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Original Research

Quality of Movement Assessment after ACL Reconstruction in Youth: A Clinical Framework to Guide Rehabilitation and Return-to-Sport Decision-Making

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Anterior cruciate ligament (ACL) injury is one of the most common knee injuries requiring surgical intervention in youth athletes. After ACL reconstruction surgery, youth athletes undergo prolonged rehabilitation which often concludes with return-to-sport (RTS) testing to determine the athlete's readiness to resume sports participation. Most rehabilitation and RTS literature have focused primarily on quantitative outcomes to guide these decisions. Given the relationship between trunk and lower extremity biomechanics with ACL injury risk, there has been a call to action for the inclusion of qualitative assessments in rehabilitation and return-to-sport assessments. The purpose of this commentary is to describe quality of movement assessment tools that can guide rehabilitation and RTS decision making in pediatric and adolescent patients following ACL reconstruction. Specifically, it provides a framework for the implementation and interpretation of tools to assess single-leg, double-leg, and change of direction tasks as well as practical strategies and considerations for their use with pediatric and adolescent patients after ACL reconstruction.

Level of Evidence

5

INTRODUCTION

One of the most common sport injuries requiring surgical intervention among young athletes is an anterior cruciate ligament (ACL) tear. Although non-surgical management to treat ACL injury is documented,[1,2] ACL reconstruction (ACLR) surgery is currently considered as the standard of care.[3,4] After ACLR surgery, post-operative rehabilitation is commonly performed and progressed over a period of 6-9 months.[5] When rehabilitation concludes, a set of physical and performance tests, called return-to-sport (RTS) tests, are typically performed to evaluate the level of ACLR recovery.[6,7] To facilitate a safe RTS, several researchers have analyzed functional mechanics of ACLR patients during RTS testing using three-dimensional (3D) motion capture systems.[8-10] Overall, the ACLR limb has shown compensatory landing mechanics including reduced knee flexion angles, excessive trunk and hip flexion, and increased frontal plane trunk and knee deviations.[8,9,11,12] Frontal and sagittal plane trunk and limb deviations have also been identified during change of direction tasks after ACLR.[13] These altered mechanics have been shown to persist for several years after ACLR and have been associated with second ACL injury risk.[8,11,14] Although 3D motion capture is often

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employed as a gold-standard method, this technology requires a trained technologist, long data processing times, and has a high cost.[15,16] As an alternative and surrogate measure to 3D analysis, two-dimensional (2D) video analysis has been used to analyze movement patterns during RTS testing in ACLR patients.[17-19] Using cutting movements as an example, several 2D video analysis methods such as the expanded cutting alignment scoring tool (E-CAST) and the cutting movement assessment score (CMAS) have been developed.[20-24] One of the emerging, unique features of both the E-CAST and the CMAS is the use of a simple dichotomized (yes or no check box) list to assess the task qualitatively.[20-24] One study that used the E-CAST during RTS testing in youth athletes after ACLR identified dynamic knee valgus as a risk factor for second ACL injury.[25] The study's findings are important given the increased risk of second ACL injury in young athletes after primary ACLR and provide support for the use of 2D quality of movement assessment in RTS testing. Using 2D assessment as an alternative to 3D motion capture does not require a trained technologist, reduces data processing time, and decreases financial cost. However, despite these advantages, the use of 2D quality of movement assessments during ACLR rehabilitation and RTS testing remains underutilized and insufficiently described. Furthermore, most studies reporting outcomes of RTS testing after ACLR fail to include quality of movement as a variable. Thus, the purpose of this clinical commentary is to describe quality of movement assessment tools that can guide rehabilitation and RTS decision making in pediatric and adolescent patients following ACLR. Specifically, this commentary will describe the implementation and interpretation of tools to assess single-leg, double-leg, and change of direction tasks as well as practical strategies and considerations for their use with pediatric and adolescent patients after ACLR.

