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Clinical Commentary/Current Concept Review

Oh, My Quad: A Clinical Commentary And Evidence-Based Framework for the Rehabilitation of Quadriceps Size and Strength after Anterior Cruciate Ligament Reconstruction.

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Quadriceps weakness after anterior cruciate ligament reconstruction (ACLR) is a well-known phenomenon, with more persistent quadriceps weakness observed after ACLR with a bone-patellar tendon-bone or quadriceps tendon autograft than with a hamstring tendon autograft. Longstanding quadriceps weakness after ACLR has been associated with suboptimal postoperative outcomes and the progression of radiographic knee osteoarthritis, making the recovery of quadriceps size and strength a key component of ACLR rehabilitation. However, few articles have been written for the specific purpose of optimizing quadriceps size and strength after ACLR. Therefore, the purpose of this review article is to integrate the existing quadriceps muscle basic science and strength training literature into a best-evidence synthesis of exercise methodologies for restoring quadriceps size and strength after ACLR, as well as outline an evidence-informed quadriceps load-progression for recovering the knee's capacity to manage the force-profiles associated with high-demand physical activity.

Level of Evidence: 5

INTRODUCTION

Anterior cruciate ligament (ACL) injuries are common within athletics,[1] and ACL reconstruction (ACLR) is the preferred surgical procedure for treating knee instability after a complete ACL tear.[2-4] Regarding surgical technique, ACLR with a bone-patellar tendon-bone autograft (BPTB) may optimize ACL graft survivorship in select cohorts (e.g., athletes returning to Level-1 sports).[5-7] However, ACLR with the hamstring tendon autograft (HT) is the most popular surgical technique internationally,[8,9] and the use of the quadriceps tendon autograft (QT) for ACLR is increasing in popularity.[8,10]

Partially due to arthrogenic muscle inhibition (AMI) from harvesting the quadriceps/patellar tendon autograft,[11-13] more persistent quadriceps weakness has been observed after ACLR with a BPTB or QT than with a HT.[14-18] Ongoing quadriceps weakness after ACLR has been associated with impaired knee biomechanics,[19,20] a slower functional progression within rehabilitation,[21] low return to sport rates and patient satisfaction scores,[22-27] and is correlated with the progression of radiographic knee osteoarthritis.[28,29] Subsequently, recent literature has focused on improving postoperative strength outcomes,[13,30-32] and therapeutic interventions prescribed to optimize the sensory/motor function of the surgical knee have shown efficacy for treating AMI after ACLR.[12,31,32]

Although the management/treatment of AMI is an important component of ACLR rehabilitation, prescribing exercise to stimulate improvements in muscle size and strength is also required to maximize performance-based outcomes, especially within cohorts returning to high-demand physical activities. Previous literature has explored the indications for various strengthening exercises and their ability to improve outcomes after ACLR,[31,33-35] but few articles have been written for the specific purpose of

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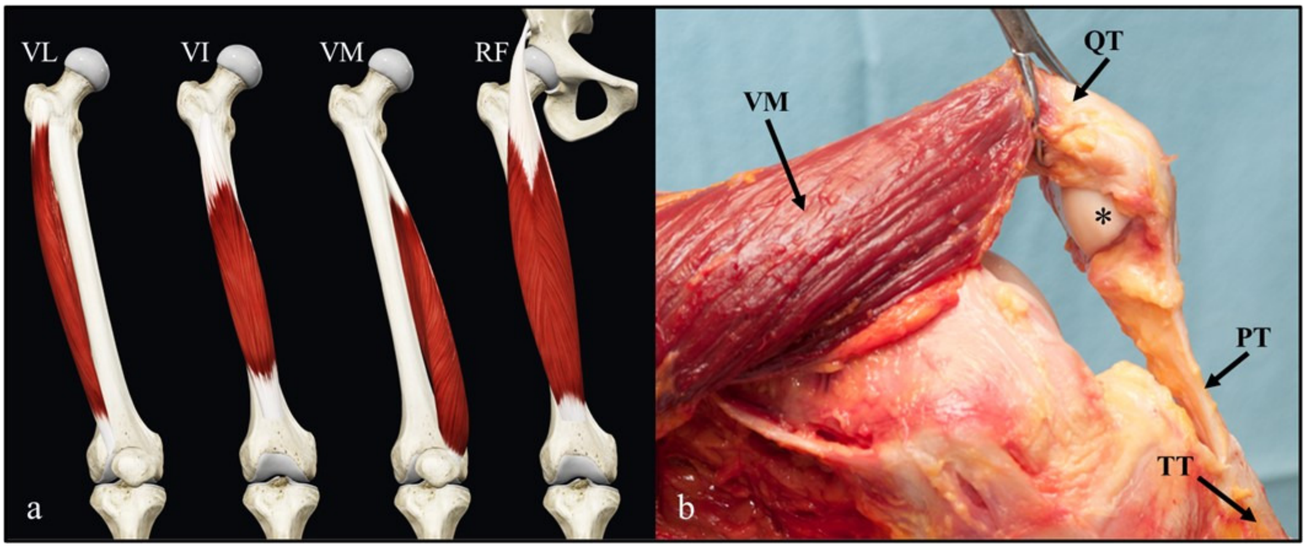

Figure 1. Quadriceps Anatomy.

The quadriceps muscle group consists of four muscles (a); all four muscles share a common insertion on the patella and tibial tuberosity via the patellar tendon (b). Asterisks, patella; PT, patellar tendon; QT, quadriceps tendon; RF, rectus femoris; TT, tibial tuberosity; VI, vastus intermedius; VL, vastus lateralis; VM, vastus medialis.

optimizing quadriceps size and strength after ACLR.[31] Moreover, few authors have integrated the existing muscle basic science and strength training literature into a review article.[36,37] Therefore, the purpose of this commentary is to integrate the existing muscle basic science and strength training literature into a best-evidence synthesis of exercise methodologies for restoring quadriceps size and strength after ACLR.

QUADRICEPS BASIC SCIENCE

QUADRICEPS ANATOMY

The quadriceps (i.e., quadriceps femoris) is typically divided into four muscles: (1) rectus femoris, (2) vastus lateralis, (3) vastus intermedius, and (4) vastus medialis (Figure 1a).[38] All four muscles share a common insertion on the patella and tibial tuberosity (via the patellar tendon) and contribute to the primary action of knee extension (Figure 1b). Subsequently, exercises which isolate open-kinetic-chain (OKC) and closed-kinetic-chain (CKC) knee extension will be highly-specific in activating/loading the quadriceps.

The rectus femoris originates on the anterior inferior iliac spine, making it the only biarticular quadriceps muscle (Figure 1a).[38] It contributes to the primary action of hip flexion and knee extension and has an intramuscular tendon running longitudinally from its origin[38-40]; the intramuscular tendon is utilized to store/transfer energy during the combined motion of hip flexion and knee extension (e.g., mid-swing phase of running).[41,42] These anatomic features suggest optimal targeting of the rectus femoris should include exercises that isolate the combined motion of hip flexion with knee extension, such as the straight leg raise (SLR) exercise or high-velocity running/kicking,[41-43] whereas combining the primary actions of hip extension with knee extension (e.g., leg press exercise) can reduce rectus femoris recruitment/involvement relative to the other quadriceps muscles.[44,45]

QUADRICEPS INNERVATION

Motor branches from the femoral nerve produce regional innervation pathways within the anterior thigh, which facilitates selective motor unit recruitment within the quadriceps.[38,46,47] For example, performing exercises at longer muscle lengths and with the primary action of knee extension can selectively activate the more distal regions of the quadriceps,[47,48] whereas exercising with shorter muscle lengths and/or combining the primary action of hip flexion with knee extension may recruit the more proximal regions.[46,47] Likewise, OKC tasks may recruit the more proximal regions of the quadriceps/rectus femoris, producing a proximal-to-distal sequence of muscle activity (e.g., OKC knee extensions, kicking, and the swing phase of gait),[41-43,45,49] whereas CKC tasks produce a more distal-to-proximal sequence of quadriceps activation and demand less of the rectus femoris (e.g., squatting or a sagittal deceleration task).[44,46,49] Altogether, the task-specific activation of the quadriceps exemplifies the need for a variety of OKC and CKC exercises to maximally stimulate quadriceps hypertrophy and strength.

QUADRICEPS ACTIVATION-THRESHOLD AND FIBER-TYPE DISTRIBUTION

Compared to other muscles of the lower extremity, previous work has observed the quadriceps to possess a relatively high volitional recruitment threshold (Figure 2).[50] While higher quadriceps recruitment thresholds may help produce larger knee extension torque-outputs,[50] a higher baseline recruitment threshold makes volitional activation of the quadriceps a challenge after ACLR.[13,51] Considering this, Boccia et al[52] observed higher motor unit discharge

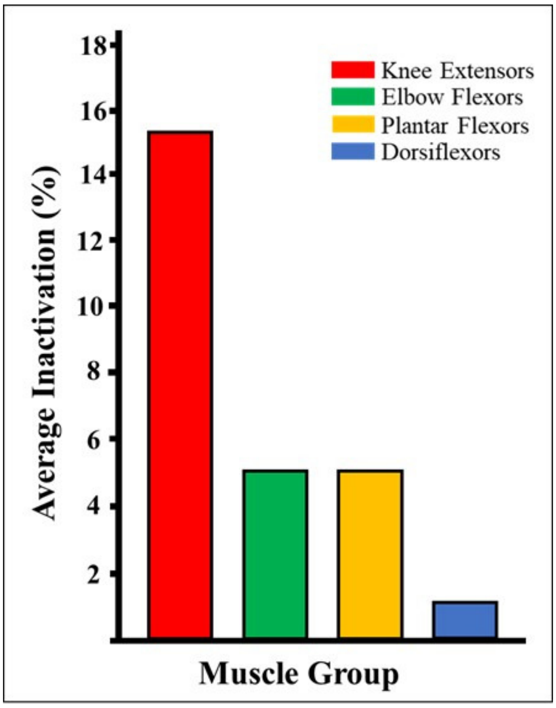

Figure 2. Average inactivation by muscle group.

