Dynamic intraligamentary stabilization: novel technique for preserving the ruptured ACL

S. Eggli · H. Kohlhof · M. Zumstein · P. Henle · M. Hartel · D. S. Evangelopoulos · H. Bonel · S. Kohl

Received: 15 April 2012 / Accepted: 11 March 2014 / Published online: 21 March 2014
© The Author(s) 2014. This article is published with open access at Springerlink.com

Abstract
Purpose Replacement of the torn anterior cruciate ligament (ACL) with a transplant is today’s gold standard. A new technique for preserving and healing the torn ACL is presented. Hypothesis: a dynamic intraligamentary stabilization (DIS) that provides continuous postinjury stability of the knee and ACL in combination with biological improvement of the healing environment [leucocyte- and platelet-rich fibrin (L-PRF) and microfracturing] should enable biomechanically stable ACL self-healing.

Methods Ten sportive patients were treated by DIS employing an internal stabilizer to keep the unstable knee in a posterior translation, combined with microfracturing and platelet-rich fibrin induction at the rupture site to promote self-healing. Postoperative clinical [Tegner, Lysholm, International Knee Documentation Committee (IKDC), visual analogue scale patient satisfaction score] and radiological evaluation, as well as assessment of knee laxity was performed at 6 weeks, 3, 6, 12, and 24 months.

Results One patient had a re-rupture 5 months postoperative and was hence excluded from further follow-ups. The other nine patients presented the following outcomes at 24 months: median Lysholm score of 100; IKDC score of 98 (97–100); median Tegner score of 6 (range 9–5); anterior translation difference of 1.4 mm (−1 to 3 mm); median satisfaction score of 9.8 (9–10). MRI showed scarring and continuity of the ligament in all patients.

Conclusions DIS combined with microfracturing and L-PRF resulted in stable clinical and radiological healing of the torn ACL in all but one patient of this first series. They attained normal knee scores, reported excellent satisfaction and could return to their previous levels of sporting activity.

Level of evidence Case series with no comparison group, Level IV.

Keywords Anterior cruciate ligament · Dynamic intraligamentary stabilization · Arthroscopic surgery · Sports injury · Knee injury

Introduction
Rupture of the anterior cruciate ligament (ACL) is the most common injury of the knee requiring surgical treatment [18]. While a conservative treatment approach leads to satisfactory results in a population that places low demand on the knee joint [31, 41], persisting instability prevents patients from participating in activities that require high levels of joint pivoting, such as soccer and skiing.
Today’s gold standard in ACL repair was developed by Brückner in 1966 and uses the middle third of the patellar ligament as transplant to restore knee joint stability [10]. Although arthroscopic techniques have improved tremendously since then, and current ACL reconstruction techniques are an excellent option for restoring sagittal plane stability of the knee, the clinical results with tendon grafts are still under discussion. Despite numerous publications reporting good-to-excellent results, the meta-analysis of Biau et al. [8] revealed that only 40 % of patients achieve full recovery independent of surgical technique. One explanation could be that removal of the native ACL tissue containing sensory nerve fibres causes the ligament to lose its function within the joint’s ‘proprioceptive envelope’ [3, 23], thus impairing muscular stabilization of the knee. Based on this theory, the authors started to investigate a strategy for preserving the torn ACL in 2007.

The main challenge is posed by the torn ligament’s poor healing capacity. This can be partly explained by biological factors such as cell deficiencies, alterations in cellular metabolism, the hostile environment of the synovial fluid [12, 42], and the lack of blood supply [2, 26]. Moreover, the postinjury instability does not allow the torn ligament to heal.

While recent studies support the potential of biological self-healing for the ruptured ACL [34, 35, 38], the persisting postinjury translation in the antero-posterior plane separates the ligament stumps by 5–10 mm and prevents possible self-healing and formation of stable scar tissue [1, 16, 43]. To address this problem, a new technique was developed, dynamic intraligamentary stabilization (DIS), hypothesizing that continuous posttraumatic stabilization of the knee can enable mechanically stable ACL healing. Encouraged by the success of DIS in a sheep model [27], the technique was applied in a series of 10 physically active individuals with a torn ACL.