DOUBLE-LEG TASKS

Double-leg movement assessments provide clinically feasible methods to evaluate bilateral movement competency during squatting, jumping, landing, and repeated plyometric tasks. These assessments allow clinicians to observe trunk position, lower extremity alignment, sagittal plane loading strategy, frontal plane knee motion, foot position, landing symmetry, and the athlete's ability to absorb force during bilateral tasks. The tools summarized in this section vary in their level of standardization and in the availability of psychometric properties reported in the literature. Therefore, clinicians should select double-leg assessments based on the athlete's movement competency, stage of rehabilitation, sport demands, and the specific movement quality being assessed. Table 1 and Appendix A summarize the task set-up, instructions, scoring methods, reliability and validity evidence, recommended scorers, and populations for each double-leg assessment.

OVERHEAD SQUAT ASSESSMENT

The overhead squat assessment (OSA) may be used as a preliminary clinical screen of bilateral movement competency. The task involves an athlete performing repeated bilateral squats with the arms held overhead while the examiner observes compensatory deviations in trunk, hip, knee, and ankle alignment. When used clinically, the athlete should complete five controlled bilateral squats with the feet approximately shoulder-width apart and the arms held overhead. Clinicians should observe for visible compensations including excessive forward trunk lean, medial knee displacement, heel rise, asymmetry, or inability to maintain the testing position. Because peer-reviewed evidence supporting the OSA as a standardized, validated test is limited, the OSA should not be interpreted as a diagnostic tool or stand-alone RTS assessment.[26] Rather, findings should be used to guide further assessment and exercise selection, particularly before progressing to higher-demand jump-landing or change-of-direction tasks.

LANDING ERROR SCORING SYSTEM (LESS)

The Landing Error Scoring System (LESS) is among the most rigorously studied clinical jump-landing assessments.[26] The standard protocol has the athlete jump forward from a 30 cm box to a distance equal to approximately 50% of the athlete's height, land bilaterally, and then immediately perform a maximal vertical jump. Two synchronized video cameras (frontal and sagittal) record the landing, and a 17-item rubric scores observable movement "errors" such as knee valgus, trunk position, or foot stability. The sum of errors constitutes the LESS score; higher scores imply more movement flaws. Best reliability arises when raters receive systematic training, use standardized camera placement, and calibrate scoring with reference examples. Athletic trainers, physical therapists, and movement science professionals are appropriate scorers. The LESS has been widely used in adolescent, collegiate, and high-level athletic populations, including athletes post-ACLR.

RELIABILITY & VALIDITY

In a systematic review, Hanzlíková and Hébert-Losier reported that the overall LESS score demonstrates good to excellent intrarater reliability (ICC 0.82-0.99), interrater reliability (ICC 0.83-0.92), and intersession reliability (ICC 0.81).[27] The authors note that while many individual items show moderate to excellent agreement with 3D metrics, variability exists in item-level reliability. Concurrent reliability of the LESS-RT (real-time scoring) version demonstrated interrater ICCs between 0.72 and 0.81.[26] Additional studies confirm the stability of the overall error score under standardized conditions.[28] The systematic review concluded that criterion validity of the overall LESS score versus 3D motion capture is acceptable when participants are grouped by score, though some individual error items show only moderate correlations with 3D data.[27] Automated and modified versions (e.g., DEEP LESS) have been developed to