Relative to other muscle groups within the human body, the knee extensors (i.e., quadriceps femoris) have the largest inactivation percentage.[50] This higher inactivation percentage suggests maximal, volitional recruitment/activation of the quadriceps is a challenge at baseline (i.e., before knee injury or surgery). %, percentage.

rates and synaptic input to the vastus medialis and vastus lateralis with the use of resisted OKC knee extensions compared to the leg press exercise, suggesting OKC exercise may more specifically activate the quadriceps muscles.

The relative distribution of muscle fiber-type does not appear uniform within the quadriceps; the vastus lateralis is roughly 50% type-II muscle fiber,[53] whereas the rectus femoris may be as much as 62%.[54] These findings suggest the rectus femoris may experience more post-exercise fatigue and muscle damage than the vastus lateralis,[55-57] requiring more time to recover in between exercise bouts (e.g., 72-96 hours of recovery in between fatiguing exposures to high velocity running). The combination of a high volitional recruitment threshold and a relatively lower distribution of type-II fibers within the vastus lateralis may suggest a higher training frequency may be indicated for the single-joint quadriceps muscles (e.g., 48-72 hours of recovery in between exposures to resistance training on a leg press).[53,58]

QUADRICEPS LENGTH-TENSION

Although a variety of training variables can be manipulated to improve muscle size and strength, exercising within a muscle's ideal length-tension relationship may help stimulate a greater amount of mechanotransduction,[59] and optimal muscle length-tension can improve the intramuscular force-output at any muscle activation level.[60,61] Multiple studies have reported different muscular adaptations in response to the manipulation of exercise range-of-motion (ROM),[62,63] to which superior improvements in muscular hypertrophy have been observed with resistance training at longer muscle lengths[64]; this observation may be partially explained by a more optimal length-tension relationship within the muscle when resistance training is prescribed at relatively long muscle lengths.[61] Considering the quadriceps consists of four separate muscles, the rehabilitation specialist should understand which hip/knee joint positions will optimize the length-tension properties within each muscle.

Previous work has outlined the sarcomere lengths of each quadriceps muscle (Figure 3).[65,66] Due to its biarticular nature, the rectus femoris is the only quadriceps muscle that operates within the ascending limb of the length-tension curve (Figure 3a)[65]; loading the rectus femoris within higher degrees of hip flexion in combination with low levels of knee extension (e.g., OKC knee extensions between 0-40 degrees of knee flexion with the trunk positioned in 90+ degrees of hip flexion) may create a suboptimal length-tension relationship, producing active insufficiency and impaired force-output.[60,61,63,65,67]

At any degree of knee flexion, it appears the single-joint quadriceps muscles have sarcomere lengths operating within the plateau to descending limb of the length-tension curve (Figure 3b-d).[60] Therefore, active insufficiency considerations may only apply to the rectus femoris. Resistance training between 0-90 degrees of knee flexion may best activate/load the vastus intermedius,[65] because greater regional hypertrophy has been observed within the vastus intermedius when performing the half squat exercise compared to the full squat.[68] Inversely, resistance training at longer muscle lengths (i.e., 60-110+ degrees of knee flexion) may best facilitate regional hypertrophy within the distal vastus medialis and vastus lateralis by exercising within the descending limb of their length-tension curves[48,65]; the vastus medialis has a slightly longer sarcomere length than the vastus lateralis at 90 degrees of knee flexion (Figure 3c-d),[66] suggesting resistance training within an even deeper level of knee flexion (i.e., a full squat to 140 degrees of knee flexion) may further facilitate regional hypertrophy within the distal vastus lateralis.[48,68]

QUADRICEPS INTERNAL MOMENT ARM

Considering the quadriceps shares a common insertion on the patella (via the quadriceps tendon) and the tibial tuberosity (via the patellar tendon), it is important to consider the internal moment arm curve of each muscle as well as the quadriceps/patellar tendons. When analyzing each quadriceps muscle in isolation, previous literature has reported similar internal moment arm curves for all four muscles (Figure 4)[69]; the internal moment arm curve for the single-joint quadriceps muscles slightly increases and peaks from 0-30 degrees of knee flexion, then gradually decreases from 30-100 degrees.[69] Similarly, the internal moment arm curve of the rectus femoris peaks at 20-30 degrees of knee flexion but has a slightly steeper moment arm curve (Figure 4).[69,70]

To best manage the graft harvest site after ACLR with the BPTB or QT autograft, the internal moment arms of the patellar and quadriceps tendons should also be con-

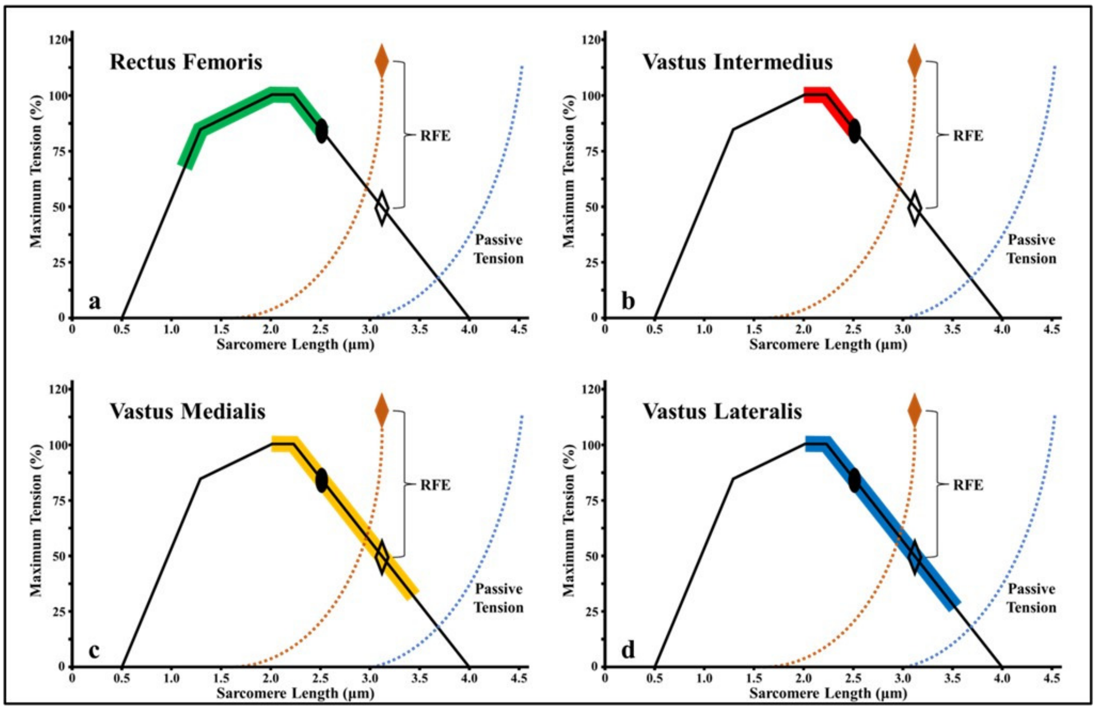

Figure 3. Length-tension properties of the quadriceps muscle group.

Previous work has outlined the sarcomere lengths of each quadriceps muscle throughout its functional operating range.[65,66] The rectus femoris is the only quadriceps muscle that operates within the ascending limb of the length-tension curve. At any degree of knee flexion, the single-joint quadriceps muscles (i.e., vastus medialis, intermedius and lateralis) have sarcomere lengths that are working within the plateau to descending limb of the length-tension curve. %, percentage; µm, micrometers; RFE, residual force enhancement.

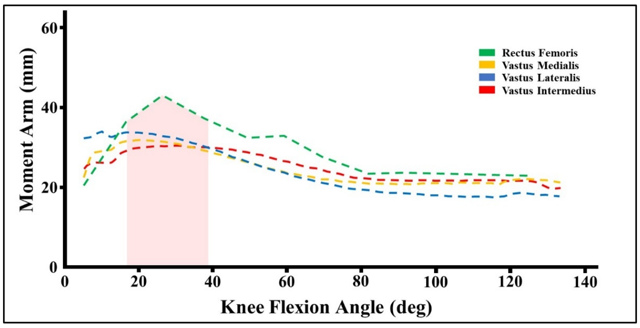

Figure 4. The internal moment arm curves of the quadriceps muscle group.

