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Original Research

Graft-Specific Surgical and Rehabilitation Considerations for Anterior Cruciate Ligament Reconstruction with the Quadriceps Tendon Autograft

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Anterior cruciate ligament reconstruction (ACLR) with a bone-patellar tendon-bone (BPTB) or hamstring tendon (HT) autograft has traditionally been the preferred surgical treatment for patients returning to Level 1 sports. More recently, international utilization of the quadriceps tendon (QT) autograft for primary and revision ACLR has increased in popularity. Recent literature suggests that ACLR with the QT may yield less donor site morbidity than the BPTB and better patient-reported outcomes than the HT. Additionally, anatomic and biomechanical studies have highlighted the robust properties of the QT itself, with superior levels of collagen density, length, size, and load-to-failure strength compared to the BPTB. Although previous literature has described rehabilitation considerations for the BPTB and HT autografts, there is less published with respect to the QT. Given the known impact of the various ACLR surgical techniques on postoperative rehabilitation, the purpose of this clinical commentary is to present the procedure-specific surgical and rehabilitation considerations for ACLR with the QT, as well as further highlight the need for procedure-specific rehabilitation strategies after ACLR by comparing the QT to the BPTB and HT autografts.

Level of Evidence

Level 5

INTRODUCTION

Rupture of the anterior cruciate ligament is a well-known sports injury, with a higher injury incidence in females and those who participate in Level 1 sports.[1–4] Traditionally, anterior cruciate ligament reconstruction (ACLR) with a bone-patellar tendon-bone (BPTB) or hamstring tendon (HT) autograft has been the preferred surgical procedure for managing complete tears of the anterior cruciate ligament, with a surgeon-preference towards the BPTB as the standard of care.[5–9] Recently, international utilization of the quadriceps tendon (QT) autograft for primary and revision ACLR has increased in popularity[10–13]; ACLR with the QT may yield less graft harvest site morbidity than the BPTB and better patient-reported outcomes than the HT.[14–16] However, revision ACLR outcomes from the Danish Knee Ligament Reconstruction Registry suggests higher graft laxity and failure rates when performing primary ACLR with the QT than both the BPTB and HT[17]; these findings have been debated,[18,19] along with other literature reporting similar graft survivorship between the QT, BPTB and HT.[14–16,20]

Justifying the increased utilization of the QT for ACLR, anatomic and biomechanical studies have highlighted the robust properties of the QT itself, with superior levels of collagen density, length, size and load-to-failure strength than the BPTB.[21–25] However, due to the multiple muscular origins of the quadriceps tendon, the QT has the potential for more variation in laminar structure and fiber orientation than the BPTB and HT.[26–28] This non-uniformity of

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the quadriceps tendon, along with variation in surgeon skill and reconstruction technique, has been suggested as a reason for the higher QT failure rates within the Danish Knee Ligament Reconstruction Registry.[17–19]

In addition to intra-graft characteristics, graft-specific considerations for ACLR should also include fixation technique, management of the graft harvest site and the overall graft ligamentization process. For example, graft fixation with an interference screw may facilitate better graft incorporation than suspensory fixation and reduce the incidence of bone tunnel widening.[29–31] Regarding the graft harvest site, ACLR with the QT and BPTB may produce more postoperative quadriceps weakness than the HT,[14,32–34] whereas a higher incidence of kneeling-related knee pain has been reported with the BPTB than both the QT and HT autografts.[14,15] Lastly, the bone-to-bone healing of the BPTB within the bone tunnels facilitates graft osteointegration, which is a more efficient incorporation process than the fibrovascular healing of an all soft-tissue graft[35]; these considerations influence surgical decision-making and the rehabilitation plan-of-care, to which the rehabilitation specialist must tailor their exercise prescription in an effort to optimize outcomes after ACLR.

Although previous literature has described rehabilitation considerations for the BPTB and HT autografts,[28,36–39] there is less published with respect to the QT.[39–41] Therefore, the purpose of this clinical commentary is to present the graft-specific surgical and rehabilitation considerations for ACLR with the QT, as well as further highlight the need for graft-specific rehabilitation strategies after ACLR by comparing the QT to the BPTB and HT autografts.

ANATOMIC AND BIOMECHANICAL CONSIDERATIONS

The quadriceps and hamstring tendons are different than the patellar tendon in their innate function to connect muscle-to-bone, whereas the patellar tendon connects bone-to-bone. Considering this, differences in stiffness and elastic properties are known to exist between autograft tissue used for ACLR,[42–44] with the quadriceps tendon producing more absolute stiffness than both the patellar and semitendinosus tendons but a lower elastic modulus and relative strain tolerance than the patellar tendon[24,28,44–46] (Table 1).

While these findings reflect total-graft biomechanical properties, previous work has highlighted the fact that regional variation in tendon elasticity and stiffness may also exist; the tendon region closest to the myotendinous junction is less stiff than the tendon region adjacent to the enthesis.[48] This is an important consideration, as biomechanically-induced graft failure studies have reported a difference in failure location for the QT harvested with a patellar bone block (B-QT) than that of the BPTB and multiple-strand HT autografts; failure of the B-QT was most common at the bone-tendon interface,[28,44] whereas universal stretch/mid-substance failures have been reported with the all soft-tissue QT (S-QT), BPTB and multiple-strand HT.[28,43–45,47] These observations suggest the B-QT has more within-graft variation in regional elasticity and structure, creating increased stress at the bone-tendon interface and the observed graft failure-location.[26,44,49]

Compared to the HT and BPTB, more variation in laminar structure is present with the QT. In contrast to the continuous structure of the hamstring and patellar tendons, the quadriceps tendon is typically described as a common tendon with a three-layered arrangement; a superficial layer derived from rectus femoris, an intermediate layer from vastus medialis and vastus lateralis, and a deep layer from vastus intermedius.[26–28] Although the extent to which laminar structure contributes to graft fixation pull-through is unknown, a biomechanical study by Arakagi et al[50] reported significant suspensory fixation pull-through with a 150-newton load on the S-QT relative to a bone-block control.

