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Opinion

Surgical Graft Selection in ACL Reconstruction: Implications for Walking and Running Biomechanics

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Anterior cruciate ligament (ACL) injury is common, and ACL reconstruction is widely performed.[1] Although ACL reconstruction can improve mechanical stability and short-term clinical outcomes, deficits in movement symmetry often persist after surgery.[2,3] Subtle alterations in lower-limb loading and interlimb coordination may persist despite restoration of mechanical stability.[4] Thus, restoration of mechanical stability does not necessarily restore normal locomotor function, highlighting a gap between structural success and functional recovery.

In this opinion article, we discuss how graft selection may affect postoperative walking and running biomechanics. Graft choice may influence donor-site morbidity, biological integration, and sensory feedback mechanisms involved in neuromuscular control. Collectively, these factors may shape postoperative gait mechanics and long-term joint-loading patterns.

Commonly used graft types have distinct biological and mechanical characteristics that may affect locomotor biomechanics after surgery. Graft construction and healing may influence tissue integration and subsequent neuromuscular adaptation. The bone–patellar tendon–bone (BPTB) autograft comprises the central third of the patellar tendon with bone plugs from the patella and tibial tubercle, allowing relatively rapid bone-to-bone healing and strong initial fixation.[5] However, anterior knee pain, quadriceps inhibition, and patellofemoral discomfort are commonly reported donor-site complications. Hamstring tendon autografts, typically harvested from the semitendinosus tendon with or without the gracilis tendon, may provide greater elasticity and less anterior knee morbidity; however, tendon-to-bone healing is slower, and hamstring weakness may persist after harvest.[5,6] Quadriceps tendon autografts have shown favorable clinical outcomes, and several studies suggest less donor-site morbidity than with BPTB grafts, although long-term biomechanical evidence remains limited.[7] Allografts avoid harvest-site morbidity and may reduce surgical time but generally undergo slower biological remodeling; their mechanical properties may also vary with processing methods such as irradiation or freeze-drying.[5,6,8] Table 1 summarizes the biological and mechanical profiles of common graft types and their potential locomotor implications.[5,6,8-13]

Recovery of walking biomechanics after ACL reconstruction (ACLR) depends in part on coordinated activation of the quadriceps and hamstring muscles. Studies indicate that patients who receive BPTB grafts often have reduced quadriceps function, which may contribute to compensatory gait strategies.[6,10] Motion-analysis studies indicate that gait asymmetry can persist for up to 24 months after reconstruction and may include reduced knee flexion during weight acceptance and asymmetric peak vertical ground-reaction forces.[3,14] Reduced knee flexion during loading response is often accompanied by a lower peak external knee-flexion moment, a compensatory pattern commonly described as quadriceps-avoidance gait. Hamstring tendon grafts may alter medial hamstring function and reduce dynamic restraint of tibial rotation, potentially contributing to variable interlimb loading during stance.[12] Running may reveal graft-specific biomechanical deficits more clearly than walking because it imposes greater mechanical and neuromuscular demands on the reconstructed knee. Unlike walking, running includes a flight phase, higher vertical ground-reaction forces, larger impact transients at initial contact, and greater eccentric knee-extensor power absorption during early stance. These demands may expose persistent donor-site weakness or neuromuscular inhibition that is less apparent during slower locomotion.[15] For example, in patients with BPTB grafts, quadriceps inhibition and anterior knee symptoms may impair knee-extensor impact absorption and contribute to altered lower-limb loading during running.[10,15] In patients with hamstring tendon grafts, residual medial hamstring weakness may contribute to altered lower-limb coordination during high-speed locomotion.[6,15] Although quadriceps tendon grafts have shown favorable findings in dynamic tasks, direct evidence from running assessments remains limited.[6] Overall, current evidence suggests that running may be more sensitive than walking for detecting graft-specific functional deficits. However, relatively few studies have directly compared graft types during running using comprehensive kinetic, kinematic, and neuromuscular assessments.[15]