Materials and methods

Inclusion criteria were an ACL rupture not older than 14 days, patient age <45 years, no previous surgery on the injured knee, and regular participation in sports requiring pivoting of the knee joint. Ten consecutive patients (eight males, two females) met the inclusion criteria and underwent surgery between August 2009 and February 2010. Median age was 25.4 years (range 19–41 years); the right/left knee ratio was 7/3. The median accident-surgery interval was 9.9 days (range 2–13 days). The rupture was located in the middle third of the ligament in seven patients and in the proximal third in three patients. Eight patients showed additional meniscal lesions, which were surgically treated in six patients.

Surgical technique

Each patient was placed in a supine position with the knee positioned in a static knee holder with a tourniquet inflated to 350 mm Hg. An antero-lateral portal was used for the camera and an antero-medial portal for the instruments. The infrapatellar area was freed from the hypertrophic portions of Hoffa’s fat pad. Removal of too much tissue, especially from the inferior part of the fat pad, was avoided to preserve nutritional arteries to the ACL passing through this area [2]. The tibial footprint of the ACL was marked using an intra-articular guide, and a wire was passed through the tibia to this point. A 10.5-mm threaded sleeve (Mathys Ltd, Bettlach, Switzerland) was then inserted into the tibia. A suture passer was inserted through the screw into the distal ACL stump, and a preliminary thread was passed through the ligament. The femoral footprint was identified using a guide from the antero-medial portal, and a wire was passed at 120 degrees of flexion to the lateral aspect of the femur. The wire was passed through the skin, and the definitive polyethylene wire was inserted from the antero-lateral femoral position to the antero-medial aspect.
of the tibia. The wire was stabilized at the femoral position with a flip anchor. A metallic spring was inserted in the screw, and the polyethylene wire was fixed with a cover at the end of the screw at a tension of 80 N. The DIS technique holds the knee in a fixed posterior translation at every degree of flexion, ensuring that the two ligament stumps are kept as close to each other as possible at all times (Fig. 1). The surgery was then completed by microfracturing of the femoral footprint and induction of a leukocyte- and platelet-rich fibrin (L-PRF) clot at the rupture site.

Postoperative treatment consisted of the patient spending 3 days in a fixed position with the knee fully extended. The leg was then loaded with 15 kg of weight for 3 weeks and mobilized without any flexion limitations. Beginning at 4 weeks postoperative, the leg was loaded with full body weight and reinforcement training of the quadriceps and hamstrings was initiated using closed chain knee exercises. Intensive proprioceptive training was initiated with a trampoline and balancing exercises on an unstable board. Running was allowed after 6 weeks and pivoting sports after 3 months. Competitive soccer and skiing were allowed after 5 months.

Clinical evaluation

All patients were evaluated according to a prospective protocol, 6 weeks, 3, 6, 12, and 24 months after surgery. The following instruments were used for outcomes assessment at each follow-up: Tegner score, Lysholm score, the International Knee Documentation Committee (IKDC) score, and visual analogue scale (VAS) for assessment of patient satisfaction (0 = completely dissatisfied, 10 = completely satisfied). The preoperative scores were assessed retrospectively using the same questionnaires. Knee laxity was assessed by measuring anterior translation at 30 degrees flexion using a Rolimeter™ (Aircast, Neubeuern, Germany) and comparing it with the contralateral knee. All patients were informed that their treatment would involve a completely new technique, to which they gave voluntary written informed consent (Cantonal Ethics Committee of Berne, Switzerland: Ref.-Nr. KEK-BE: 048/09, ISRCTN 89368687).

Radiological evaluation

Conventional radiographic evaluation was performed immediately after surgery and at the 6-week and 12-month follow-ups. MRI investigations were conducted 6 weeks, 3, 6, and 12 months after the intervention using an advanced 3 Tesla Scanner (Magnetom Verio; Siemens, Erlangen, Germany) with a dedicated 15-channel knee coil.

All examinations were reported in random order by a specialized radiologist with a more than 15-years experience in musculoskeletal radiology. The radiologist was blinded to all clinical information except for the surgical repair of the ACL. First, image quality was assessed using a 5-point scale (5 = optimal image quality, 4 = very good image quality, 3 = diagnostic image quality, 2 = anatomic structures only identified, 1 = anatomic structures not seen). Next, the MRIs were examined for intactness of the ligament by an independent evaluator applying the following criteria:

Morphology and continuity

The ligament tear was rated in three grades similar to those used by Kühne et al. [28] after ACL repair, grade 3 representing a non-delineated ligament, grade 2 a wavy but continuous ligament contour, and grade 1 a continuous ligament.