GRAFT COMPOSITION AND HARVESTING TECHNIQUE CONSIDERATIONS

The harvesting technique of the QT can vary, and along with this, different rehabilitation considerations for graft composition are warranted. The B-QT facilitates partial graft osteointegration as early as 4-6 weeks after ACLR through the bone-to-bone healing of the single bone block within the bone tunnel,[51,52] but likewise, carries a 1.4-8.8% risk of patellar fracture due to bone block harvest.[53–55] Conversely, the S-QT is harvested without a patellar bone block and mitigates the risk of patellar fracture,[54] but will take a minimum of 10 to 12-weeks for the fibrovascular interface to form between the S-QT and the bone tunnels.[28,56–58] This between-graft difference in integration, in conjunction with the findings of Arakagi et al,[50] suggests accelerated rehabilitation approaches may be less appropriate for the S-QT fixated with suspensory fixation, especially as graft tension is highly dependent on fixation until biological integration of the graft within the bone tunnels has occurred. While this is an extrapolated suggestion, short-term increases in graft laxity have been reported with the early introduction of open-kinetic-chain (OKC) quadriceps resistance training after ACLR, to which slightly increased levels of graft laxity were reported with the HT relative to the BPTB when OKC quadriceps resistance training with distal tibial load was initiated between 0-45 degrees of knee flexion weeks 6-12 after ACLR.[59]

The theoretical advantage of graft osteointegration with the B-QT is not currently supported by the literature.[28,56–58] Specifically, a higher incidence of postoperative rotatory instability (16% vs 0%) and atraumatic graft ruptures (24% vs 0%) have been observed after ACLR with the B-QT compared to the S-QT[54]; these findings suggest ACLR with the S-QT may yield better postoperative stability than the B-QT. However, evidence is still limited,[54] and the full-thickness B-QT appears to be more biomechanically similar to the BPTB than the S-QT, as well as may better-replicate the tissue properties of the native anterior cruciate ligament[42,44] (Table 1). Lastly, ACLR with the S-QT may not provide adequate quadriceps tendon graft-length in some populations,[60] especially women,[61] and cosmetic

Table 1. Biomechanical characteristics of the native anterior cruciate ligament and common autografts used for anterior cruciate ligament reconstruction

Graft Type	Cross-Sectional Area (mm^2)	Maximal Load To Failure (N)	Ultimate Stiffness (N/mm)	Ultimate Stress (N/mm^2)	Ultimate Strain (%)	Common Failure Location
Native ACL[*§]	44	2160	242	49	20	
BPTB Autograft[†||≠]	48	1580-1810	278-324	69.9	14	Deep Layer of Patellar Interface / Femoral Origin / Mid-substance
HT Autograft[‡§||≠]	11 (1-strand) 23 (2-strand)	1060 (1-Stand) 2330 (2-stand) 1750 (4-stand)	213 (1-Stand) 469 (2-stand) 433 (4-stand)	99 (1-Stand) 100 (2-stand)	11.6 (4-stand)	Mid-Substance / Universal Stretch
B-QT[†≠] (Full Thickness)	91	1450-2186	370-466	49	11.2	Bone-Tendon Interface
S-QT[≠] (Full Thickness)		1260	257			Proximal Graft / Universal Stretch
S-QT[≠] (Partial Thickness)		972	228			Distal Graft / Universal Stretch

ACL; anterior cruciate ligament, BPTB; bone-patellar tendon-bone, HT; hamstring tendon, B-QT; quadriceps tendon with a patellar bone block; S-QT, all soft-tissue quadriceps tendon; *includes data from Woo et al[42]; †includes data from Shani et al[24]; ‡ includes data from Hamner et al[45]; § includes data from Schilaty et al[43]; || includes data from Strauss et al[44]; ≠ includes data from Magnussan et al[47]

retraction of the rectus femoris is a known complication related to proximal QT harvest.[28,53,55]

Outcomes comparing the full-thickness QT (F-QT) to the partial-thickness QT (P-QT) are limited with only one direct comparison published within the literature.[62] QT thickness does not appear to influence donor site pain, failure rates or patient-reported outcomes.[63] However, the biomechanical properties of the P-QT appear to be less robust than the F-QT[44] (Table 1).

The F-QT produces a larger diameter graft and causes deeper disruption of the tissue at the graft harvest site. With this, violation of the suprapatellar pouch with F-QT harvest can produce a suprapatellar hematoma,[53] which is a known complication after ACLR with the F-QT.[40] More postoperative quadriceps inhibition may also be theorized with the F-QT relative to the P-QT, as full-thickness quadriceps tendon harvest will disrupt the laminar layers associated with the vastus medialis, vastus lateralis and vastus intermedius.[26,27,64] Along with the inevitable increase in suprapatellar scarring, the high collagen density and graft-specific stiffness of the QT are suggested reasons for the observed incidence of arthrofibrosis after ACLR with the QT,[20,40,65,66] to which the F-QT may exacerbate.[67]

EXTENSOR MECHANISM CONSIDERATIONS

Harvesting the P-QT may reduce the tensile strength of the quadriceps tendon by as much as 34%, which is greater than the 25% reduction in patellar tendon tensile strength after BPTB harvest.[23] These findings have implications for rehabilitation, as greater impairments in quadriceps strength have been observed after ACLR with the QT and BPTB than with the HT.[14,32–34,68] Following QT harvest, reduced quadriceps activation and strength may initially create a more protective healing environment at the graft harvest site. However, long-term reductions in quadriceps strength are detrimental to knee function and are one of the reasons why it may take longer to achieve performance testing milestones after ACLR with the QT and BPTB than with the HT.[33,38,39,68]