Table 1. Double leg tasks

Task	Set-Up & Equipment	Instructions	Scoring Method	Reliability Evidence	Validity Evidence	Recommended Scorer	Populations Studied
Overhead Squat Assessment (OSA)	No equipment; open space. Athlete holds dowel/arms overhead.	Perform 5 slow bilateral squats with arms overhead, feet shoulder-width.	Checklist of deviations (trunk lean, valgus, heel rise, asymmetry).	Limited; moderate agreement with training and reference images.	Limited empirical validity; expert consensus only.	Athletic trainers, physical therapists, clinicians trained in movement screening.	Youth and adolescent athletes when basic squat competency is present; preliminary clinical screen only.
Landing Error Scoring System (LESS)	30 cm box, tape mark, 2 cameras (frontal & sagittal).	Stand on box, jump forward to mark, land bilaterally, perform maximal vertical jump.	17-item rubric of landing errors; higher score = more errors.	Intra-rater ICC 0.82–0.99; Interrater ICC 0.83–0.92; Intersession ICC 0.81	Criterion validity supported vs 3D; prospective predictive validity mixed	Trained clinicians using video playback	Adolescent, collegiate, and adult athletic populations; appropriate for youth athletes who can safely perform a bilateral jump-landing task.
Drop Vertical Jump (DVJ)	30 cm box, landing area, 1–2 cameras (frontal & sagittal).	Step off box, land bilaterally, immediately perform vertical jump.	Kinematic measures (valgus, joint flexion) or qualitative ratings.	Good to excellent ICC >0.75 for FPPA, hip, knee flexion	Associations with ACL risk, prospective prediction limited	Clinicians or researchers with video analysis experience.	Youth, adolescent, collegiate, and adult athletes; commonly used in jump-landing biomechanics and post-ACLR testing.
Tuck Jump Assessment (TJA)	No box; flat surface, 1–2 cameras.	Perform continuous tuck jumps for 10 seconds.	10-item flaw checklist (valgus, asymmetry, noise, fatigue).	ICC >0.75 for kinematic measures; flaw scoring moderate	Criterion validity limited; detects fatigue and maturation differences	Trained clinicians; calibration improves reliability.	Youth and adolescent athletes with adequate plyometric competency; interpret cautiously in pre-adolescent athletes due to movement variability.
Double-Leg Vertical Jump (Volleyball Context)	Flat surface, vertical jump setup, 1–2 cameras.	Perform maximal vertical jump and landing, repeated trials.	2D video analysis of kinematics (valgus, hip/knee symmetry).	Validated vs 3D in volleyball cohorts	Concurrent validity supported vs 3D; feasible in field settings.	Clinicians trained in 2D video analysis.	Adolescent and youth athletes; most applicable when sport demands include repeated bilateral jumping and landing.

ACL= Anterior cruciate ligament, ICC= Intraclass correlation coefficient, FPPA= Frontal plane projection angle

improve scoring consistency.[29] Prospective work by Padua D[26] suggested a cutoff of ⩾5 errors was associated with greater risk of sustaining a noncontact ACL injury; however, replication is needed.[26]

DROP VERTICAL JUMP (DVJ)

The drop vertical jump (DVJ) is a foundational jump-landing task in biomechanics research. In the standard protocol, the athlete drops off a box (commonly 31 cm), lands bilaterally, and immediately performs a vertical jump.[30] Frontal and sagittal plane video capture can be used to extract kinematic parameters such as frontal plane knee projection angle, knee valgus angle, hip flexion, and knee flexion at initial contact and during landing.[31] Clinicians or movement scientists experienced in visual kinematic evaluation or video analysis are suited to score DVJ performance. The task is applicable across youth, collegiate, and professional athlete populations, and in post-ACL rehabilitation cohorts.[31]

RELIABILITY & VALIDITY

In youth soccer athletes, Robles-Palazón[31] reported that frontal plane knee projection angle (FPPA), hip flexion, and knee flexion measured during DVJ showed good to excellent inter- and intrarater reliability (ICC > 0.75) using 2D video methods.[31] Kinematic deviations during the DVJ, including excessive medial knee collapse and limited sagittal flexion, have been linked with noncontact knee injury risk, though direct prospective evidence remains limited.[32] The DVJ remains a reference standard in jump-landing research and is frequently used for validating clinical assessment tools.

TUCK JUMP ASSESSMENT (TJA)

The tuck jump assessment (TJA) challenges neuromuscular control under repeated plyometric loading. The participant performs continuous tuck jumps for 10 seconds, and video is scored using a 10-item flaw rubric that captures observable movement deficits including knee valgus, thigh asymmetry, unequal foot placement, landing noise, pauses between jumps, and technique breakdown across repeated jumps.[33,34] The composite "flaw count" reflects movement quality across jumps, with higher scores, indicating poor performance. TJA scoring benefits from video playback, ideally with slow motion, by trained raters. The TJA is applicable in healthy youth and adult athletes and may be used in post-ACL populations as a dynamic fatiguing screening.[33, 34]