The internal moment arm curve for the single-joint quadriceps muscles slightly increases and peaks from 0-30 degrees of knee flexion, then gradually decreases from 30-100 degrees.[69] Similarly, the internal moment arm curve of rectus femoris peaks between 20-30 degrees of knee flexion but has a slightly steeper moment arm curve.[70] Deg, degrees; mm, millimeters; red shading, range of knee flexion associated with peak internal knee extension moment.

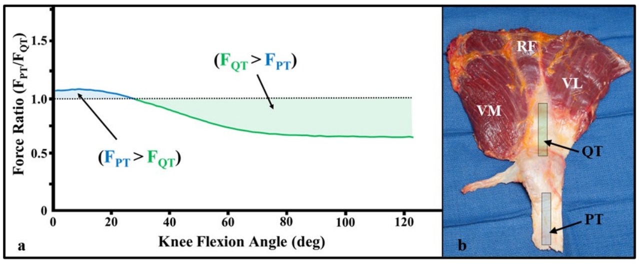

Figure 5. Force-ratio between the quadriceps and patellar tendons.

As the knee moves into deeper flexion, force transmission within the quadriceps tendon increases relative to the patellar tendon (a)[74,77]; this change in force-ratio is due to a decreasing quadriceps tendon internal moment relative to the patellar tendon (see Figure 6) with a concurrent increase in passive tension within the quadriceps muscle group (b). F, force; PT, patellar tendon; QT, quadriceps tendon; RF, rectus femoris; VL, vastus lateralis; VM, vastus medialis.

sidered.[71] The internal moment arm of the patellar tendon rises and peaks from 0-30 degrees of knee flexion, then reduces from 30-100+ degrees.[72] Therefore, exercises prescribed to preferentially load the patellar tendon may benefit from exercise prescriptions that initially emphasize low levels of knee flexion.[71,73,74] The internal moment arm of the quadriceps tendon appears relatively constant between 0-25 degrees of knee flexion, with a peak moment greater than the patellar tendon at 20 degrees.[75,76] As the knee moves into deeper flexion, force-transmission within the quadriceps tendon increases relative to the patellar tendon (**Figure 5**)[74,77]; this increase in quadriceps tendon force-transmission is due to a decrease in internal moment with a concurrent increase in the amount of passive tension within the quadriceps (Figure 6).[78] Subsequently, preferential loading of the quadriceps tendon relative to the patellar tendon can be achieved at deeper levels of knee flexion (i.e., 30-100+ degrees), but the rehabilitation specialist should also consider reducing the amount of knee flexion if quadriceps tendon pain is reported during exercise.[71]

QUADRICEPS CONTRACTION MODE

Of the various parameters utilized to stimulate exercise-induced adaptations within the neuromusculoskeletal system, muscle contraction mode appears highly influential.

Previous literature has observed specific neuromuscular adaptations from exposure to different contraction modes, to which the rehabilitation specialist should be able to effectively manipulate when designing rehabilitation programs. When prescribing the contraction mode, exercise prescriptions are commonly divided into *isometric*, *eccentric* and *isotonic* (i.e., exercises with concentric/eccentric phases) training programs.[55,79-84]

Isometric training programs are traditionally implemented during the acute phase of rehabilitation.[85] However, isometric resistance training is highly effective at improving muscle size and strength and can be prescribed within any rehabilitation phase.[62] Studies examining the muscle's response to isometric exercise have reported multiple types of isometric contractions[86-88]; *yielding/holding* isometrics require the muscle to maintain a set joint position as external force is applied, whereas *overcoming/pushing* isometrics require the muscle to produce/transfer force into a fixed structure.[88] Peripheral muscle activation and time to exhaustion may be increased with overcoming/pushing isometrics,[86,88] increasing motor recruitment relative to yielding/holding isometrics. Yielding/holding isometrics behave more like eccentric contractions,[87] producing less peripheral muscle activation but a more synchronous motor plan; these observations suggest yielding/holding isometrics may require a more complex/specific mechanism of motor control and may accelerate volitional fatigue relative to overcoming/pushing isometrics.[86,88] Collectively, overcoming/pushing isometrics may be best implemented when attempting to summate high volitional activation thresholds or mechanically stimulate a greater proportion of the recruited muscle fibers,[86,88] whereas yielding/holding isometrics can be utilized to modulate tendon pain,[89] manage/treat AMI and improve central motor excitability.[90-92]

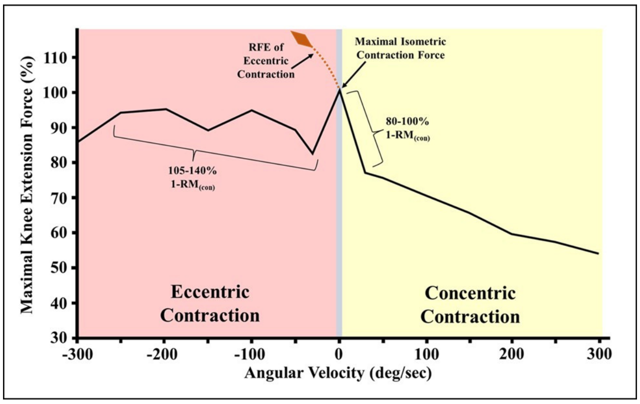

Figure 7. Depiction of the Knee Extensor Force-Velocity Relationship.

The force-velocity relationship for the quadriceps produces maximal concentric knee extension force/torque at slow contraction velocities (i.e., maximal effort pushing/overcoming isometric contractions or concentric contractions at < 60 degrees/second).[93] Partially due to residual force enhancement during eccentric contractions (i.e., active muscle lengthening at maximal effort), maximal knee extension force/torque-output will be higher during eccentric than concentric contractions.[94] %, percentage; 1-RM$_{(con)}$, 1-repitition maximum during a concentric contraction; deg, degrees; RFE, residual force enhancement; sec, second.

Partially due to *residual force enhancement* during eccentric contractions (Figure 7),[95] the eccentric 1-repitition maximum (1-RM) for a given muscle/muscle group has

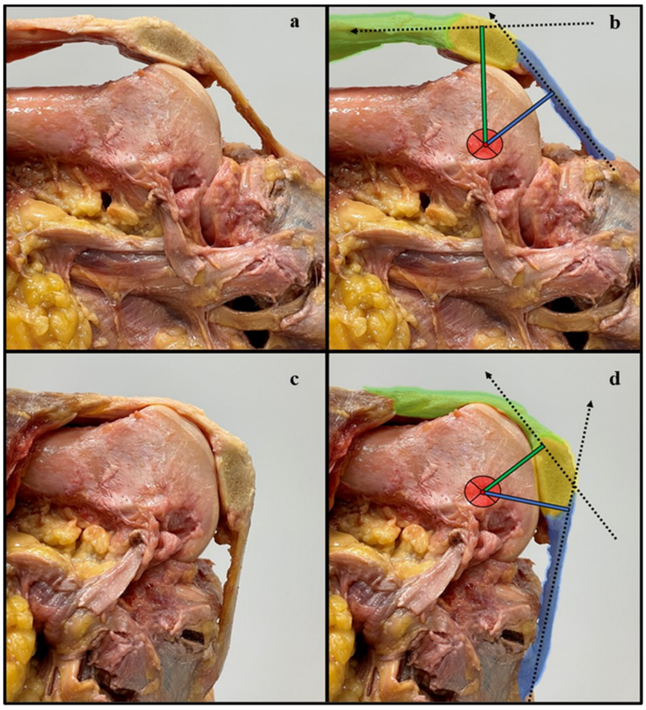

Figure 6. Internal moment arms of the quadriceps and patellar tendons.

Between 0-30 degrees of knee flexion, the internal moment arm of the quadriceps tendon is larger than the patellar tendon (a, b). The patellar tendon has a larger internal moment arm than the quadriceps tendon in deeper levels of knee flexion (c, d). Blue line, patellar tendon internal moment arm; blue shading, patellar tendon; dotted black lines; resultant intratendinous force-vector from a quadriceps contraction; green line, quadriceps tendon internal moment arm; green shading, quadriceps tendon; red circle; estimated center of joint rotation; yellow shading, patella.

been observed to be around 41% greater than the concentric 1-RM.[94] Eccentric contractions also produce less muscle activation than concentric contractions at any given force-output, making eccentric-specific exercise less metabolically demanding than isotonic/concentric exercise.[96,97] Likewise, eccentric-specific training programs can enhance motor control and hypertrophy,[51,90] improve strength outcomes,[98] and facilitate injury-protective architectural adaptations within skeletal muscle.[99,100] Therefore, any rehabilitation program designed to optimize quadriceps size and strength should gradually build the knee's load-tolerance to a level that supports eccentric-specific training at loads greater than the concentric 1-RM.

More recently, *eccentric quasi-isometric* (EQI) contractions (i.e., a muscle contraction that involves maintaining a yielding/holding isometric contraction until task failure and eccentric muscle activity ensues) has been proposed as a novel stimulus for safely exposing the musculotendinous system to a large mechanical load.[101,102] Eccentric quasi-isometric contractions produce similar architectural and neuromuscular adaptations as eccentric-specific contractions, but yield less post-exposure muscle soreness/fatigue.[101] Theoretically, EQI resistance training should be prescribed after ACLR to stimulate favorable size, strength, and architectural adaptations within the surgical knee's extensor mechanism, while concurrently protecting any desired postoperative structures within a predetermined ROM.