Considering P-QT harvest reduces the tensile strength of the quadriceps tendon by more than a third,[23] a greater initial reduction in quadriceps strength may be expected after ACLR with the QT compared to the BPTB and HT.[68] Quadriceps weakness from extensor mechanism graft harvest appears most extreme during the first three months after ACLR,[68] suggesting any difference in quadriceps strength between ACLR with the QT and BPTB may only be distinguishable during the first three to four months after

ACLR[34,68]; this suggestion is supported by the fact quadriceps strength is not statistically different between the QT and the BPTB at six to 24 month follow-up.[34,68,69]

REHABILITATION CONSIDERATIONS

EARLY PHASE (POSTOPERATIVE WEEKS 0-8)

After ACLR with the QT, the graft's composition and fixation method should be communicated to the rehabilitation specialist, as these factors dictate the overall graft ligamentization process[35,70–72]; the amount of tissue trauma at the graft harvest site[44]; and the durability of the graft-bone tunnel construct.[29–31,50,73] ACLR with the F-QT carries the risk of developing a suprapatellar hematoma[55,63]; pain and focal swelling at the graft harvest site is indicative of a hematoma and should be differentiated from a postoperative knee effusion.[40] If a suprapatellar hematoma is identified, the surgical team should be notified as physician follow-up may be indicated.

The early restoration of passive knee extension is a crucial component of rehabilitation after ACLR, regardless of graft type.[74] ACLR with the QT may carry an elevated risk of postoperative stiffness due to the larger graft size,[67] presence of suprapatellar scarring and ongoing quadriceps inhibition.[20,40,65,66] Interventions to improve patellar mobility, knee range-of-motion and soft tissue compliance should be implemented immediately after surgery. Failure to restore passive knee extension by postoperative week eight may indicate the need for a subsequent lysis-of-adhesions procedure.[20,65]

Like the BPTB, ACLR with the QT requires an isolated quadriceps training load-progression to be a cornerstone of the rehabilitation program.[33,34,75,76] Early phase quadriceps rehabilitation should include quadriceps setting and other activation exercises into terminal knee extension (TKE), with the goal of restoring active knee extension as soon as possible (Table 2). The early implementation of neuromuscular electrical stimulation and/or blood flow restriction during quadriceps exercise may improve neuromuscular recruitment and help mitigate thigh muscle atrophy,[77–80] as well as facilitate improvements in muscle size and strength throughout rehabilitation.[81–83] The quadriceps muscle load-progression should start with quadriceps setting and straight-leg raises in non-weightbearing, and progress onto closed-kinetic-chain (CKC) positions which emphasize the restoration of knee control in weightbearing (Table 2).[84] The CKC quadriceps load-progression should begin with the double-leg squat exercise and incorporate body-weight isometric and isotonic contractions in low levels of knee flexion (Figure 1A) (Table 2).[85]

Graft osteointegration with the B-QT supports the implementation of an accelerated resistance training approach within the first 4-6 weeks after ACLR,[59] such as OKC quadriceps resistance training with distal tibial load between 0-45 degrees of knee flexion[86]; the combined utilization of the B-QT with interference screw fixation may further justify this clinical decision[29–31,44,50,70,71,87] (Table 3). The S-QT fixated with suspensory fixation may warrant a more traditional approach to resistance training the first

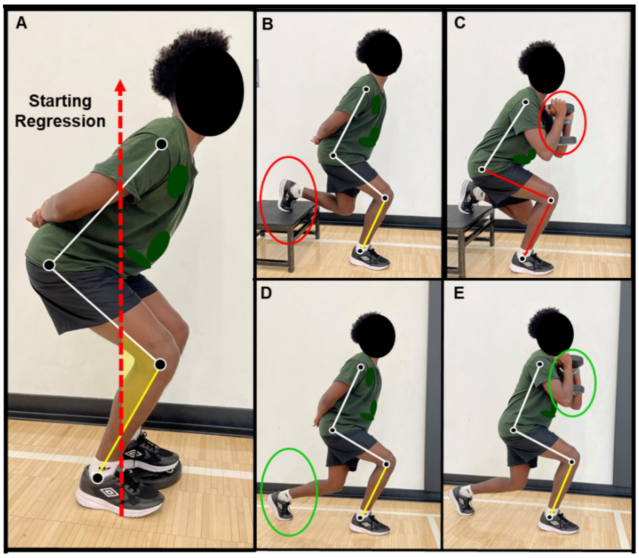

Figure 1. Closed-kinetic-chain load-progression for the surgical limb

Suboptimal progression of unilateral loading from a double leg regression (A) to a rear-foot elevated split-squat (B) with a subsequent increase in knee flexion angle and external resistance (C). Theoretically proper progression of unilateral loading from a double leg regression (A) to a split-squat (D) with the subsequent addition of external resistance (E). No change in knee flexion angle throughout progression (A-D-E). Red dash-arrow, approximate ground reaction force-vector; white lines, depiction of joint angles; red lines, depiction of increasing knee flexion; yellow lines in (A-D-E), depiction of knee/quadriceps-dominant movement with a positive shin angle; yellow shading, depiction of external knee flexion moment related to knee/quadriceps-dominant movement; red circles, improper exercise selection; green circles, proper exercise selection.