Signal intensity

The 4-level grading system for the PCL, as proposed by Howell et al., was adapted to analyse variations in the signal intensity parameters of the graft [21]. In grade I, a homogeneous, low-intensity signal was observed within the entire graft segment. In grade II, at least 50% of the ‘normal’ ligament signal was observed. In grade III, the graft segment depicted less than 50% of the normal ligament signal. In grade IV, there was a diffuse increase in signal intensity with abnormal ligament strands.

Statistical analysis

To express the variability and distribution of the underlying data, the median values of outcome scores and their range were calculated and reported. No inferential statistics were used in this exploratory descriptive study (n = 10).

Results

At 5 months after surgery, patient number 6 (a 24-year-old male sports student) suffered from a re-rupture after sustaining a direct rotation trauma playing soccer. Until then, the patient had been pain-free with a Lysholm score of 97 and a Tegner score of 5 at the 3 month follow-up. 6 weeks after the second trauma his completely ruptured ACL was replaced by a bone-tendon-bone (BTB) graft.

The remaining nine patients were all monitored according to the clinical follow-up protocol and had a
complete set of MRI investigations. The Lysholm score was 100 before injury, 99 (97–100) after 3 months, and 100 after 24 months. The IKDC score reached 98 (97–100) after 24 months, and with six points the group’s median Tegner activity score remained the same as before the accident. After 3 months, the anterior translation difference was 0.5 mm (−3 to 3) compared with the contralateral side and 1.4 mm (−1 to 3) after 24 months. Before surgery, it was 4.9 (range 3–7 mm, SD 1.2 mm). The anterior stop was hard in three patients and semi-hard in six patients. Median patient satisfaction was 9.5 (8–10) after 3 months and 9.8 (9–10) after 24 months (Table 1).

MRI

Imaging quality was rated as optimal (score 5) in nine patients and very good (score 4) in one patient at 6 weeks. Metal artefacts were detected at the site of the implanted spring mechanism. Metal artefacts obscured 18 % of the distal ACL (range 12–23 %) but did not alter the morphology of the proximal and middle third of the ligament. Continuity was rated as grade A, or ‘well defined’, in all nine patients at all times. Patient number 6 was also rated grade A before his re-rupture. All repairs were well defined, and ligament continuity was fully restored.

Applying the Howell grading system, MRI signals were rated I in 2 of the 10 patients after 6 weeks and II in the remaining 8 patients. After 3 months and for all later assessments, the signals were rated I for all patients except patient number 6 after the second rupture of his ligament (Fig. 2).

Discussion

The most important finding of the present study was that a dynamic intraligamentary stabilization of the knee with a freshly ruptured ACL in combination with biological improvement of the healing environment can lead to a biomechanically stable ACL with good functional scores and high patient satisfaction.

ACL rupture is a devastating knee injury that is associated with a significant risk of developing osteoarthritis [15]. Controversially, this risk is reported to be even higher in patients undergoing surgical stabilization of the ACL [11, 25, 29]. These problems may be attributable to loss of proprioception after complete removal of the ACL [5, 31, 37] as well as to insufficient restoration of the three-dimensional stability of the knee [6, 36, 39]. It was therefore hypothesized that conservation of the native ACL tissue is

| Scores/tests | Before injury | 3 Months | 6 Months | 12 Months | 24 Months |
|--------------|--------------|----------|----------|-----------|-----------|
| Lysholm      | 100          | 99.1 (97–100) | 99.8 (99–100) | 99.8 (98–100) | 100       |
| IKDC         | 100          | 92.1 (87–96)  | 94 (90–98)   | 97.8 (97–100) | 98 (97–100) |
| Tegner       | 6 (4–9)      | 5 (4–6)    | 5 (4–8)    | 6 (5–9)    | 6 (5–9)   |
| Δ Lachmann (mm) | 0.5 (−3–3)  | 1.0 (−3–3) | 1.2 (−2–3) | 1.4 (1–3)  |
| Pat. satisfaction VAS | 9.5 (8–10) | 9.6 (9–10) | 9.8 (9–10) | 9.8 (9–10) |

Fig. 2 Lateral MRI showing the torn ACL immediately after injury and at 12 months follow-up (after removal of screw)
necessary to preserve proprioception and restore the individual three-dimensional anatomy of the ligament.

