstructed knees than in ACL-deficient knees, but is still lesser than knees of uninjured controls.[16,25,37-39] This discrepancy between studies might be due to different measures of proprioception and kinesthesia used, variable times between injury and surgery, variable age of the subjects,[21,40] and different surgical techniques and different times of evaluation after surgery.

In a recent study, Angoules *et al.*[31] prospectively studied knee proprioception following ACL reconstruction in 40 patients, allocated into two equal groups based on reconstruction using hamstring or bone-patellar tendon-bone autograft. Joint position sense at various knee angles and threshold to detection of passive motion at 15° and 45° were used as measures of proprioception. The patients were assessed preoperatively and at 3, 6 and 12 months, postoperatively. The uninjured contralateral knee of these patients was used as an internal control. At 6 and 12 months, no statistical difference was found in the proprioceptive acuity of the reconstructed knee and uninjured knee, or in the two graft groups. The authors concluded that knee proprioception returned to normal within 6 months of ACL reconstruction, without statistically significant differences between types of autograft used.

Risberg *et al.*[41] evaluated the effect of functional knee bracing on knee proprioception in ACL-reconstructed knees. Twenty patients with ACL reconstruction using bone-patellar tendon-grafts were followed up for 2 years with active participation in controlled rehabilitation programs. Ten subjects with healthy uninjured knees were the controls. The authors found no statistically significant differences in proprioception (as measured by threshold for detection of passive movement) between the ACL-reconstructed and contra-lateral knees, or between the ACL-reconstructed group and the healthy control group. Neither was bracing found to produce any significant change in the proprioception of the ACL-reconstructed group or for the control group.

In a recently published systematic review[42] on rehabilitation protocols following ACL reconstruction, the authors indicated that an accelerated protocol of physiotherapy (without postoperative bracing) carried the maximum advantages and did not lead to stability problems. The most important aims of such a protocol include reduction of pain, swelling, and inflammation and regaining range of motion, strength, and neuromuscular control.

Muaidi *et al.*[35] tried to determine the proprioceptive acuity in rotation after ACL injury and in reconstructed knees. Apart from the differences in proprioceptive acuity, an assessment of range, laxity, and activity level was done in 20 injured knees and compared with contralateral knees and 20 healthy controls. The authors noted a deficit in preoperative knee rotation proprioception when compared with healthy controls. However 3 months after four-strand hamstring reconstruction, there was a significant improvement in proprioceptive acuity, anterior laxity, and subjective knee stability. The authors concluded that knee rotatory proprioception was reduced in patients with ACL deficiency when compared with healthy controls. Three months after ACL reconstruction, the rotation proprioceptive acuity, laxity, and function were improved and patients returned to previous activity levels within 6 months of reconstruction.

Denti *et al.*[17] found that ACL reconstruction with autologous patellar tendon in sheep (4 cases) resulted in persistence of mechanoreceptors in the reconstructed ACL. When an artificial ligament (four cases) was used in these experiments, no mechanoreceptors were subsequently found. They also found morphologically normal mechanoreceptors in two human patients with lax reconstructed ACLs 9 and 10 years after the operation. Their results indirectly showed persistent proprioceptive potential of ACL in a reconstructed knee when autologous grafts were used.

Ochi *et al.*[43] looked at somatosensory-evoked potentials (SEPs) after direct electrical stimulation of injured, reconstructed, and normal ACLs during arthroscopy under general anesthesia. They studied position sense of the knee before and after reconstruction and also looked for the correlation between the SEP and instability. Detectable SEPs similar to the normal group were found in all ligaments reconstructed with autogenous hamstring tendons. The authors thus concluded that some degree of sensory reinnervation did occur in the reconstructed human ACL, and this was reflected in the subsequent function of the knee.

Proprioceptive Potential of the Stump of an Injured ACL

A few authors have tried to identify if any proprioceptive

potential exists in the residual stump of an injured ACL. Denti *et al*.[17] used Ruffini gold chloride staining to look for mechanoreceptors in the injured ACL stumps. In untreated ACL lesions in humans (n=20), morphologically normal mechanoreceptors persisted in the ACL remnant for about 3 months after injury. Beyond that time, the number of receptors gradually decreased. By the ninth month after injury, only a few nerve endings were found, and they were totally absent after 1 year. Their results indicate the reduced proprioceptive potential of the stump with the passage of time, and may have a bearing on surgical outcomes in cases where reconstruction is delayed.

Ochi *et al*.[43] also demonstrated reproducible cortical somatosensory evoked potentials induced by electrical stimulation in 15 of 32 ACL remnants. They hypothesized that the original sensory neurons are preserved in the ACL remnants to some extent.