10-12 weeks after ACLR[59,72,73,87,88] (Table 2); healing time is needed to mitigate the risk of fixation slippage,[50,73,85,89] graft laxity and bone tunnel widening with an all soft-tissue graft,[17,29–31,50] as well as facilitate optimal fibrovascular integration of the graft within the bone tunnels[72,87,89–93] (Table 3).

MIDDLE PHASE (POSTOPERATIVE WEEKS 8-16)

As goals related to joint homeostasis are achieved, the focus of rehabilitation transitions from resolving impairments in muscle activation and knee range-of-motion, to rebuilding the surgical limb's functional capacity to manage load. Ongoing quadriceps weakness is expected after ACLR with the QT,[14,15,33,34,75] and knee-specific load-progressions should be designed to best-manage the graft harvest site while stimulating improvements in quadriceps size and strength. Prior research has highlighted associations between knee position and extensor mechanism biomechanics,[94–96] from which the quadriceps training load-progressions can be derived (Table 2).

As the knee moves into deeper knee flexion, preferential loading of the quadriceps tendon increases relative to the patellar tendon.[94] This load-transition is the result of an improving patellar tendon mechanical advantage with a concurrent increase in passive tension within the quadriceps.[94,95] Considering the laminar structure of the quadriceps tendon, variations in quadriceps length-tension can predispose the quadriceps tendon to greater levels of shear/compressive load, as well as non-uniform intratendinous

Table 2. Example of a quadriceps muscle/tendon load-progression after anterior cruciate ligament reconstruction with an all soft-tissue quadriceps tendon autograft fixated with suspensory fixation

Postoperative Month	Single-Leg Progression	Split-Squat Progression	Open-Kinetic-Chain Progression
Month 0-1	**Banded TKE** **(Sitting at Edge of Surface)** **Prescription Type:** Neuromuscular Reeducation and Muscle Activation **F:** 3-4 times/day **I:** Elastic resistance band exercise (light to heavy) **T:** Isotonic (concentric/eccentric phase) **T:** 10-15 minutes each exposure **V:** 2-4 sets of 10-20 repetition with a 1-3 second isometric contraction in TKE **P:** Progression of elastic resistance band level; superimposition of NMES with exercise; progression onto blood flow restriction exercise (1-2 times/day, 3-4 set to volitional fatigue at 80% LOP)	**Quadriceps Setting** **(Straight Leg Raise)** **Prescription Type:** Neuromuscular Reeducation and Muscle Activation **F:** 3-6 times/day **I:** Progressive increase in contraction intensity onto the straight leg raise exercise **T:** Isometric quadriceps contraction training **T:** 8-10 minutes each exposure **V:** 2-4 sets of 10-20 repetition with a 1-3 second isometric contraction in TKE **P:** Progression of body position and/or onto the straight leg raise exercise (with/without external resistance at the ankle); superimposition of NMES with exercise; progression onto blood flow restriction exercise (1-2 exposures/day, 3-4 set to volitional fatigue at 80% LOP)	**Short/Long-Arc Quad** **(AROM)** **Prescription Type:** Neuromuscular Reeducation and Muscle Activation **F:** 3-4 times/day **I:** Weight of lower leg **T:** Isotonic (concentric/eccentric phase) **T:** 10-15 minutes each exposure **V:** 2-4 sets of 10-20 repetition with a 1-3 second isometric contraction in TKE **P:** Progression of contraction intensity and knee flexion angle during exercise; superimposition of NMES with exercise; progression onto blood flow restriction exercise (1-2 times/day, 3-4 set to volitional fatigue at 80% LOP)
Month 1-2	**Banded TKE** **(Standing)** **Prescription Type:** Neuromuscular Reeducation and Muscle Activation **F**: 2-3 times/day **I**: Elastic resistance band (light to heavy) **T**: Isotonic (concentric/eccentric phase) **T:** 10-15 minutes each exposure **V:** 3-4 sets of 10-20 repetition with a 1-3 second isometric contraction in TKE **P:** Progression of elastic resistance band level; progression onto blood flow restriction exercise (1-2 times/day, 3-4 set to volitional fatigue at 80% LOP)	**Double-Leg Squat** **(0-60 Degrees of Knee Flexion)** **Prescription Type:** Neuromuscular Reeducation and Muscle Activation **F:** 2-3 times/day **I:** Body weight (0-60 degrees of knee flexion) **T**: Isotonic (concentric/eccentric phase) or Isometric **T**: 10-15 minutes each exposure **V:** 3-4 sets of 10-15 repetition followed by a 45-90 second isometric contractions in 45-60 degrees of knee flexion | 30-90-second rest periods between sets **P**: Progression of knee flexion angle, positive shin angle and duration of isometric contraction; redistribution of weight toward the surgical limb	**Long-Arc Quad** **(AROM with Blood Flow Restriction)** **Prescription Type:** Cell Swelling/Atrophy Mitigation/ Hypertrophy **F:** 1-2 times/day **I:** Weight of lower leg, blood flow restriction at 80% LOP **T:** Isotonic (concentric/eccentric phase) | 0-90+ degrees of knee flexion **T:** 10-20 minutes each exposure **V:** 3-4 sets to volitional fatigue | 30-90-second rest periods between sets **P:** Addition of progressive isometric contractions at 45-90 degrees of knee flexion with/without the superimposition of NMES