The paradigm that a torn ACL has insufficient healing capacity and must be replaced by a tendon graft remains prevalent [14, 20]. Opposing this paradigm, a series of publications have indicated that under certain circumstances the injured ACL can produce a stable scar. Träger et al. [43] reported a better clinical outcome and improved stability with suturing the ACL and augmenting the tissue with polydioxanone than with ACL replacement. Steadman et al. [40] described a method known as the ‘healing response’ wherein placement of undifferentiated stem cells into the rupture zone induced stable healing of the torn ACL in an athletically active, skeletally immature patient. In 2002, Fujimoto et al. [17] published the results of 31 ACL ruptures in patients with low athletic demands treated conservatively for 2–3 months with an extension block soft brace without anterior stabilization: 23 knees (74 %) were stable with a continuous ACL on MRI at final follow-up. Boldrini et al. [19] reported stable healing in 26 athletes with an incomplete ACL tear using primary sutures in combination with bone marrow stimulation.

The literature to date indicates that stability and biology are the two main determinants for ACL healing. Every tissue demands a certain level of stability to heal [24], but since a knee with an injured ACL shows a significant increase in antero-posterior translation of the tibio-femoral joint [13], normal knee movements result in a constant disconnection of the two ACL stumps, creating an unstable healing environment. The published method of knee bracing in a constant posterior translation for 3 months has already produced a remarkable number of healed ligaments, but it is not widely accepted because of the discomfort it causes [17, 22]. The authors have developed a new technique called dynamic intraligamentary stabilization (DIS) that restores the intrinsic stability of the knee with minimal discomfort for the patient. The DIS device employs an internal screw-spring mechanism that acts as a dynamic internal fixator which pushes the knee into a maximum posterior translation in any degree of flexion. The spring is also functional when the intraligamentary thread is not placed in an isometric position. This technique has already been shown to provide sufficient mechanical stability to enable biomechanically stable healing of the ACL in a sheep model [27].

Recent studies have demonstrated that introduction of a collagen-platelet composite into a transected ACL can significantly increase its healing capacity [30, 32, 33]. Murray et al. [32] used a collagen-platelet composite to bridge the wound site and reported healing with recovery of over 50 % of the initial ligament strength after 4 weeks. Zumstein et al. [44, 45] have demonstrated that solid scaffolds can be used for long-term (up to 28 days) delivery of growth factors; in particular, L-PRF can be used as a regenerative in situ tissue engineering method during treatment of ACL injuries. This technique was adapted in combination with microfracturing according to Steadman to optimize the biological healing capacity of the ACL.

The MRI investigations at 3, 6, and 12 months showed a continuous increase in scar tissue as represented by fibres of low signal intensity. In addition, clear remodelling of the ligament was detectable at 6 months, and the independent evaluator judged the continuity of the ligaments as restored. Furthermore, the dynamic aspect of the repair resulted in a straight appearance of the fibre bundles without the wavelike morphology observed with other surgical techniques.

Clinically, all patients exhibited practically normal knee function after 1 year with a Lysholm score of almost 100 and an IKDC score of 98. These results are strikingly improved in comparison with the outcome after conventional ACL repair with a tendon graft. However, the reported ceiling effects of the Lysholm score need to be considered in this series of highly motivated and active patients [9]. A better discriminating outcome instrument may be needed for these types of patients in the future. In their meta-analysis, Biau et al. [8] reported that only about 40 % of patients made a full recovery after ACL reconstruction, with only 33 % having a normal IKDC score after a semitendinosus transplant and 41 % having a normal IKDC after a BTB (ligamentum patellae) transplant. Thus, more than 60 % of patients (708 of 1,125 for the two reconstruction groups) did not fully recover (final overall IKDC score class A) after reconstruction.