Recently, *heavy-slow resistance training* (HSRT) (i.e., high-load isotonic training at slow contraction velocities) has become popular for treating tendinopathy,[103,104] and *velocity-based training* (i.e., a training method that monitors intraset muscle contraction/exercise velocity) has proven effective in eliciting desirable power/performance adaptations.[105] Collectively, individuals with less resistance training experience may benefit from the use of isotonic/concentric training during the early phase of rehabilitation, when self-motivation is low, or when fatigue is high. To treat patellar/quadriceps tendinopathy at the autograft harvest site after ACLR, quadriceps HSRT should be prescribed at a load-intensity ⩾ 70-100% of the concentric 1-RM,[104] because this load-intensity will produce slow contraction velocities and maximize intramuscular force on the concentric side of the quadricep's force-velocity relationship (Figure 7).[93,106] Lastly, velocity-based training methods can be utilized throughout ACLR rehabilitation to optimize motor unit discharge-rates and quadriceps rate-of-force development.[105,107]

QUADRICEPS REHABILITATION AFTER ACLR

After ACLR, a *needs analysis* should be completed and modified throughout rehabilitation based on patient presentation and their objective progress.[108] Information regarding the ACLR procedure (e.g., primary vs. revision ACLR); graft selection, composition, and fixation method; or any concomitant repairs/reconstructions should be considered.[71] This information dictates the ACL graft ligamentization timeline,[109-112] the durability of the graft-bone tunnel construct,[113-115] the amount of tissue trauma at the autograft harvest site and other areas,[71,116] and the presence of quadriceps weakness related to BPTB or QT harvest from the extensor mechanism.[14-18,117] Lastly, non-modifiable risk factors for graft laxity and/or failure should be identified (e.g., knee hypermobility, allograft, hamstring autograft, meniscectomy, and high tibial slope),[118-122] because the rehabilitation specialist may elect to change/modify exercises when multiple risk factors are present (e.g., OKC quadriceps resistance training between 0-45 degrees of knee flexion produces more ACL strain than 45-100+ degrees).[123,124]

The quadriceps rehabilitation program should include both OKC and CKC exercise progressions,[31,125] which should be prescribed in line with best-evidence recommendations for hypertrophy and strength training (Figure 8).[126] Likewise, exercise prescriptions should consider the procedure specific ACLR technique, biological healing, joint homeostasis and patient preference.[71] The sweep test and pain-monitoring model should be used throughout rehabilitation to objectively quantify knee irritability (Figure 8).[71,127] Lastly, ACLR rehabilitation should include best-practice strategies for managing AMI,[32] and mitigating AMI after ACLR may improve the effectiveness of the quadriceps load-progressions.[13,31,51,128]

IMMEDIATE POSTOPERATIVE PHASE (WEEKS 0-3 AFTER ACLR)

The immediate postoperative exercise selection should restore active knee extension as soon as possible (Figure 8),[129] because the slightest postoperative loss of knee extension can produce impaired knee arthrokinematics; provoke quadriceps inhibition[130,131]; and may increase the risk of developing knee osteoarthritis.[129,132,133] Given the presence of AMI after ACLR and the high volitional recruitment threshold of the quadriceps (Figure 2),[13,50] an OKC quadriceps training program may be more beneficial than a CKC program during the immediate postoperative phase.[52] Lastly, high daily exercise-frequencies should be prescribed (Appendix A); high frequency/short duration exercise may work best when pain levels are high, knee motion is limited,[134] exercise intensity is low,[135] and neuroplastic improvements in quadriceps activation are desired (Appendix A).[136]

OPEN-KINETIC-CHAIN LOAD-PROGRESSION

The OKC quadriceps load-progression should start with quadriceps setting (Figure 8) (Appendix A)[71]; quadriceps setting in low levels of hip flexion (i.e., a recumbent trunk position) may optimize length-tension of the rectus femoris.[63] Likewise, positioning the knee in 20-45 degrees of flexion may be preferred when high levels of AMI are present (Figure 9A) (see Video, Supplemental Material 1, which demonstrates quadriceps setting), because this position will improve quadriceps length-tension and its internal moment arm(s).[69,70,137] Prescribing yielding/holding quadriceps isometrics for longer durations (i.e., 45-90+ seconds) may be an effective strategy for improving motor re-

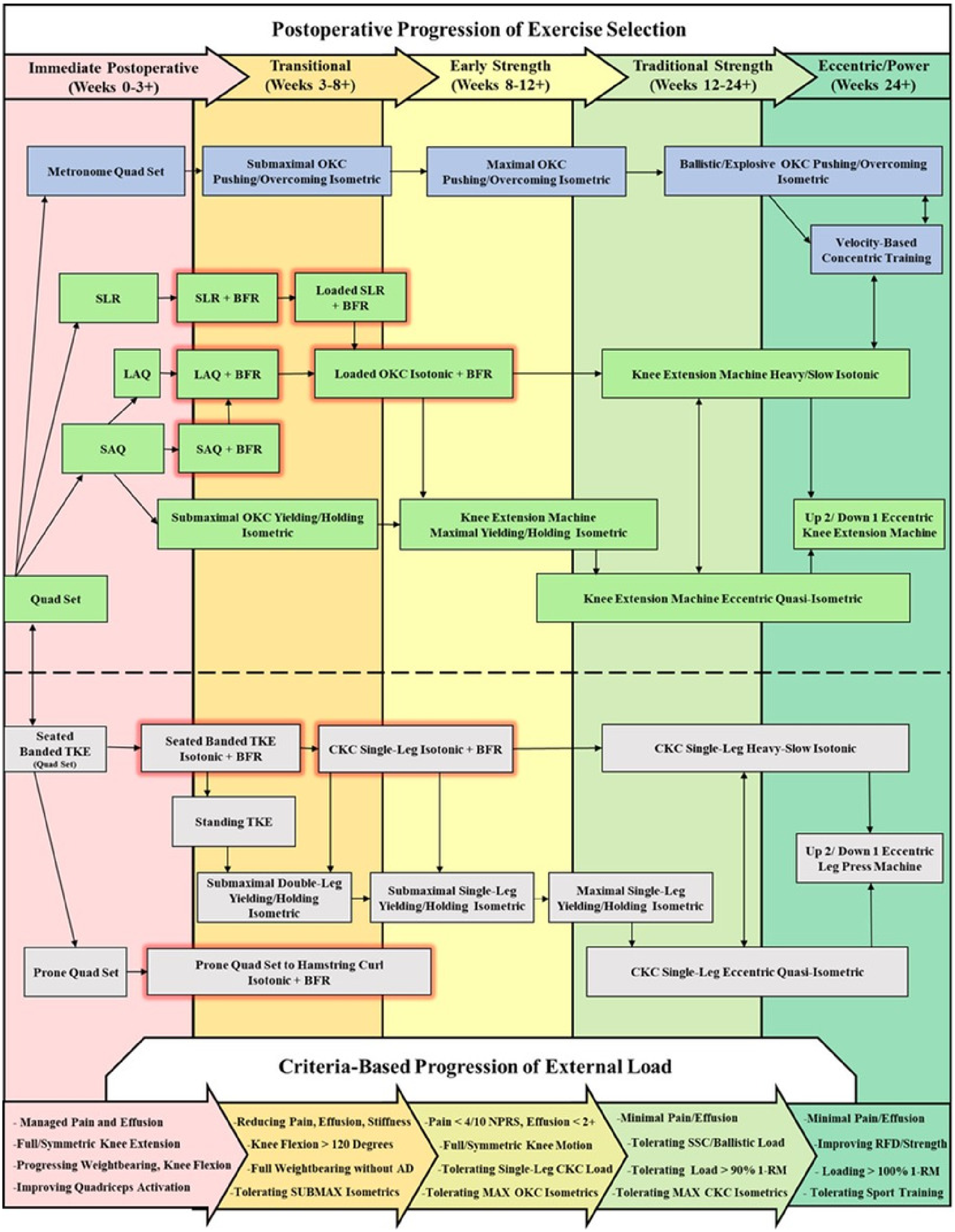

Figure 8. Overview of exercise selection for quadriceps training after anterior cruciate ligament reconstruction (ACLR).

After anterior cruciate ligament reconstruction, quadriceps training should begin with quadriceps setting and be developed onto both open and closed-kinetic-chain load progressions. Strength training load progressions should be primarily advanced through the progression of external load, and exercises that load the quadriceps close to volitional fatigue/task failure at relatively long muscle lengths should be prescribed to enhance muscular hypertrophy. Lastly, a specific load progression to enhance quadriceps rate-of-force development should be prescribed throughout rehabilitation.