Postoperative Month	Single-Leg Progression	Split-Squat Progression	Open-Kinetic-Chain Progression
Month 2-3	**Double-Leg Wall Squat (60-90+ Degrees of Knee Flexion)** **Prescription Type:** Extensor Mechanism Load-Tolerance/ Hypertrophy **F:** 3-5 times/week I: Body weight (60-90+ degrees of knee flexion) **T**: Isometric **T**: 5-10 minutes each exposure **V**: 3-4 sets of 45-90 second isometric contractions | 2-5-minute rest periods between sets **P**: Progression of knee flexion angle, positive shin angle, or duration of isometric contraction; pressure redistribution of additional weight onto the surgical limb	**Split-Squat (0-60 Degrees of Knee Flexion)** **Prescription Type:** Neuromuscular Reeducation and Muscle Activation **F:** 2-3 times/day **I:** Body weight (0-60 degrees of knee flexion) on involved limb **T:** Isotonic (concentric/eccentric phase) or Isometric **T:** 5-10 minutes each exposure **V:** 3-4 sets of 10-15 repetition followed by a 45-60 second isometric contractions in shallow knee flexion | 30-90-second rest periods between sets **P:** Progression of knee flexion angle, positive shin angle or duration of isometric contraction; redistribution of weight onto the surgical limb	**Knee Extension Machine (Single-Leg with Blood Flow Restriction)** **Prescription Type:** Hypertrophy/Strength **F:** 3-5 times/week **I:** 15-30 RM (<40-65% 1-RM) of involved limb, blood follow restriction at 80% LOP **T:** Isotonic (concentric/eccentric phase) | 45-90+ degrees of knee flexion **T:** 5-10 minutes each exposure **V:** 3-4 sets to volitional fatigue | 2-5-minute rest periods between sets **P:** Progression of external resistance at the distal tibia
Month 3-4	**Leg Press Machine (Single-Leg with Blood Flow Restriction)** **Prescription Type:** Hypertrophy/ Strength **F**: 2-4 times/week **I:** 10-20 RM (40-75% 1-RM) on the involved limb, blood follow restriction at 80% limb occlusion pressure **T:** Isotonic (concentric/eccentric phase) **T:** 5-10 minutes each exposure **V:** 3-4 sets to volitional fatigue | 2-5-minute rest periods between sets **P:** Progression of knee flexion angle, positive shin angle or external resistance	**Split -Squat (60-90+ Degrees Knee Flexion)** **Prescription Type:** Hypertrophy/Strength **F:** 2-4 times/week **I:** Body weight (60-90+ degrees of knee flexion) on the involved limb **T:** Isometric **T:** 5-10 minutes each exposure **V:** 3-4 sets of 45-90 second isometric contractions in progressively deeper knee flexion | 2-5-minute rest periods between sets **P**: Progression of knee flexion angle, positive	**Knee Extension Machine (Single-Leg with Blood Flow Restriction)** **Prescription Type:** Hypertrophy/Strength **F:** 2-4 times/week **I:** 15-20 RM (40-65% 1-RM) of involved limb, blood follow restriction at 80% limb occlusion pressure **T:** Isotonic (concentric/eccentric phase) | 0-90+ degrees of knee flexion **T:** 5-10 minutes each exposure **V:** 3-4 sets to volitional fatigue | 2-5-minute rest periods between sets **P:** Progression of external resistance at the distal tibial

Postoperative Month	Single-Leg Progression	Split-Squat Progression	Open-Kinetic-Chain Progression
Month 4-6	**Leg Press (Single-Leg with Increasing Load)** **Prescription Type:** Hypertrophy/ Strength **F:** 2-4 times/week **I:** 6-15 RM (65-85% 1-RM) on the involved limb **T:** Isotonic (concentric/eccentric phase) **T:** 5-10 minutes each exposure **V:** 3-4 sets to volitional fatigue | 2-5-minute rest periods between sets **P:** Progression of knee flexion angle, positive shin angle or external resistance	**Split-Squat (Rearfoot-Elevated Position)** **Prescription Type:** Hypertrophy/Strength **F:** 2-4 times/week **I**: 6-15 RM (65-85% 1-RM) on the involved limb **T:** Isotonic (concentric/eccentric phase) **T:** 5-10 minutes each exposure **V:** 3-4 sets to volitional fatigue | 2-5-minute rest periods between sets **P:** Progression of knee flexion angle, positive shin angle or external resistance	**Knee Extension Machine (Single-Leg with Increasing Load)** **Prescription Type:** Hypertrophy/Strength **F**: 2-4 times/week **I:** 6-15 RM (65-85% 1-RM) on the involved limb **T:** Isotonic (concentric/eccentric phase) | 0-90+ degrees of knee flexion **T:** 5-10 minutes each exposure **V:** 3-4 sets to volitional fatigue | 2-5-minute rest periods between sets **P:** Progression of external resistance at the distal tibial
Month 6+	**Eccentric Leg Press (2-Legs Up Concentric / 1-Leg Down Eccentric)** **Prescription Type:** Hypertrophy/ Eccentric Strength **F:** 2-3 times/week **I:** 1-5 RM (85-100% 1-RM) on the involved limb **T:** Eccentric resistance training **T:** 5-10 minutes each exposure **V:** 3-4 sets of 8-15 eccentric repetitions | 2-5-minute rest periods between sets **P:** Progression of knee flexion angle, positive shin angle or external resistance greater than a 1-RM (e.g., 120% 1-RM)	**Split-Squat Jumps (Lunge or Rearfoot-Elevated Position)** **Prescription Type:** Power **F**: 2-4 times/week **I**: Body weight to 40-60% 1-RM on the involved limb **T:** Isotonic (concentric/eccentric phase), emphasis on speed/effort during the concentric phase of the movement **T**: 5-10 minutes each exposure **V**: 4-5 sets of 3-5 reps | 2-5-minute rest period between sets **P:** Progression of knee flexion angle, positive shin angle, contraction speed or external load	**Eccentric Knee Extension Machine (2-Legs Up Concentric / 1-Leg Down Eccentric)** **Prescription Type:** Hypertrophy/ Eccentric Strength **F**: 2-3 times/week **I**: 1-5 RM (85-100% 1-RM) on the involved limb **T:** Eccentric resistance training | 0-90+ degrees of knee flexion **T**: 5-10 minutes each exposure **V:** 3-4 sets of 8-15 eccentric repetitions | 2-5-minute rest periods between sets **P:** Progression of external resistance greater than a 1-RM (e.g., 110% 1-RM)