Patients with BPTB grafts have been reported to show altered neuromuscular responses during high-intensity running, which

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Table 1. Overview of common ACL graft types and potential locomotor implications

Graft type	Biological and mechanical profile	Common donor-site issues	Potential walking-related implications	Potential running and dynamic-task implications	Clinical considerations
BPTB autograft[5,6,9,10,13]	Strong initial fixation; bone-to-bone healing	Anterior knee pain; quadriceps inhibition; patellofemoral discomfort	Reduced knee flexion and external knee-flexion moment during loading response	High-impact tasks may reveal persistent quadriceps-related deficits	Often considered for highly active patients; anterior knee symptoms remain a limitation
Hamstring tendon autograft[5,6,9-12]	Tendon-to-bone healing; less anterior knee morbidity	Residual hamstring weakness	Potential asymmetric loading during stance and altered control of knee motion	Dynamic tasks may reveal altered coordination and transverse-plane control	Less anterior knee morbidity; possible hamstring-related deficits
Quadriceps tendon autograft[9,11]	Large graft size; favorable tensile profile	Mild anterior thigh soreness; generally less donor-site morbidity than BPTB	Available studies suggest variable recovery of sagittal-plane gait mechanics	Findings from dynamic tasks are favorable, but direct running evidence remains limited	Increasing clinical use; long-term biomechanical evidence remains limited
Allograft[5,6,8]	No harvest-site morbidity; slower biological incorporation	No donor-site morbidity	Persistent loading asymmetry may occur in some patients	Higher-demand tasks may reveal reduced dynamic knee function, although direct allograft-specific evidence remains limited	May be considered for patients with lower activity demands; failure risk remains a concern in young athletes

The biomechanical implications are based on the available literature and should be interpreted cautiously, particularly where direct graft-specific evidence from running assessments is limited. References listed with each graft type support the corresponding information in that row. ACL, anterior cruciate ligament; ACLR, anterior cruciate ligament reconstruction; BPTB, bone–patellar tendon–bone.

may reflect impaired impact attenuation and reduced knee-extensor contribution during early stance.[13] However, direct evidence quantifying graft-specific knee-extensor power absorption during running remains limited. Hamstring tendon grafts may be associated with altered transverse-plane control during locomotor tasks, which could affect interjoint coordination; however, direct running-specific evidence on variability in tibial rotation remains insufficient.[12] Quadriceps tendon grafts have shown favorable findings in some biomechanical studies of walking and dynamic tasks, but running-specific evidence remains sparse.[6] Across graft types, running-related deficits may include altered lower-limb work distribution and incomplete restoration of locomotor efficiency, although direct evidence on graft-specific stride efficiency and running economy remains limited.

Beyond mechanical considerations, neurosensory factors may also influence functional recovery after ACLR. Mechanoreceptors in the native ACL contribute to joint-position sense and reflex stabilization of the knee. Removal of the injured ligament and ACL reconstruction may disrupt these sensory pathways and alter afferent feedback to the central nervous system.[16,17] Arthrogenic muscle inhibition (AMI) may contribute to persistent quadriceps weakness after ACL injury and reconstruction. AMI is characterized by reflexive inhibition of quadriceps motor-neuron excitability resulting from altered afferent signaling from injured joint structures.[16] In patients with BPTB grafts, impaired vastus lateralis neuromuscular responses during high-intensity running have been reported.[13] Direct evidence linking BPTB donor-site trauma specifically to AMI remains limited. Functional neuroimaging studies have identified altered cortical activation patterns after ACLR, suggesting long-term neuroplastic changes in sensorimotor control.[17] These supraspinal adaptations may coexist with or be related to persistent peripheral inhibitory mechanisms such as AMI. Figure 1 presents a conceptual, hypothesis-generating pathway linking graft selection, graft-related effects, AMI/neural adaptations, altered locomotor biomechanics, and a potentially increased risk of post-traumatic osteoarthritis.