1-RM, concentric one-repetition maximum of the surgical limb; AD, assistive device; BFR, blood flow restriction; quad set, quadriceps setting exercise; black arrows, exercise progression pathway; blue boxes, exercise progression for quadriceps rate-of-force development; boxes with red glow, exercise with blood flow restriction; CKC, closed-kinetic-chain; green boxes, open-kinetic-chain exercise selection; grey boxes, closed-kinetic-chain exercise selection; LAQ, long-arc-quad exercise; MAX, maximal; NPRS, numeric pain rating scale; OKC, open-kinetic-chain; RFD, rate-of-force development; SAQ, short-arc-quad exercise; SCC, stretch-shortening cycle; SLR, straight leg raise exercise; SUBMAX, submaximal; TKE, terminal knee extension.

cruitment,[86,88,138] and the superimposition of neuromuscular electrostimulation (NMES) during exercise may accelerate the recovery of quadriceps force-output (Appendix A) (see Video, Supplemental Material 2, which demonstrates quadriceps setting with NMES).[139] The rehabilitation specialist should also consider advancing the tempo/cadence of quadriceps setting (Appendix A), because higher-velocity quadriceps contractions (i.e., velocity-based training principles) may improve motor recruitment.[107] A metronome can be used to advance the tempo/cadence of quadriceps setting, and metronome training should be progressed onto higher cadence drills that challenge the capacity to quickly summate/regulate motor activity (Figure 8) (Appendix A) (see Video, Supplemental Material 3, which demonstrates high tempo quadriceps setting with a metronome).[136,140,141]

Once a volitional quadriceps contraction is achieved, exercise selection should include the SLR exercise (Figure 8) (Appendix A). To minimize knee flexion lag, cueing should reinforce the initiation of quadriceps setting into maximal superior patellar glide prior to the initiation of the SLR (see Video, Supplemental Material 4, which demonstrates proper straight leg raise technique); slight femoral external rotation with ankle dorsiflexion should be maintained throughout the SLR (Figure 9b), because this positioning can maximize force output from the quadriceps.[142] The SLR exercise should start in tall sitting/standing and be progressed into the long-sitting position. Long-duration SLR isometrics and/or *blood flow restriction* (BFR) can be utilized to accelerate muscular fatigue,[138,143-145] and exercise intensity can be advance by adding external load distal to the knee joint (Figure 8).

Quadriceps setting can be progressed onto OKC knee extensions as soon as tolerated (Figure 8).[146,147] The rehabilitation specialist may elect to first perform knee extensions between 0-45 degrees (see Video, Supplemental Material 5, which demonstrates the short-arc-quad exercise), because external knee moments are highest within this range.[148] As knee flexion improves, full-arc knee extensions may best mechanically-stimulate the distal muscle fibers of the quadriceps and should be preferred to partial ROM exercise at shorter muscle lengths.[41-43,45,47-49,61,149] Exercise with BFR can be utilized to accelerate muscular fatigue, and prescribing sets close to volitional fatigue/task failure may best stimulate muscular hypertrophy with low loads (Figure 8) (Appendix A).[71,150,151] Lastly, submaximal OKC yielding/holding isometrics can be prescribed between 45-60 degrees of knee flexion to improve quadriceps activation and knee load-tolerance (Appendix A) (see Video, Supplemental Material 6, which demonstrates a submaximal OKC yielding/holding isometric)[88]; this ROM will preferentially target the quadriceps within the descending phase of the length-tension curve (Figure 3),[65,66,137] improve the quadriceps' internal moment arms relative to deeper knee flexion (Figure 4),[69,70] optimize knee extension torque-output,[137] decrease ACL graft strain relative to 0-45 degrees of knee flexion,[123,152] and may downregulate patellar/quadriceps tendon pain after autograft harvest from the extensor mechanism.[89]

CLOSED-KINETIC-CHAIN LOAD-PROGRESSION

The CKC quadriceps load-progression should begin in sitting with the *terminal knee extension* (TKE) exercise (Figure 8) (Figure 9c-d),[71] which should be utilized to preferentially activate the single-joint quadriceps muscles.[44-46,49] The sitting TKE exercise can be progressed by increasing the level of elastic band resistance (Appendix A),[71] prescribing longer-duration yielding/holding isometrics,[138] or the addition of BFR (Figure 8).[143-145] The rehabilitation specialist should also prescribe prone quadriceps setting (Appendix A), because this exercise omits visual feedback and may facilitate improvements in knee proprioception (see Video, Supplemental Material 7, which demonstrates prone quadriceps setting).[136]

TRANSITIONAL PHASE (WEEKS 3-8 AFTER ACLR)

As active knee ROM and volitional quadriceps activation have been recovered, the rehabilitation specialist should transition their quadriceps exercise prescription(s) from volume and variety-based load-progressions,[135] onto more seminal load progressions that can be advanced throughout the remainder of the ACLR rehabilitation program.[153] During this phase, joint irritability and a knee effusion are likely still present,[35] and low-load exercise with BFR is indicated to recover joint homeostasis while mitigating atrophy/stimulating hypertrophy (Appendix A).[71,154]

EXERCISE WITH BLOOD FLOW RESTRICTION

Non-weightbearing quadriceps exercise with BFR should be prescribed 1-2x/day to maximize the anabolic response to exercise with very light loads (i.e., < 20% concentric 1-RM),[155,156] and the use of higher individualized occlusion pressures may be recommended.[157-159] To specifically stimulate quadriceps hypertrophy, each BFR set (when possible) should be prescribed close to volitional fatigue/task failure (e.g., 0-2 repetitions in reserve) (Appendix A),[126,150,151] and combining OKC knee extension variations with the CKC seated TKE exercise may optimally stimulate all four quadriceps muscles in sitting (i.e., both the proximal and distal quadriceps) (Appendix A) (Figure 8) (see Video, Supplemental Material 8 and 9, which demonstrates the long-arc-quad and seated TKE exercise with BFR).[45] The rehabilitation specialist should also consider prescribing the prone quad set to hamstring curl exercise (Figure 8); this exercise may improve mechanical signaling/regional hypertrophy within the distal quadriceps through the maximal lengthening of its sarcomeres (see Video, Supplemental Material 10, which demonstrates the prone quad set to hamstring curl exercise with BFR).[48,65] Similarly, prescribing loaded inter-set stretching with the prone knee flexion stretch or reverse Nordic exercise can be utilized to therapeutically shear/mobilize the graft harvest site after ACLR with the QT autograft and can help stimulate stretch-mediated quadriceps hypertrophy/sarcomerogenesis (see Video, Supplemental Material 11 and 12, which demonstrates the prone knee flexion stretch and reverse Nordic exercise).[71,160,161]

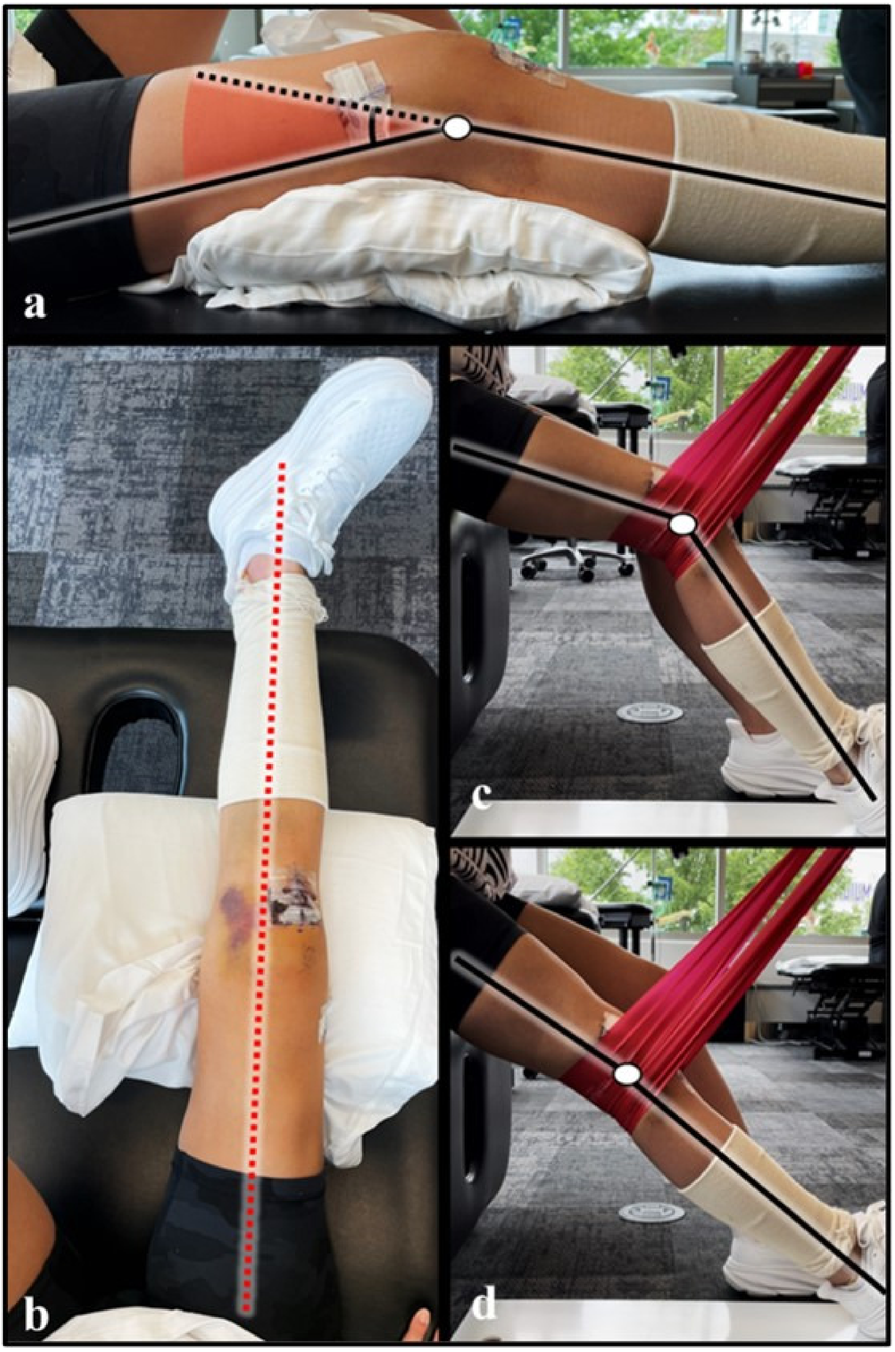

Figure 9. Exercise selection for the immediate postoperative phase.