F, frequency; I, intensity; T, type; T, time; V, volume; P, progression; AROM, active range-of-motion; TKE, terminal knee extension; LOP, limb occlusion pressure, RM, repetition maximum, 1-RM, 1-repetition maximum force-transmission. Specifically, performing the prone knee flexion stretch will preferentially tension the superficial layer of the quadriceps tendon by maximally lengthening rectus femoris, compressing/shearing the deeper layers of the tendon[95,97,98]; this unique type of tendon loading can be prescribed in addition to strength training to mobilize the graft harvest site and may help stimulate quadriceps tendon remodeling (Figure 2).

Months 2-4 after ACLR with the QT, the CKC quadriceps load-progression should include isometric or isotonic contractions with a light to moderate external resistance. Initially, body weight isometric exercise in low levels of knee flexion may best manage graft harvest site irritability[94,99] (Figure 1A) (Table 2). As exercise tolerance improves, the quadriceps load-progression should be advanced by monitoring the graft harvest site for any increase in pain/irritability with exercise while gradually progressing external resistance or the level of knee flexion[95] (Figure 1A-D-E). The rehabilitation specialist should not advance too many variables at once, as simultaneously increasing external resistance and the level of knee flexion can exponentially load the quadriceps tendon and may provoke graft harvest site pain[94,95] (Figure 1C).

Graft-specific load-progressions for the P-QT may also exist, in which more specific targeting of the superficial layer of the quadriceps tendon/rectus femoris with OKC exercise may be indicated.[98,100] The long-arc-quad exercise should be advanced from active range-of-motion during the early phase of rehabilitation,[85] to OKC quadriceps resistance training on a knee extension machine (Table 2); the rehabilitation specialist may elect to perform OKC quadriceps resistance training with the hip positioned in lower levels of hip flexion to preferentially load rectus femoris (i.e., performing OKC quadriceps resistance training with the trunk positioned in supine).[95,97,98] External resistance should be thoughtfully progressed, as performing OKC quadriceps resistance training between 0-45 degrees of knee flexion will increase patellofemoral compartment stress and preferentially strain the reconstructed ACL graft[85,86,101] (Figure 3A), whereas performing OKC quadriceps resistance training in deeper levels of knee flexion will preferentially load the quadriceps tendon and may provoke irritability at the graft harvest site[94,95] (Figure 3B).

LATE PHASE (POSTOPERATIVE WEEKS 16+)

As the surgical limb develops the capacity to perform higher-load activities at slow contraction velocities, higher demand exercise progressions should be introduced. Patients participating in physically demanding activities, such as Level 1 sports, will benefit from exposure to plyometric and ballistic-type exercise progressions. The rehabilitation specialist should consider the quadriceps tendon a rate-limiting tissue for the introduction of plyometric exercise,[23] as the QT harvest site must store and transfer energy during these progressions. Plyometric exercise should be initiated with knee-specific regressions that temper the demand for elastic energy-storage within the quadriceps tendon, such as running drills in triple-extension or frontal plane plyometric exercise[94,102,103] (Figure 4).

As mentioned previously, specific consideration should be given for ballistic activities that require the quadriceps tendon to transfer load while in the combined position of hip extension and knee flexion, such as the wind-up phase of kicking or high-velocity running[104,105] (Figure 2B); these activities combine high angular velocities and tendinous compressive/shear force by the selective-tensioning of the superficial layer of the quadriceps tendon running continuous with rectus femoris.[95,97] Sagittal plane deceleration training will also preferentially load the quadriceps tendon. During deceleration, the combination of large external knee flexion moments, increasing knee flexion angles, and high-force eccentric quadriceps contractions can produce exponentially higher load-transmission within the quadriceps tendon (Figure 4); sagittal plane deceleration training must be thoughtfully progressed per exercise-tolerance and symptom-response at the graft harvest site.

RETURN TO ACTIVITY CONSIDERATIONS

Regardless of the graft type used for ACLR, most individuals expect to restore knee joint stability and function to a level that supports the return to their pre-injury activity level.[106] However, only 65% of individuals may return to their pre-injury level of sports participation,[107] with knee re-injury rates between 20-30% within higher-risk cohorts.[108–110] Equally troubling is the unclear association between return-to-activity testing batteries and the subsequent risk of knee re-injury within various cohorts,[111–117] and although the restoration of limb function on objective performance tests appears to improve return-to-sport rates,[118–120] the use of performance testing cut-points as strict, medically-required, return-to-activity criteria remains controversial.[112,121–123] Recent literature has highlighted the importance of shared decision-making after ACLR,[124,125] to which the use of a decision-making framework may improve the return-to-activity decision-making process.[124,126–129]

To best inform shared decision-making, serial physical examinations and performance testing batteries should be completed throughout rehabilitation.[130,131] Physical examinations should include the assessment of knee homeostasis (effusion and irritability), stability and range-of-motion.[132] After ACLR with the QT, quadriceps strength testing should be a fundamental component of the performance testing battery, as quadriceps strength appears most affected by QT harvest,[33,34,68] and quadriceps strength deficits are common 9-12 months after ACLR.[34] Other components of a performance testing battery may include jump/hop testing and the assessment of movement quality; these tests should include both qualitative and quantitative measurements.[132] Collectively, this information can be utilized throughout rehabilitation to confirm the effectiveness of exercise interventions, adjust the exercise prescription(s), and inform return-to-activity decision-making.[133]