Understanding these graft-dependent biomechanical and neurophysiological adaptations may help clinicians develop more individualized rehabilitation strategies. For example, patients with BPTB grafts may benefit from progressive quadriceps strengthening and patellar-mobility exercises to address extensor-mechanism inhibition. Patients with hamstring tendon grafts may benefit from targeted strengthening of the medial hamstrings and neuromuscular training to address hamstring-related functional deficits.[18] Interpretation of graft-specific biomechanical findings should also account for important confounding variables.

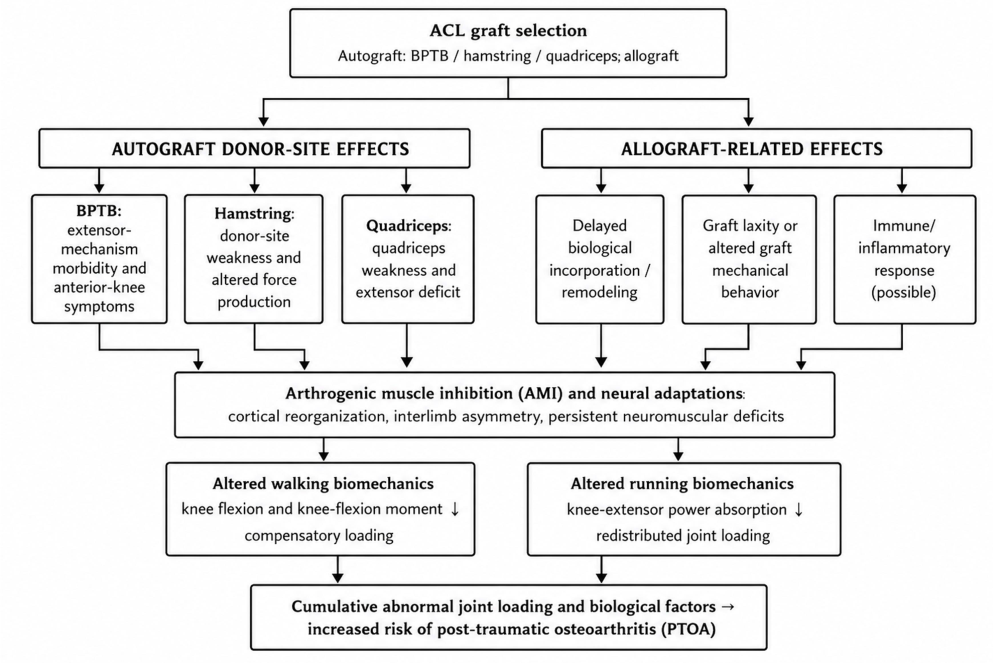

Fig. 1. Conceptual, hypothesis-generating schematic of the proposed graft-specific pathway after anterior cruciate ligament reconstruction (ACLR). Arrows indicate proposed pathways rather than established causality. ACL, anterior cruciate ligament; BPTB, bone–patellar tendon–bone.

Concomitant intra-articular injuries and procedures, such as meniscal injury or repair and chondral lesions, may substantially alter postoperative weight-bearing protocols and gait recovery. Preoperative biomechanical status, sex-specific neuromuscular strategies, and surgical factors such as graft-fixation angle or tunnel placement may also influence postoperative locomotor patterns. Several limitations constrain the available evidence. Comparative studies often use heterogeneous rehabilitation protocols, small samples, and inconsistent biomechanical outcome measures. Few studies have simultaneously evaluated kinetics, kinematics, electromyographic activity, and neural adaptations after ACLR. Future studies should integrate biomechanical analyses with biological and neurological indicators of recovery. Computational musculoskeletal modeling and machine-learning approaches applied to motion-analysis data may help identify patients at risk of persistent asymmetry or secondary injury.

Graft selection in ACLR has implications beyond restoring ligament continuity. The structural characteristics of each graft type, together with donor-site effects and sensory alterations, may influence neuromuscular control and locomotor biomechanics during walking and running. Recognizing these interactions may help clinicians individualize surgical decision-making and rehabilitation strategies to support long-term functional recovery.

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