Motion Analysis and Biomechanical Evaluation Following Anterior Cruciate Ligament Reconstruction

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Introduction

Annually, it is estimated over 3.5 million young athletes in the U.S. sustain sports-related injuries.[1,2] The knee is the second most common site of injury in athletes aged 15-25, resulting a substantial surgical and economic burden on both patients and healthcare systems.[2,3] Anterior cruciate ligament (ACL) ruptures, many of which occur via a non-contact mechanism, make up over 25% of knee injuries in high school athletes and require surgical intervention and prolonged postoperative rehabilitation before return to sport.[4] Motion analysis of biomechanical risk factors for primary, or repeat ACL injuries have been a topic of extensive research within sports medicine, given the opportunity to mitigate further injury and improve recovery.[5] This paper aims to detail recent progress and established views (2020-2024) regarding biomechanical evaluations and motion analysis post-ACL reconstruction (ACLR), while highlighting necessary points for future investigation.

Return to Sport Analysis and Longitudinal Investigation

Assessments at Return-To-Sport Time Point

Return to sport clearance (RTS), or the clearance granted to begin progression back to pre-injury activities, gradually introduces high-intensity stress on the new ACL graft, which may cause limb movement pattern asymmetry. Losciale et al. found that subjects post-ACLR, regardless of meeting RTS criteria, defined as achieving satisfactory strength and functional performance, did not show normalized landing mechanics on double-leg landing, and some achieved limb symmetry more by unloading the uninjured leg rather than loading the injured leg to the same standard of their uninjured limb.[6] Vij et al. evaluated sex-specific biomechanical changes post-ACLR, showing females exhibited smaller hip adduction moments and larger average knee joint extension moments, potentially increasing risk factors for reinjury.[7]

There have been recent efforts in validating 2D motion analysis systems, which are generally simpler to clinically implement and operate than 3D motion analysis systems.[8,9] A 2022 study performed by Di Paolo et al. validated a 2D scoring system for single leg hop tests that effectively identified stiffer landing patterns which have been correlated with increased injury and reinjury risk.[8] This system offers an adjunct to limb symmetry performance metrics that incorporates movement quality assessments at the time of RTS decision making.

Despite passing limb symmetry based RTS criteria, athletes may still exhibit abnormal landing mechanics. Developing accurate 2D motion analysis metrics can enhance movement quality assessment, complement existing outcome metrics, and potentially improve ACLR rehab outcomes.

Asymmetry at Longer Term Follow Up

Recent efforts have been made to evaluate kinematics at follow up time points beyond the point of RTS. Ithurburn et al. evaluated quadriceps strength, measured at time of RTS, against 3D biomechanical performance during the drop-vertical jump test two years post-ACLR.[10] They found those with low quadriceps strength at RTS testing had greater asymmetry during landing for knee flexion excursion and peak vertical ground reaction force two years postoperatively.[10] Webster et al. assessed landing biomechanics at one and three years post ACLR and found that differences between limbs existed for most biomechanical variables, with minimal variation observed throughout the study's duration.[11] These results suggest asymmetries persist beyond RTS and symmetrical biomechanics are not organically reacquired through sports participation, potentially heightening the risk of reinjury.

Larson et al. performed 3D motion analysis of college aged female athletes, 1-3 years after ACLR, during crossover hop testing and found that roughly half of subjects landed with an "extended knee," indicating a potential quadriceps avoidance pattern and a subsequent increased reinjury risk.[12] One study by Naili et al. studied an athlete pre- and post-ACLR, finding persistent asymmetry at 29 months postoperatively, eventually corrected by adjusting strength in the uninjured limb to achieve limb symmetry.[13] These studies reveal that biomechanical asymmetries, can persist years after ACLR, and may be more prevalent in those with quadriceps weakness.

Gait analysis

Two recent studies have evaluated that gait of young patients following ACL injury.[14,1]5 Ursei et al. evaluated compensatory movements using 3D motion analysis in children who had suffered ACL injuries, but not yet undergone treatment.[14] The subjects were found to exhibit increased plantar flexion at initial contact and decreased dorsiflexion during the stance period.[14] These findings are not only the first regarding compensation patterns in ACL-deficient children, but also are different from those reported in adults. Knurr et al., performed a longitudinal study comparing running biomechanics in collegiate athletes prior to ACL injury and again at months four, six, eight, and twelve, postoperatively.[15] By the one-year postoperative time point, the surgical limb had not yet recovered its pre-injury biomechanics, suggesting that deficits in mechanics likely persist beyond the typical RTS timeframe.[15] These findings illustrate that postoperative biomechanical asymmetries likely exist in nearly all aspects of sport, not only in landing, cutting, and jumping.

Future research and Lateral Extraarticular Tenodesis

Recent research in the pediatric population has suggested biomechanical benefits in terms of decreased residual rotatory instability, and clinical benefits of decreased reinjury from performing a lateral extraarticular tenodesis (LET).[16–18] During this procedure, concomitant with the ACLR, an additional soft tissue structure is constructed on the lateral portion of the knee with the intention of introducing additional stability. However, a common concern regarding LET procedures is potential over constraint and alteration of native knee biomechanics from the introduction of an additional stabilizing structure.[19–21]

Currently, no literature exists within the pediatric population regarding in vivo kinematic motion analysis for patients who underwent combined ACLR-LET. Future investigations should look to evaluate knee kinematics for patients following ACLR-LET to better understand the effects this procedure has in comparison to both native knee kinematics and those of patients receiving ACLR only.

Conclusion

Current research around motion analysis following ACLR reveals significant and persistent biomechanical between-limb asymmetries and compensatory movement strategies that develop postoperatively. Clinically, motion analysis offers the ability to monitor these movement patterns, identify biomechanical changes for each patient, and ultimately personalize treatment to acquire optimal kinematics to minimize reinjury risk. It may also be used as an adjunct evaluation tool at time of RTS testing. Future research should expand to assess differences among surgical techniques like LET and continue the current lines of investigation with larger sample sizes and higher level of evidence.

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