RELIABILITY & VALIDITY

Robles-Palazón[31]also reported that FPPA, hip flexion, and knee flexion measured during TJA demonstrated good to excellent inter- and intra-rater reliability (ICC > 0.75) in youth male soccer players using 2D video methods.[31] Additional work by Racine[35] shows moderate to good intrarater and interrater reliability for flaw scoring, with rater training improving consistency.[35] Because the TJA is scored on observable flaws rather than precise kinematics, empirical studies of criterion validity versus 3D motion capture remain limited. However, the TJA may offer added sensitivity to neuromuscular fatigue or movement control deficits across repeated jumps.[31] It may also discriminate maturation-related differences more effectively than DVJ metrics in adolescent populations. When interpreting TJA performance in pediatric and adolescent athletes, clinicians should consider developmental stage, task familiarity, and plyometric competency. Younger or pre-adolescent athletes may demonstrate greater movement variability due to neuromuscular immaturity, lower plyometric experience, and reduced ability to maintain repeated jump mechanics across the full testing interval. Additional familiarization trials may be needed before scoring. In older adolescents who demonstrate adequate task mastery, repeated movement flaws across trials may more clearly represent modifiable neuromuscular control deficits, fatigue-related breakdown, or landing strategy impairments.

SINGLE-LEG TASKS

Following progression into later phases of rehabilitation, the athlete may perform more dynamic, sport specific, single leg (SL) tasks. These tasks may include the SL squat,[36] SL hops and SL drop landings.[37] Assessing quality of movement during SL tasks is imperative to identify unilateral movement deviations and prescribe appropriate interventions to remedy those faults prior to returning to sport.[11] Multiple qualitative assessments for SL tasks have been described in the literature and are summarized below.[38,39] Table 2 and Appendix A summarize the task set-up, instructions, scoring methods, reliability and validity evidence, recommended scorers, and populations for each single-leg assessment.

MOVEMENT SCREENING FOR VOLLEYBALL

Ulman et. al.[38] describes a three-item dichotomous tool that assesses frontal plane knee position, frontal plane trunk lean, and sagittal trunk position (flexion/extension) during a SL squat and a SL drop land task.[38] The Movement screening for volleyball is scored using 2D video playback from one frontal plane view and one sagittal plane view. The assessment tool involves scoring each fault as either present or not present during the respective task. This tool may be used during early to mid-phase rehabilitation for the SL squat and during late phase rehabilitation for the SL drop landing task.

RELIABILITY & VALIDITY

The validity of the Movement screening for volleyball was assessed in a group of female volleyball players with a mean age 14.7 years, for a SL squat and a SL drop land task. The tool demonstrated excellent percent agreement for trunk flexion (86.8%) and trunk lean (85.3%), moderate percent agreement for trunk extension (69.1%), but poor percent agreement for knee position (45.6%) when compared to 3D

Table 2. Single-leg tasks

Task	Set-Up & Equipment	Instructions	Scoring Method	Reliability Evidence	Validity Evidence	Recommended Scorer	Populations Studied
Movement Screening for Volleyball *SL squat*	1 camera captures 2 trials; athlete facing forward then sideways. Athlete maintains hands on hips with opposite leg bent behind.	Squat down as far as you can comfortably and then return to the starting position. Do not put your stance leg down or remove your hands from your hips.	Dichotomous scoring of 3 variables: poor knee position, lateral trunk lean, and excessive trunk flexion or extension.	Reliability for this tool has not been tested.	Excellent to moderate percent agreement for trunk positioning. Poor percent agreement for knee position.	Athletic trainers, physical therapists, clinicians trained in movement screening.	Healthy athletes and early to mid-phase rehab patients.
Movement Screening for Volleyball *SL drop landing*	1 camera captures 2 trials; athlete facing forward then sideways. 31 cm box.	Stand on top of a 31-cm plyometric box with your hands on your hips, then jump down from the box landing on one leg and hold the landing for at least 2 seconds.	Dichotomous scoring of 3 variables: poor knee position, lateral trunk lean, and excessive trunk flexion or extension.	Reliability for this tool has not been tested.	Excellent to moderate percent agreement for trunk positioning. Poor percent agreement for knee position.	Athletic trainers, physical therapists, clinicians trained in movement screening.	Healthy athletes and late phase rehab patients.
Athletic Ability Assessment *SL squat*	Box of any height.	Perform 5 repetitions of a SL squat while maintaining perfect trunk, hip, knee, and ankle alignment and achieving a depth of the hip below the knee for all repetitions.	3 main assessment points (trunk angle, hip/knee/ ankle alignment and depth) scored as 3, 2, or 1 for each. Maximum score is 9 reflecting perfect performance	Good inter and intra rater reliability for SL squat.	Limited validity evidence with one discriminant/ ecological study available.[40]	Strength coaches, physical therapists, athletic trainers, experience with movement assessment scoring.	Athletes within the continuum of athletic development with a focus on load and movement complexity. Best used to profile movement quality and track changes over time.
Qualitative Analysis of Single Leg Loading (QASLS)	Equipment is dependent on the task; SL squat, SL landing, SL hopping.	Hands placed on hips for the duration of the task.	10-item checklist to include trunk, hip, and knee variables. Athletes are awarded 1 point for each present fault. Higher scores indicate poorer performance.	Intra-rater near perfect reliability. Inter rater weak to moderate reliability.	Limited criterion validity.	Trained clinicians; standardization in training between raters to improve reliability, especially for complex tasks.	Adolescent and collegiate athletes participating in multidirectional activities. Rehabilitation patients' phase of rehab determines appropriate task.