The present authors attribute the excellent clinical results of their new technique to the restored stability of the knee on one hand, but even more to the preservation of the ACL tissue, which allows for the restoration of a physiological proprioception. Barret points out that ligament tests and knee scores correlate poorly with patient satisfaction scores, but proprioception is a major factor in measuring the overall outcome of ACL reconstruction [4]. Patients in the present study reported a satisfaction of 9.8 on VAS after 1 year, indicating that healing of the ACL tissue may restore not only the three-dimensional stability of the knee but also the physiological proprioceptive envelope. Casteley states that the real benchmark of success in the treatment of ACL ruptures has to be the avoidance of treatment morbidity, secondary surgery, and osteoarthritis [11]. In the meta-analysis of Biau et al. [7], 13–22 % of the patients complained of persisting knee pain, mainly associated with donor-site morbidity. The DIS technique requires no additional ligament extraction, thus minimizing the surgical trauma.

There are limitations to this study. The sample size is small, there is no control group, and the follow-up is not
long enough to address posttraumatic arthritis, which results in an evidence level of only IV.

The authors conclude that this study could revitalize the discussion of preserving the torn ligament. It could be an additional option between the conservative treatment and the replacement of the ACL. Further studies need to be carried out to proof this concept.

Conclusion

Dynamic intraligamentary stabilization in combination with L-PRF and microfracturing of the notch can lead to stable clinical and radiological healing of the torn ACL after 1 year. Patients exhibited normal knee function reported excellent satisfaction and were able to return to their previous levels of sporting activity. The present findings support the discussion of a new paradigm in ACL treatment based on preservation and self-healing of the torn ligament.

Acknowledgments The authors thank D. Delfosse and A. De Cesari for their innovative engineering of the DIS prototypes and the mechanical testing of the implants. This study was funded by the Swiss National Accident Insurance Fund.

Conflict of interest The authors declare that they have no conflict of interest.

Open Access This article is distributed under the terms of the Creative Commons Attribution License which permits any use, distribution, and reproduction in any medium, provided the original author(s) and the source are credited.