Georgoulis *et al*.[44] studied the presence of proprioceptive mechanoreceptors in the remnants of the ruptured ACL as a possible source of re-innervation of the ACL autograft. They identified two types of ACL remnants; in 15 patients the ACL was found adhered to the PCL, and in all these mechanoreceptors were found. In five patients mushroom-like remnants were found which revealed either none or small numbers of mechanoreceptors; however, free nerve endings were found in both patient groups. The authors concluded that in patients with an ACL remnant adherent to the PCL, mechanoreceptors exist even 3 years after injury and the residual stump may actually act as a possible source of reinnervation of the graft.

Dhillon *et al*.[45] evaluated the proprioceptive potential in residual ACL remnants. The authors harvested the remnants of ruptured ACLs in 63 consecutive patients undergoing arthroscopic ACL reconstruction. These were then examined for evidence of residual proprioceptive fibers using H and E, and monoclonal antibodies to S-100 and NFP (neurofilament protein). Histological findings included good subsynovial and intra-fascicular vascularity with free nerve endings in the majority of the residual stumps. Morphologically normal mechanoreceptors (H and E) and proprioceptive fibers (positivity with monoclonal antibody for NFP) were found in 46% and 52.4% of stumps, respectively. A statistically significant relationship was found between injury duration and persistence of mechanoreceptors and proprioceptive fibers. The proprioceptive potential was also higher in stumps in which ACL remnant was adherent to PCL. Their study showed persistent residual proprioceptive fibers in an injured ACL, (especially early cases with PCL adherence). They thus concluded that preserving the ACL remnants might improve functional outcome after ACL reconstruction as some re-innervation and recovery of proprioception is likely in such cases.

Remnant Preserving ACL Reconstruction

ACL reconstruction involves surgical graft replacement of the torn ligament. Arthroscopic reconstruction using bone-patellar tendon-bone autograft or hamstrings is the gold standard.[1,22,46] Conventionally the torn ligament remnants are shaved off from the knee before the graft is inserted, as it is well documented that this removal of the remnant ACL stumps helps reduce chances of arthrofibrosis[47,48] and the so-called cyclops lesion at a later stage. Effective shaving also facilitates visualization and technical performance of the procedure.[44]

Previous studies of ACL anatomy and histology have shown that the maximum concentration of the nerve endings is mainly in close proximity to the bone (i.e. the attachment sites) and this serves as this main tract for proprioceptive feedback.[17] These are the stumps which are seen at arthroscopy and are routinely removed; evolving understanding of the importance of these ACL stumps has made many surgeons aware that routine stump shaving may actually aggravate sensory damage of the knee joint.

Lee *et al*.[49] first described an arthroscopic ACL reconstruction with a tibial remnant preserving technique using a hamstring graft. Lee *et al*.[50] subsequently analyzed the clinical results of ACL reconstruction with the remnant-preserving technique. The authors used a hamstring graft and looped sutures according to the amount of the tibial ACL remnant. They divided the patients into two groups on the basis of extent of tibial remnant: group 1 with more than 20% and group 2 with less than 20% of tibial remnant. Evaluation of the functional outcomes did not reveal any significant differences in terms of mechanical stability between the two groups. However a significant difference was detected in functional outcome and proprioception in the two groups with group one (>20% remnant) showing better results. The authors thus postulated that the more the tibial remnant was kept intact, the better would be the preservation of proprioceptive function and the functional outcome for the patient.

Kim *et al*.[51] developed a remnant preserving double-bundle ACL reconstruction technique using autogenous quadriceps tendon graft. They suggested that the remnant-preserving technique could be an effective alternative to traditional techniques. Such a technique provided comparable mechanical stability and improved proprioceptive and vascular recovery as compared to remnant shaving techniques.

Li *et al*.[52] reviewed the methods and progress of arthroscopic reconstruction of ACL with the remnant preservation techniques. They found that the preserved remnant provided synovium for the reconstructed ACL, and it could accelerate revascularization of the graft. Apart from improving proprioception, certain remnants provided mechanical stability to the knee as well. The preserved remnant could prevent the enlargement of the tibial tunnel by avoiding the washing effect of the joint fluid. However, cyclops lesion might occur if the remnant was preserved and this could lead to impingement. The authors concluded that remnant preservation in ACL reconstruction, although technically demanding, can provide better clinical results as compared to remnant sacrificing techniques.

Summary

Our understanding of recovery of knee function in ACL-deficient knees is still evolving. Although most of the focus today is on anatomic placements and the number and positions of various bundles during reconstruction, enough evidence is coming to light that establishes that proprioception of the knee suffers after an ACL tear. Proprioception is emerging as an important factor to determine post operative results of ACL reconstruction. Various studies have demonstrated the presence of mechanoreceptors in remnant ACL stumps; based on this there have been proposals of preserving these ACL remnants during ACL reconstruction to ensure a better functional outcome. We believe that proprioception is an important aspect of knee stability, and that it is lost after ACL injury, and all attempts must be made to recover as much proprioception as possible by modifying surgical methods and rehabilitation protocols. Remnant preserving surgery may be one of the options that needs to be explored in more detail, and could potentially be a solution to some of the poor functional outcomes in mechanically well-done ACL reconstructions.

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