Positioning the knee in 20-45 degrees of knee flexion prior to quadriceps setting will improve global quadriceps length-tension and its internal moment arm(s) (a). Slight femoral external rotation with active ankle dorsiflexion should be maintained throughout the straight leg raise exercise, as this position may maximize force output from the quadriceps (b). The CKC quadriceps load-progression should be initiated in sitting with the terminal knee extension exercise (i.e., isotonic, terminal knee extension with elastic band resistance); this exercise can be utilized to preferentially activate the distal / single-joint quadriceps muscles (c, d). Black lines, approximate tibial and femoral bone markers; dotted red line, midline/neutral hip rotation within the surgical limb; red shading, depiction of a knee flexion angle of 20-45 degrees; white circle; estimated center of joint rotation.

OPEN-KINETIC-CHAIN LOAD-PROGRESSION

To enhance motor unit recruitment and/or manage tendon pain after ACLR with the BPTB or QT autograft, the OKC quadriceps load-progression should be advanced from yielding/holding quadriceps isometrics at 45-60 degrees of knee flexion, onto overcoming/pushing isometrics between 60-90 degrees of knee flexion (Appendix A) (Figure 8); overcoming/pushing isometrics will summate more motor activity than yielding/holding isometrics.[88] Likewise, progressing the level of knee flexion during OKC overcoming/pushing isometrics may help facilitate regional hypertrophy within the distal quadriceps,[48,61,65,66] and the superimposition of NMES may improve quadriceps torque-output (see Video, Supplemental Material 13, which demonstrates an OKC overcoming/pushing isometric with NMES).[139,162,163]

CLOSED-KINETIC-CHAIN LOAD-PROGRESSION

Seated TKE contractions should be advanced onto the standing TKE exercise (Figure 8) (see Video, Supplemental Material 14, which demonstrates the standing TKE exercise)[71]; this exercise should be prescribed to recover TKE control in weightbearing and can be progressed through the addition of elastic band resistance (Appendix A). Due to the relatively large increase in the knee's articular load when transitioning from non-weightbearing to weightbearing exercises,[164,165] consideration should be given for the use of yielding/holding isometrics as the initial form of CKC resistance training; yielding/holding isometrics behave like eccentric contractions and stimulate muscle fatigue faster than overcoming/pushing isometrics.[86-88]

The double-leg squat exercise can serve as the base regression for a CKC yielding/holding isometric program (Figure 8),[71] and the non-surgical limb should be slightly posted to facilitate weight redistribution towards the surgical limb (Figure 10a).[71,166] Prescribing submaximal yielding/holding isometrics from 45-60 degrees of knee flexion may be initially recommended, because this level of knee flexion will optimize knee extension torque-output and the internal moment arms of the quadriceps muscles (Figure 4) (Appendix A).[69,70,137] Each exposure should include 3-6 sets of long-duration yielding/holding isometric contractions (e.g., submaximal contractions for 45-90 seconds), which are prescribed to improve motor unit recruitment[86,88,138]; stimulate exercise-induced muscle fatigue[138]; facilitate stress relaxation of the quadriceps and patellar tendons[167,168]; and downregulate anterior knee/tendon pain.[89] After ACLR with a BPTB or QT, CKC yielding/holding isometrics should be implemented at a frequency of 2 exposures/day (6-8+ hours apart) to optimally stimulate collagen synthesis/repair at the autograft harvest site (Appendix A).[71,168,169] Double-leg yielding/holding isometrics should be progressed onto the split-squat position (Figure 10a-b),[71] because this progression may mitigate the *bilateral force deficit* phenomenon as well as other inter-limb compensations.[170,171] Lastly, the front-foot elevated split-squat can be used to advance the level of knee flexion from the 45–60-degrees onto 60-90 degrees (see Video, Supplemental Material 15, which demonstrates the front-foot elevated split squat exercise).

EARLY STRENGTH PHASE (WEEKS 8-12 AFTER ACLR)

Weeks 8-12 after ACLR, rehabilitation should focus on facilitating the resolution of any knee effusion/joint irritability while progressively loading the quadriceps.[35,71] The rehabilitation specialist should consider increasing the level of knee flexion during resistance training before adding external load, because deeper flexion may optimize quadriceps hypertrophy (Figure 10d).[48,61,149] However, knee flexion angle does effect the intratendinous force-ratio between the patellar and quadriceps tendons, making frequent monitoring of the autograft harvest site an important component of rehabilitation after ACLR with the BPTB or QT (Figure 5a).[71]

OPEN-KINETIC-CHAIN LOAD-PROGRESSION

The OKC quadriceps load-progression should include resistance training between 45-100+ degrees of knee flexion (unless contraindicated by a concomitant procedure), because autograft harvest from the extensor mechanism appears to produce greater quadriceps weakness at deeper knee flexion angles (Figure 8).[71,172-174] Likewise, 45-100+ degrees of knee flexion produces low ACL graft strain (relative to 0-45 degrees) and provides a better length-tension position for facilitating regional hypertrophy within the distal quadriceps.[61,123,149] Isometric and/or HSRT should be the preferred contraction mode for loading the quadriceps (especially after ACLR with the BPTB or QT) because the provocation of anterior knee pain with resistance training is still a concern.[83,89,91,103,104] Submaximal yielding/holding quadriceps isometrics should be advanced onto maximal effort isometric strength training through the addition of external load,[126] and holding isometric contractions close to the point of volitional fatigue/failure may best-stimulate quadriceps hypertrophy.[126] Once maximal OKC yielding/holding isometrics can only be sustained for 20-45 seconds in duration,[138] resistance training with EQI contractions can be prescribed (Figure 8) (Figure 11).

EQI resistance training should be prescribed on a knee extension machine (Figure 11d-f) (see Video, Supplemental Material 16, which demonstrates an EQI contraction on a knee extension machine). It is advisable to begin EQI contractions between 45-70 degrees of knee flexion before progressing onto deeper flexion angles (Appendix A), because EQI contractions in deeper flexion (i.e., 70-120+ degrees of knee flexion) could theoretically trigger knee irritability if not progressed appropriately.[101,102] This recommendation is based on the fact: (1) the internal moment arm of the quadriceps is reducing from 45-100+ degrees of knee flexion (Figure 4); (2) passive quadriceps tension will increase as knee flexion increases[78]; and (3) eccentric contractions will increase total force within the extensor mechanism (Figure 7).

CLOSED-KINETIC-CHAIN LOAD-PROGRESSION

The CKC load-progression should include unilateral exercises that optimize lower extremity stability, because high exercise stability can improve volitional quadriceps activation/force-output.[175] Therefore, resistance training machines (e.g., leg press) or other weightbearing exercises with high stability are preferred to free-weight or compound exercises without external support/stability (Figure 10c-d). Similarly, a decline wedge/heel lift can be used to increase the relative contribution of the quadriceps during CKC exercise (**Figure 10c**).[176,177] Submaximal to maximal CKC yielding/holding isometrics in 45-90+ degrees of knee flexion should be prescribed close to volitional fatigue/failure within 20-45 seconds (Appendix A), and task failure should be achieved more quickly as knee flexion/knee moment is increased.[138] Once maximal effort CKC yielding/holding isometrics are tolerated for 20-45 seconds in deeper knee flexion (Figure 10d), the addition of external load to the CKC quadriceps load-progression is indicated.

Figure 10. Closed-Kinetic-Chain Yielding/Holding Isometric Load-Progression.

The closed-kinetic-chain (CKC) yielding/holding isometric load progression should start with the double-leg squat exercise in low levels of knee flexion (a, non-surgical limb posted). Exercise selection can be advanced to include the split-squat exercise (b), and a heel wedge can be utilized to increase external knee flexion moment/load on the quadriceps (c). Submaximal yielding/holding isometric contractions should be advanced onto maximal effort contractions through increasing the degree of knee flexion/external knee flexion moment (d) or the progression of external load. Maximal effort CKC machine or weightbearing exercises with upper body stabilization (c, d) are preferred to free-weight or compound exercises prescribed without external support. Asterisk, use of wall support to stabilize the body during exercise (c, d); black lines, approximate tibial and femoral bone markers; red arrows; approximate ground reaction force-vector; white arrows, progression of knee/quadriceps load through the advancement of exercise position (a-c); white circle; estimated center of joint rotation; yellow arrow, progression of knee/quadriceps load by advancing the degree of knee flexion/external knee flexion moment (d); yellow shading; depiction of knee/quadriceps-dominant loading with increasing external knee flexion moment (a-d).