Of the various data synthesized for return-to-activity decision-making, some information may be more important than others. The timeframe between ACLR and return-to-activity has been observed to be a modifiable risk factor

Table 3. Rehabilitation Overview

	Consideration	Location	Description of Consideration(s)
Early Phase Rehabilitation Considerations (Postoperative Weeks 0-8)	Graft Composition	Intra-Articular	**B-QT** • Partial graft osteointegration within first 4-6 weeks **S-QT** • Graft fibrovascular integration takes a minimum of 10-12 weeks • Accelerated rehabilitation approaches may be less appropriate when fixated with suspensory fixation (Table 2) **F-QT** • Consider risk of a range-of-motion complications with large graft diameter and robust biomechanical properties
	OKC Quadriceps Resistance Training / Graft Fixation	Intra-Articular	**OKC Exercise with Interference Screw Fixation (B-QT)** • AROM: as tolerated • OKC quadriceps resistance exercise with distal tibial load: ◦ 45-90+ degrees weeks 3-4 ◦ 0-45+ degrees weeks 4-6+ **OKC Exercise with Suspensory Fixation (S-QT)** • AROM: as tolerated • OKC quadriceps resistance exercise with distal tibial load: ◦ 45-90+ degrees weeks 3-10 ◦ 0-45+ degrees weeks 10-12+
	Graft Harvest Site	Extra-Articular	**B-QT** • Low risk of patellar fracture (1.4-8.8%) **F-QT** • Possibility of more persistent and global quadriceps inhibition • Differentiation of a postoperative knee effusion from a suprapatellar hematoma at graft harvest site
Middle Phase Rehabilitation Considerations (Postoperative Weeks 8-16)	Graft Composition	Extra-Articular	**P-QT** • Superficial tendon trauma will result in more isolated involvement of the rectus femoris muscle • OKC exercise may be more provocative to graft harvest site than CKC **F-QT** • Full-thickness tendon trauma may increase the potential for more global graft harvest site irritability with CKC/OKC quadriceps resistance training
	Graft Harvest Site	Extra-Articular	**Gradual and Progressive Quadriceps Loading into Deep Knee Flexion** • Prone knee flexion stretching will preferentially tension the superficial layer of quadriceps tendon • Increasing the level of knee flexion during resistance training will preferentially increase the load within the quadriceps tendon relative to the patellar tendon
Late Phase Rehabilitation Considerations (Postoperative Weeks 16+)	Graft Harvest Site	Extra-Articular	**Ongoing Quadriceps Strengthening Program** • Quadriceps strengthening program 2-3x/week (OKC + CKC) • Progressive resistance training, eccentric training, and power training **Progression of Energy Storage Activities into Increasing Knee Flexion** • Combination of hip extension and knee flexion preferentially tensions the superficial layer of the quadriceps tendon (e.g., wind-up phase of kicking) • Avoid acute spikes in plyometric load into increasing levels of knee flexion • Thoughtful progression of high velocity running speed/intensity, distance and volume • Thoughtful progression of high-velocity kicking and sagittal plane deceleration training

B-QT, quadriceps tendon autograft with patellar bone-block; S-QT, all soft-tissue quadriceps tendon autograft; F-QT, full-thickness quadriceps tendon autograft; OKC, open-kinetic-chain; AROM, active range-of-motion; P-QT, partial-thickness quadriceps tendon autograft; CKC, closed-kinetic-chain

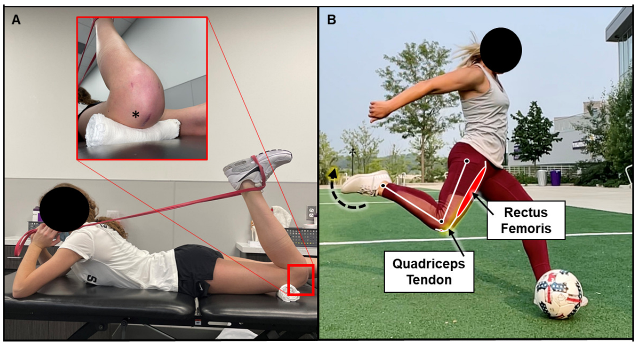

Figure 2. Selective tensioning of the superficial layer of the quadriceps tendon

Selective tensioning of the superficial layer of the quadriceps tendon is achieved by maximally lengthening rectus femoris into the combined motion of hip extension and knee flexion; low-velocity stretching may be therapeutically prescribed to shear/mobilize the graft harvest site (A), whereas high-velocity activities should be thoughtfully progressed with ongoing monitoring of the graft harvest site for any increase in tissue irritability. Asterisk, quadriceps tendon autograft harvest site; white lines, depiction of joint angles; black dash-arrow, high-velocity eccentric lengthening of the quadriceps muscle during the wind-up phase of kicking

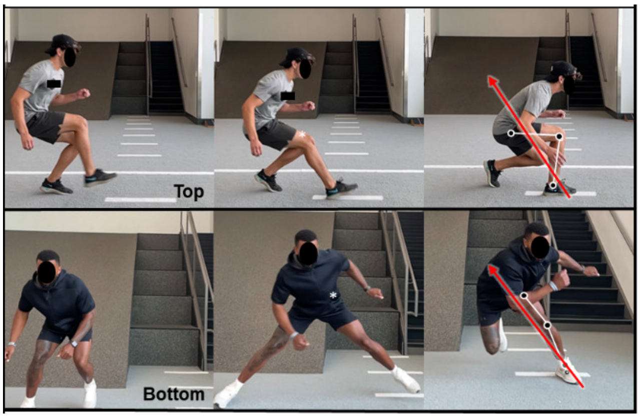

Figure 4. Sagittal deceleration task vs lateral plyometric task

The resultant ground reaction force during a sagittal plane deceleration task (top sequence from left to right) places a large amount of load on the knee and quadriceps tendon, whereas a lateral plyometric task places more relative load proximally on the lateral hip and trunk (bottom sequence from left to right). Red arrows, resultant ground reaction force-vector; white lines, depiction of joint angels; asterisks, area of high load-demand during task.