References

1. Ahn JH, Chang MJ, Lee YS, Koh KH, Park YS, Eun SS (2010) Non-operative treatment of ACL rupture with mild instability. Arch Orthop Trauma Surg 130(8):1001–1006
2. Amoczyz SP (1983) Anatomy of the anterior cruciate ligament. Clin Orthop Relat Res 172:19–25
3. Barrack RL, Skinner HB, Buckley SL (1989) Proprioception in the anterior cruciate deficient knee. Am J Sports Med 17(1):1–6
4. Barrett DS (1991) Proprioception and function after anterior cruciate reconstruction. J Bone Jt Surg Br 73(5):833–837
5. Beard DJ, Kyberd PJ, Fergusson CM, Dodd CA (1993) Proprioception after rupture of the anterior cruciate ligament. An objective indication of the need for surgery? J Bone Jt Surg Br 75(2):311–315
6. Bedi A, Maak T, Musahl V, Citak M, O’Loughlin PF, Choi D, Pearle AD (2011) Effect of tibial tunnel position on stability of the knee after anterior cruciate ligament reconstruction: is the tibial tunnel position most important? Am J Sports Med 39(2):366–373
7. Biau DJ, Katsahian S, Nizard R (2007) Hamstring tendon autograft better than bone-patellar tendon-bone autograft in ACL reconstruction—a cumulative meta-analysis and clinically relevant sensitivity analysis applied to a previously published analysis. Acta Orthop 78(5):705–707
8. Biau DJ, Tournoux C, Katsahian S, Schranz P, Nizard R (2007) ACL reconstruction: a meta-analysis of functional scores. Clin Orthop Relat Res 458:180–187
9. Briggs KK, Kocher MS, Rodkey WG, Steadman JR (2006) Reliability, validity, and responsiveness of the Lysholm knee score and Tegner activity scale for patients with meniscal injury of the knee. J Bone Jt Surg Am 88(4):698–705
10. Brückner H (1966) Eine neue Methode der Kreuzbandplastik. Chirurg 37(9):413–414
11. Castelmeun FF (1999) Management of anterior cruciate ligament lesions: surgical fashion, personal whim or scientific evidence? Study of medium- and long-term results. Acta Orthop Belg 65(3):327–339
12. Durabos N, Hendric-Haspl Z, Haspl M, Markotic A, Darabos A, Moser C (2009) Correlation between synovial fluid and serum IL-1beta levels after ACL surgery-preliminary report. Int Orthop 33(2):413–418
13. Dejour H, Bonnin M (1994) Tibial translation after anterior cruciate ligament rupture. Two radiological tests compared. J Bone Jt Surg Br 76(5):745–749
14. Feagin JA Jr, Curl WW (1996) Isolated tear of the anterior cruciate ligament: 5-year followup study. Clin Orthop Relat Res 325:4–9
15. Ferretti A, Conteduca F, De Carli A, Fontana M, Mariani PP (1991) Osteoarthritis of the knee after ACL reconstruction. Int Orthop 15(4):367–371
16. Fleming BC, Carey JL, Spindler KP, Murray MM (2008) Can suture repair of ACL transection restore normal anteroposterior laxity of the knee? An ex vivo study. J Orthop Res 26(11):1500–1505
17. Fujimoto E, Sumen Y, Ochi M, Ikuta Y (2002) Spontaneous healing of acute anterior cruciate ligament (ACL) injuries—conservative treatment using an extension block soft brace without anterior stabilization. Arch Orthop Trauma Surg 122(4):212–216
18. Gianotti SM, Marshall SW, Hume PA, Bunt L (2009) Incidence of anterior cruciate ligament injury and other knee ligament injuries: a national population-based study. J Sci Med Sport 12(6):622–627
19. Gobbi A, Bathan L, Boldrini L (2009) Primary repair combined with bone marrow stimulation in acute anterior cruciate ligament lesions: results in a group of athletes. Am J Sports Med 37(3):571–578
20. Grontvedt T, Engebretsen L, Bemun P, Fasting O, Molster A, Strand T (1996) A prospective, randomized study of three operations for acute rupture of the anterior cruciate ligament. Five-year follow-up of one hundred and thirty-one patients. J Bone Jt Surg Am 78(2):159–168
21. Howell SM, Clark JA, Farley TE (1992) Serial magnetic resonance study assessing the effects of impingement on the MR image of the patellar tendon graft. Arthroscopy 8:350–358
22. Jacobi M, Reischl N, Wahl P, Gautier E, Jakob RP (2010) Acute isolated injury of the posterior cruciate ligament treated by a dynamic anterior drawer brace: a preliminary report. J Bone Jt Surg Br 92(10):1381–1384
23. Jerosch J, Prymka M (1996) Knee joint proprioception in normal volunteers and patients with anterior cruciate ligament tears, taking special account of the effect of a knee bandage. Arch Orthop Trauma Surg 115(3–4):162–166
24. Kanzler MH, Gorusulowsky DC, Swanson NA (1986) Basic mechanisms in the healing cutaneous wound. J Dermatol Surg Oncol 12(11):1156–1164
25. Kessler MA, Behrend H, Henz S, Stutz G, Rukavina A, Kuster MS (2008) Function, osteoarthrits and activity after ACL-rupture: 11 years follow-up results of conservative versus