Figure 11. Open and closed-kinetic-chain eccentric quasi-isometric quadriceps contractions.

Eccentric quasi-isometric (EQI) quadriceps resistance training can be completed on a leg press with a decline ankle-wedge (a-c) or knee extension machine (d-f) by (1) performing a concentric contraction to externally load the surgical knee/limb (a, d), (2) performing a yielding/holding isometric contraction to the point of volitional fatigue/failure (b, e), and (3) continuing to maximally resist the ensuing eccentric contraction throughout the prescribed range of knee motion. Black arrows, contraction direction; black lines, approximate tibial and femoral bone markers; green shading, concentric contractions; red shading, ensuing eccentric contractions as part of the EQI contraction; white asterisk, heel wedge; white circle, estimated center of joint rotation; yellow shading, depiction of large external knee flexion moment during yielding/holding isometric contractions

TRADITIONAL STRENGTHENING PHASE (WEEKS 12-24 AFTER ACLR)

Under normal healing conditions, most ACL grafts have integrated by 12-weeks after ACLR,[178,179] and any autograft harvest-site within the extensor mechanism has remodeled with scar-like tendon tissue[180]; this objective increase in load-tolerance permits the full transition to maximal effort quadriceps loading.[181] Subsequently, rest and recovery are important during this phase, and training schedules may need to be modified based on muscular soreness and/or the presence of fatigue. Lastly, exercise-intensity should be progressed with frequent monitoring of the knee for soreness/tissue irritability,[127,182,183] and loading should be prescribed with graft/procedure-specific considerations in mind.[71]

OPEN-KINETIC-CHAIN LOAD-PROGRESSION

For reasons previously mentioned, OKC resistance training between 45-100+ degrees of knee flexion should be continued during this phase.[61,65,123,148,149,160,184] Eccentric quasi-isometric contractions on a knee extension machine can be prescribed to isometric failure within 20-45 seconds (Figure 11d-f),[101,102,138] and more formal HSRT can be prescribed close to volitional fatigue/failure with an external load > 70-80% of the concentric 1-RM (Figure 8) (see Video, Supplemental Material 17, which demonstrates heavy-slow resistance exercise on a knee extension machine)[104]; these load-intensities will produce maximal effort concentric contractions at slow velocities (i.e., < 60 degrees/second), optimizing intramuscular force/mechanical tension within the quadriceps (Figure 7).

CLOSED-KINETIC-CHAIN LOAD-PROGRESSION

Single-leg CKC exercises with large external knee flexion moments should be prescribed during this phase (Figure 11b), because unilateral exercises may improve volitional motor unit recruitment/force-output relative to the use of bilateral exercises.[170,185,186] To target the quadriceps more specifically, a decline wedge/heel lift should be used to increase knee flexion moment during CKC exercise,[176,177] and maximal yielding/holding isometrics can be advanced by increasing the level of knee flexion[44,149,160]; this progression should be monitored because increasing knee flexion can provoke knee symptoms by increasing compression/shear-forces within the quadriceps/extensor mechanism (Figure 4) (Figure 6d).[69,70] As load-tolerance improves, surgical limb EQI contractions can be prescribed by holding a maximal yielding/holding isometric for 20-45 seconds and continuing to resist the ensuing eccentric contraction from 60-90+ degrees of knee flexion (Figure 11a-c) (see Video, Supplemental Material 18, which demonstrates surgical limb EQI contractions on a leg press).[187] Likewise, HSRT can be prescribed between 45-120+ degrees of knee flexion with no more than 4-6 achievable repetitions per set (Figure 8) (Appendix A) (see Video, Supplemental Material 19, which demonstrates surgical limb HSRT on a leg press).[104,187]

ECCENTRIC STRENGTHENING/POWER PHASE (WEEKS 24+ AFTER ACLR)

As the quadriceps develops the capacity to perform high-load resistance training (i.e., >85% of the concentric 1-RM), the quadriceps load-progression should be advanced onto exercises with force-profiles similar to high-level functional tasks. For athletes returning to Level-1 sports, these load-progressions should consider the forces associated with cutting/pivoting, to which peak patellofemoral forces have been reported to be as high as 13-18 times bodyweight.[188] Considering this, previous studies have investigated the force-profiles associated with different exercise interventions[165]; a full squat (to 120 degrees of knee flexion) with a load-intensity of ≥85% of the concentric 1-RM produces a patellofemoral force-profile similar to cutting/pivoting,[165,189] but a maximal OKC overcoming/pushing knee extension isometric (at 90 degrees of knee flexion) may only produce a peak patellofemoral force of 7-8 times body weight.[190] Collectively, these observations suggest CKC quadriceps resistance training should be progressed into 120+ degrees of knee flexion to best-replicate the force profiles associated with cutting/pivoting[165,188,189]; but to achieve a similar force-profile, submaximal depth CKC and OKC quadriceps resistance training should be progressed onto eccentric-specific training at a load-intensity > 100% of the concentric 1-RM.[190]

ECCENTRIC-SPECIFIC QUADRICEPS TRAINING

Due to the load-intensity for eccentric-specific training being greater than the concentric 1-RM, the surgical and non-surgical limb should complete the concentric phase of each repetition, with the subsequent transition to the isolated use of the surgical limb during the eccentric phase (i.e., double-limb concentric, single-limb eccentric training) (**Figure 12**). Eccentric-specific CKC exercises should be prescribed between 0-110+ degrees of knee flexion and between 45-100+ degrees of knee flexion during OKC exercises (Figure 12) (see Video, Supplemental Material 20 and 21, which demonstrates the technique for both OKC and CKC eccentric-specific training).[61,65,123,148,149,160,190] Eccentric-specific training should be integrated with progressive deceleration/change-of-direction tasks, because these tasks require the quadriceps to perform high-velocity eccentric contractions into large external knee flexion moments.[44,46,49,71,188]

POWER AND VELOCITY-BASED TRAINING

The rehabilitation specialist should implement load-progressions with the specific intent of improving quadriceps rate-of-force development/knee power.[191] Higher level evidence has observed longstanding impairments in quadriceps rate-of-force development after ACLR, and the use of a BPTB or QT autograft for ACLR may exacerbate these impairments.[192] Velocity-based training can be utilized to improve quadriceps rate-of-force development,[105] and the integration of these exercises with ballistic/plyometric exercise may enhance change-of-direction performance,[193]

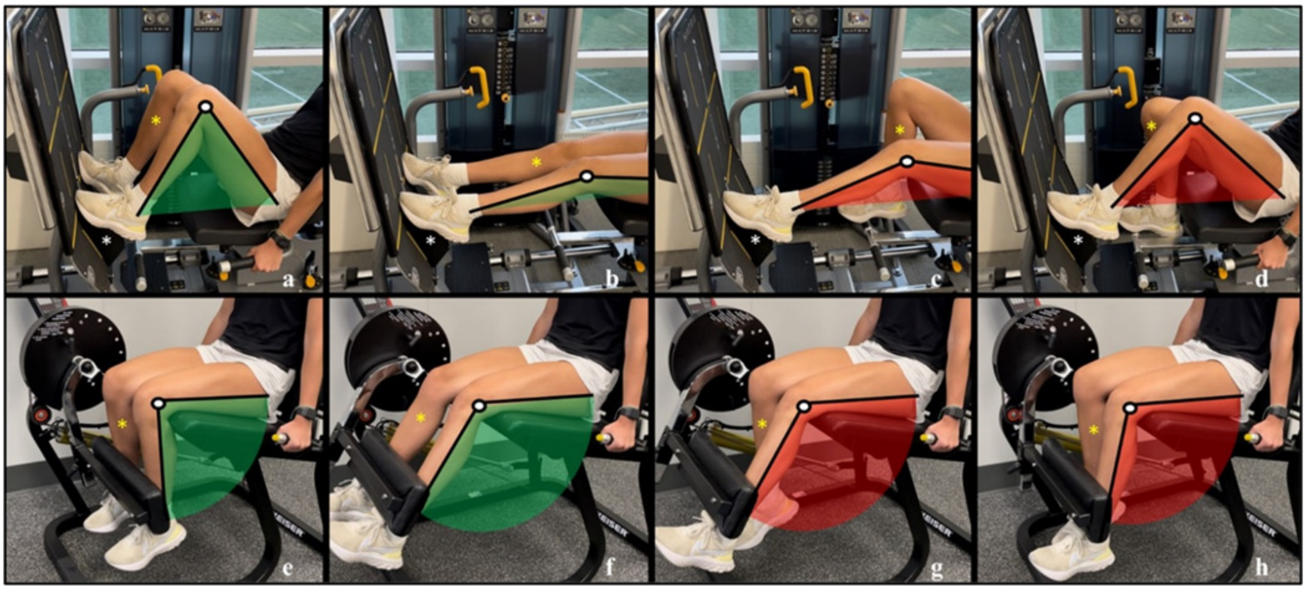

Figure 12. Preferred exercise technique for eccentric-specific resistance training.