for knee re-injury,[111,134] with the suggestion that most individuals should wait a minimum of nine months before returning to unrestricted sports participation.[111,122,132] Risk calculator algorithms formulated to predict the risk of revision ACLR have been recently validated for clinical use[135,136]; these algorithms are based upon data that is specific to the individual of interest, including age, body mass index, preoperative knee laxity, activity level and graft type.[135,136] The ACL-Return to Sport after Injury (ACL-RSI) is a validated psychometric scale, and should be used to assess an individual's psychological readiness for sports participation after ACLR.[132]

Comprehensive rehabilitation and return-to-sport programming can facilitate improved limb function on objective performance tests,[133,137] achieve higher return-to-sport rates and reduce the risk of knee re-injury.[133,138–141] Comprehensive programming should include formal strength and conditioning sessions, as well as the integration of jumping/hopping, cutting and sport-specific load-

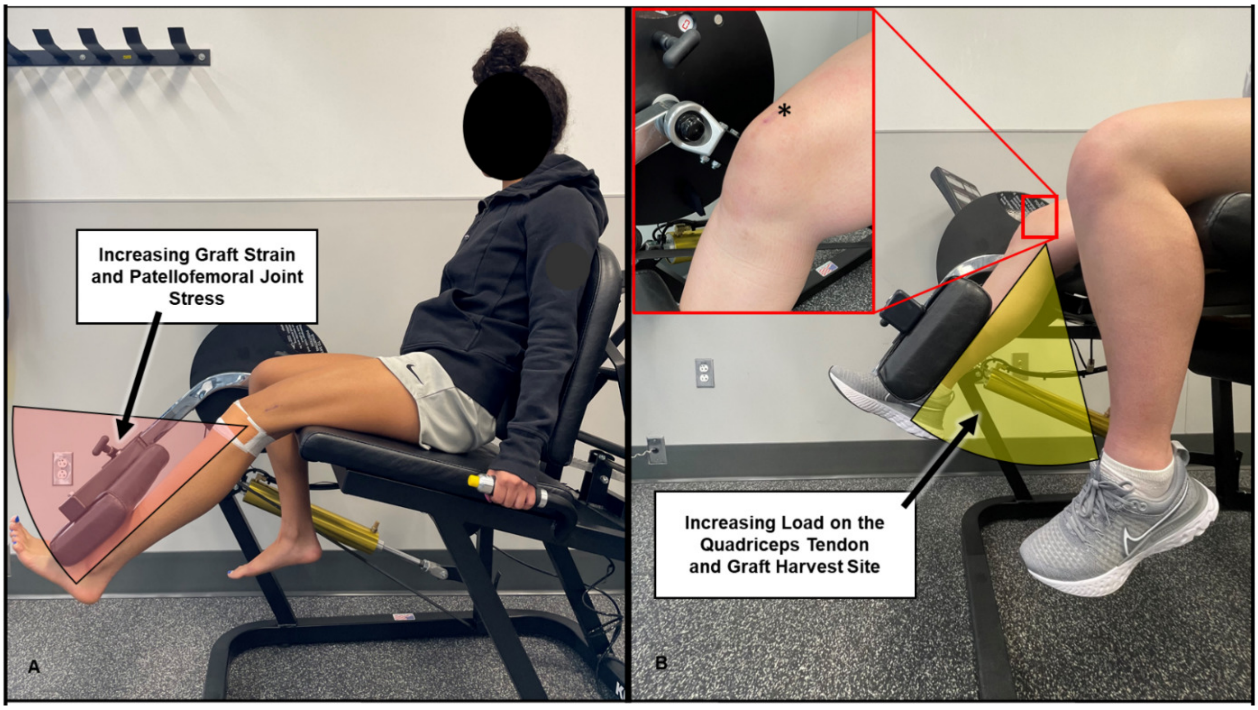

Figure 3. Considerations for open-kinetic-chain quadriceps resistance training with distal tibial load

Performing quadriceps resistance training between 0-45 degrees of knee flexion with distal tibial load will produce higher patellofemoral joint stress and increase strain on the reconstructed anterior cruciate ligament (A), whereas performing resisted knee extensions in deeper levels of knee flexion will preferentially load the quadriceps tendon relative to the patellar tendon. Red arc, 0-45 degrees of knee flexion; yellow arc, >45 degrees of knee flexion; Black asterisk, quadriceps tendon autograft harvest site progressions. Late phase load-progressions should include a period of on-field rehabilitation with all relevant stakeholders (e.g., athlete, coach, guardian, and rehabilitation specialist) in agreement with the return-to-practice and competition progressions.[131,133,142] On-field rehabilitation should follow the control-chaos continuum and facilitate graded exposure to sports participation.[133,135,142,143]

Prior to commencing unrestricted activity, a final physical examination and performance testing battery should be completed with all relevant information clearly synthesized for analysis within the shared decision-making framework.[124–129,133] If the individual is returning to an activity with a high risk of knee re-injury, such as Level 1 sports, secondary injury reduction strategies should be implemented regardless of performance testing status.[144] Pre-activity neuromuscular warmups, such as the FIFA 11+, appear highly effective at mitigating known biomechanical risk factors for anterior cruciate ligament injury,[145–148] and can significantly reduce the overall injury incidence rate.[149]

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