reconstructive treatment. Knee Surg Sports Traumatol Arthrosc 16(5):442–448
26. Kobayashi S, Baba H, Uchida K, Negoro K, Sato M, Miyazaki T, Nomura E, Murakami K, Shimizubata M, Meir A (2006) Microvascular system of anterior cruciate ligament in dogs. J Orthop Res 24(7):1509–1520
27. Kohl S, Evangelopulos DS, Kohlhof H, Hartel M, Bonel H, Henle P, von Rechenberg B, Eggli S (2013) Anterior cruciate ligament rupture: self-healing through dynamic intraligamentary stabilization technique. Knee Surg Sports Traumatol Arthrosc 21(3):599–605
28. Kühne JH, Krüger-Franke M, Refior HJ (1997) Reconstruction of acute anterior cruciate ligament rupture by suture and semitendinosus tendon augmentation. Oper Orthop Traumatol 9(1):37–47
29. Lohmander LS, Ostenberg A, Englund M, Roos H (2004) High prevalence of knee osteoarthritis, pain, and functional limitations in female soccer players twelve years after anterior cruciate ligament injury. Arthritis Rheum 50(10):3145–3152
30. Mastrangelo AN, Vavken P, Fleming BC, Harrison SL, Murray MM (2011) Reduced platelet concentration does not harm PRP effectiveness for ACL repair in a porcine in vivo model. J Orthop Res 29(7):1002–1007
31. Muaidi QI, Nicholson LL, Refshauge KM, Adams RD, Roe JP (2009) Effect of anterior cruciate ligament injury and reconstruction on proprioceptive acuity of knee rotation in the transverse plane. Am J Sports Med 37(8):1618–1626
32. Murray M, Spindler K, Abreu E, Muller JA, Nedder A, Kelly M, Frino J, Zarakowski D, Valenza M, Snyder BD, Connolly SA (2007) Collagen-platelet rich plasma hydrogel enhances primary repair of the porcine anterior cruciate ligament. J Orthop Res 25(1):81–91
33. Murray MM, Palmer M, Abreu E, Spindler KP, Zarakowski D, Fleming BC (2009) Platelet-rich plasma alone is not sufficient to enhance suture repair of the ACL in skeletally immature animals: an in vivo study. J Orthop Res 27(5):639–645
34. Murray MM, Spindler KP, Ballard P, Welch TP, Zarakowski D, Nanney LB (2007) Enhanced histologic repair in a central wound in the anterior cruciate ligament with a collagen-platelet-rich plasma scaffold. J Orthop Res 25(8):1007–1017
35. Murray MM, Spindler KP, Devin C, Snyder BS, Muller J, Takahashi M, Ballard P, Nanney LB, Zarakowski D (2006) Use of a collagen-platelet rich plasma scaffold to stimulate healing of a central defect in the canine ACL. J Orthop Res 24(4):820–830
36. Scopp JM, Jasper LE, Belkoff SM, Moorman CT III (2004) The effect of oblique femoral tunnel placement on rotational constraint of the knee reconstructed using patellar tendon autografts. Arthroscopy 20(3):294–299
37. Serrano-Fernandez JM, Espejo-Baena A, Martin-Castilla B, De La Torre-Solis F, Mariscal-Lara J (2010) Augmentation technique for partial ACL ruptures using semitendinosus tendon in the over-the-top position. Knee Surg Sports Traumatol Arthrosc 18(9):1214–1218
38. Silva A, Sampaio R (2009) Anatomic ACL reconstruction: does the platelet-rich plasma accelerate tendon healing? Knee Surg Sports Traumatol Arthrosc 17(6):676–682
39. Sonnery-Cottet B, Lavoie F, Ogassawara R, Scussiato RG, Kidder JE, Chambat P (2009) Selective anteromedial bundle reconstruction in partial ACL tears: a series of 36 patients with mean 24 months follow-up. Knee Surg Sports Traumatol Arthrosc 17(1):47–51
40. Steadman JR, Cameron-Donaldson ML, Briggs KK, Rodkey WG (2006) A minimally invasive technique (“healing response”) to treat proximal ACL injuries in skeletally immature athletes. J Knee Surg 19(1):8–13
41. Strehl A, Eggli S (2007) The value of conservative treatment in ruptures of the anterior cruciate ligament (ACL). J Trauma 62(5):1159–1162
42. Tang Z, Yang L, Wang Y, Xue R, Zhang J, Huang W, Chen PC, Sung KL (2009) Contributions of different intraarticular tissues to the acute phase elevation of synovial fluid MMP-2 following rat ACL rupture. J Orthop Res 27(2):243–248
43. Träger D, Pohle K, Tschirner W (1995) Anterior cruciate ligament suture in comparison with plastic. A 5-year follow-up study. Arch Orthop Trauma Surg 114(5):278–280
44. Zamstein M, Bielecki T, Dohan Ehrenfest DM (2011) The future of platelet concentrates in sports medicine: platelet-rich plasma, platelet-rich fibrin, and the impact of scaffolds and cells on the long-term delivery of growth factors. Oper Tech Sports Med 19(3):190–197
45. Zamstein MA, Berger S, Schober M, Boileau P, Nyffeler RW, Horn M, Dahinden CA (2012) Leukocyte- and platelet-rich fibrin (L-PRF) for long-term delivery of growth factor in rotator cuff repair: review, preliminary results and future directions. Curr Pharm Biotechnol 13(7):1196–1206