Eccentric-specific open and closed-kinetic-chain quadriceps resistance training should be progressed onto load-intensities > 100% of the surgical limb's concentric 1-repitition maximum. Eccentric-specific quadriceps training can be completed on a leg press with a decline ankle-wedge (a-d) or knee extension machine (e-h) by (1) performing a concentric contraction with both limbs from the machine's bottom position (a, e) to the top position (b, f), (2) removing/moving the non-surgical limb to place all load on the surgical limb (c, g), and (3) eccentrically lowering the load through the desired range of knee motion. Green shading, concentric phase of exercise; red shading, eccentric phase of exercise; white asterisk, heel wedge; yellow asterisk; movement of the non-surgical limb throughout exercise.

improve knee biomechanics/motor control,[194,195] and can mitigate the overall risk of ACL re-injury.[196]

Velocity-based quadriceps training may be most specifically prescribed utilizing a jump training machine and/or barbell equipped with a linear positioning transducer/accelerometer (Figure 13) (see Video, Supplemental Material 22 and 23, which demonstrate single and double-leg velocity-based training).[197,198] To best stimulate improvements in peak quadriceps contraction-velocity/knee power, emphasis should be placed on the importance of a maximal effort/intent on each repetition, and working sets should be discontinued at a 10% velocity-loss threshold.[198] Lastly, velocity-based quadriceps training should be integrated with ballistic/plyometric exercises, which may improve the function of the stretch-shortening cycle within the quadriceps (see Video, Supplemental Material 24, which demonstrates a plyometric exercise example).[191,193,199]

HIGH-VELOCITY RUNNING

To prepare the proximal quadriceps/rectus femoris for sport, graded exposure to high-velocity running should be integrated into the power phase of rehabilitation.[30,200] High-velocity running produces large angular velocities at the knee, requiring the quadriceps to perform repeated high-load eccentric contractions (see Video, Supplemental Material 25, which demonstrates high-velocity running on a curved treadmill).[201] With this, load management is of extreme importance, and the rehabilitation specialist should gradually increase running volume and intensity. Likewise, an upwards of 3-4 days of recovery may be initially required in between fatiguing exposures to high-velocity running until the *repeated bout effect* of eccentric training on muscle soreness is reported,[202] especially as the rectus femoris appears to have a higher proportion of type-II muscle fibers relative to the other quadriceps muscles.[54]

CONCLUSION

Quadriceps weakness after ACLR is a well-known phenomenon.[13,51,128] Although recent literature has investigated the best-practice methodologies for mitigating AMI after knee injury,[31-33] less has been published with respect to the use of exercise therapy to restore quadriceps size and strength after ACLR.[31] By combining common ACLR rehabilitation principles with muscle basic science and strength training literature, this review article provides a rehabilitation framework that can be used to optimize the recovery of quadriceps size and strength after ACLR, as well as recover the knee's ability to manage the force-profiles associated with high-demand physical activities (i.e., Level-1 sport). Lastly, this review article may serve as a foundational piece of literature for the further development of more robust ACLR rehabilitation programs, to which the rehabilitation specialist can use the exercise progressions outline within this article to organize any other loading exposures needed to optimize individualized outcomes after ACLR.

PRACTICAL APPLICATION

After ACLR, optimal quadriceps load-progressions can be derived from combining common rehabilitation principles with the existing muscle basic science and strength training literature. The anatomy, regional innervation, and task-specific activation/sequencing of the quadriceps necessitates the rehabilitation specialist to utilize both OKC and CKC exercises to maximally stimulate quadriceps hyper-

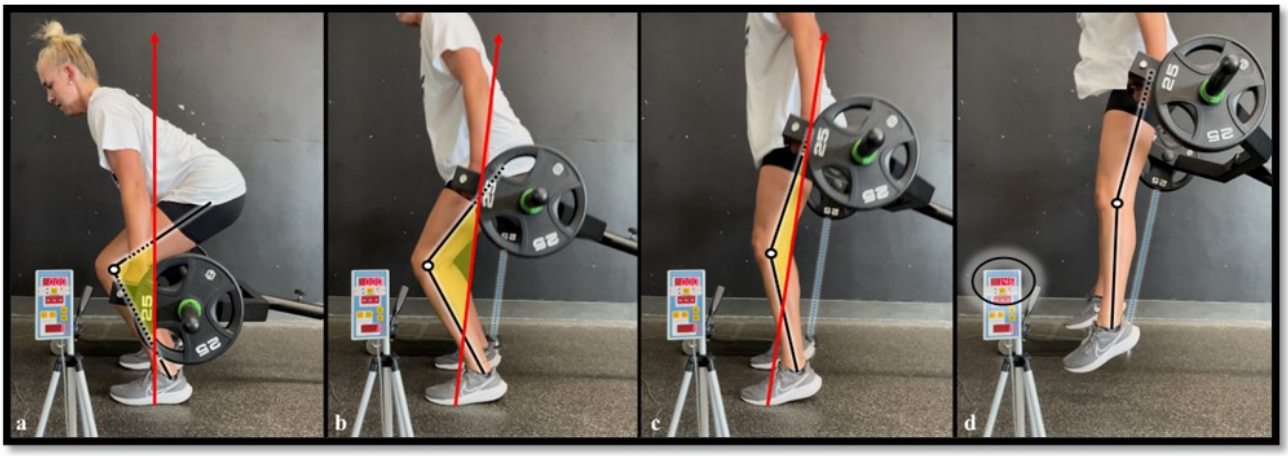

Figure 13. Example of velocity-based training with a linear positioning transducer/accelerometer.

Velocity-based training methods can be utilized after anterior cruciate ligament reconstruction to improve quadriceps motor recruitment and rate-of-force development (a-d). To best stimulate improvements in peak quadriceps contraction-velocity/knee power, emphasis should be placed on the importance of a maximal effort/intent on each repetition. Black lines, approximate tibial and femoral bone markers; black circle, feedback monitor from linear positioning transducer/accelerometer; blue lines, ripcord connecting the exercise bar to the linear positioning transducer/accelerometer; red arrows; approximate ground reaction force-vector; white circles; estimated center of joint rotation; yellow shading; depiction of external knee flexion moment.

trophy and strength. Graft-specific load progressions are also indicated after ACLR, and the rehabilitation specialist should consider the exercise type; muscle contraction mode; intensity of external load; and knee flexion angle when prescribing resistance training. To enhance the hypertrophic response to resistance training, exercise selection should include stable, single-limb exercises that load the quadriceps close to volitional fatigue/task failure at relatively long muscle lengths. Lastly, load-progressions for both OKC and CKC quadriceps strength training should be primarily advanced through the progression of knee flexion and external load.

CONFLICTS OF INTEREST

The above authors have no conflicts of interest related to the development and publication efforts of this manuscript. The authors certify that they have no affiliations with or financial involvement in any organization or entity with a direct financial interest in the subject matter or materials discussed in this manuscript.

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SUPPLEMENTARY MATERIALS

Video Legend

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Supplemental Material 1: Quadriceps Setting | .MOV file

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Supplemental Material 2: Quadriceps Setting with NMES | .MOV file

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Supplemental Material 3: High Tempo Quadriceps Setting with a Metronome | .MOV file

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Supplemental Material 4: Optimal Straight Leg Raise Technique | .MOV file

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Supplemental Material 5: The Short-Arc-Quad Exercise | .MOV file

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Supplemental Material 6: Submaximal OKC Yielding/Holding Isometric | .MOV file

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Supplemental Material 7: Prone Quadriceps Setting | .MOV file

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Supplemental Material 8: Long-Arc-Quad Exercise with BFR | .MOV file

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Supplemental Material 9: Seated TKE Exercise with BFR | .MOV file

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Supplemental Material 10: Prone Quad Set to Hamstring Curl with BFR | .MOV file

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Supplemental Material 11: Prone Knee Flexion Stretch | .MOV file

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Supplemental Material 12: Reverse Nordic Exercise | .MOV file

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Supplemental Material 13: OKC Pushing/Overcoming Knee Extension with NMES | .MOV file

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Supplemental Material 14: Standing TKE Exercise with Elastic Band Resistance | .MOV file

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Supplemental Material 15: Front-Foot Elevated Split Squat Exercise | .MOV file

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Supplemental Material 16: EQI Contraction on a Knee Extension Machine | .MOV file

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Supplemental Material 17: Heavy-Slow Resistance Exercise on a Knee Extension Machine | .MOV file

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Supplemental Material 18: EQI Contractions on a Leg Press | .MOV file

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Supplemental Material 19: Heavy-Slow Resistance Exercise on a Leg Press | .mp4 file

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Supplemental Material 20: Eccentric-Specific Strength Training on a Leg Press | .MOV file

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Supplemental Material 21: Eccentric-Specific Strength Training on a Knee Extension Machine | .MOV file

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Supplemental Material 22: Velocity-Based Training on a Jump Training Machine | .MOV file

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Supplemental Material 23: Velocity-Based Training with a Hex/Jammer Bar | .MOV file

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Supplemental Material 24: Single-Leg Plyometric Exercise | .MOV file

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Supplemental Material 25: High Velocity-Running on a Curved Treadmill | .MOV file

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Appendix A

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