SL = Single leg

capture in a SL squat.[38] Additionally, for a SL drop landing task, this tool again demonstrated excellent percent agreement for trunk flexion (100%) and trunk lean (88.2.3%), moderate percent agreement for trunk extension (69.1%), and poor percent agreement for knee position (44.1%).[38] While the reliability of the tool has not been assessed, these findings provide preliminary support for the use of this tool in assessing frontal and sagittal plane trunk alignment, with more work needed to support the assessment of frontal plane knee position and to establish tool reliability.

SINGLE-LEG SQUAT

Several SL squat assessments are reported in the literature. The majority assess the trunk, pelvis, hip, and knee joints and include a point-based rating scale for identified faults.[41-50] The SL squat assessment included in the Athletic Ability Assessment (AAA) is recommended and assessed by having the participant complete five repetitions of a SL squat.[45] It can be scored in real time or with video recording. The athlete receives a score of one (poor), two (inconsistent), or three (ideal) depending on trunk angle, LE alignment, and depth. This tool may be used to assess movement competency within a rehabilitation setting or performance setting.

RELIABILITY & VALIDITY

In a meta-analysis, Ressman et. al[39] concluded that across all SL squat tests, moderate reliability is noted in a clinical setting. Specifically, Ressman et. al[39] identified ten tools as having both moderate to almost perfect inter and intra-rater agreement. SL squat assessments that are within a three-point rating scale demonstrate greater inter-rater reliability when compared to four-point rating scales.[39] For example, McKeown et al.[45] administered the Athletic Ability Assessment (AAA) to 17 national female footballers with a mean age of 22 $\pm$ 4 years. The AAA is an assessment tool designed to capture movements in an athletic population and includes a SL squat task. Each movement is scored as either three (perfect performance), two (slight deviation from ideal or inconsistent performance), or one (unable to perform or poor performance). The AAA composite score demonstrates excellent inter (ICC: 0.96, 95%CI 0.94 - 0.95) and intra (ICC: 0.97, 95% CI 0.92-0.99) rater reliability.[45] The SL squat assesses trunk angle, LE alignment, and depth. For the SL squat, the AAA demonstrated good inter and intra rater reliability and small error margins with a minimal detectable change (MDC) of 0.6 - 0.8.[45]

QUALITATIVE ANALYSIS OF SINGLE LEG LOADING

The Qualitative Analysis of Single Leg Loading (QASLS) is an assessment tool designed to evaluate SL tasks using dichotomous scoring for ten trunk, hip, and knee variables.[51] Athletes are awarded 1 point for each present fault, with higher scores indicating poorer performance. The QASLS can be applied to any dynamic SL task including a SL squat, SL hop, or SL drop land task. The tool is recommended to be used by trained clinicians throughout rehabilitation to help identify movement deviations.

RELIABILITY & VALIDITY

Parry et al.[52] utilized the QASLS to compare a SL squat and SL landing tasks in 15 healthy females with a mean age of 19 $\pm$ 2 years. For the SL squat task, intra rater reliability demonstrated almost perfect (kappa: 0.85, 95% CI 0.73 - 0.98) to perfect agreement and ranged from slight (kappa = 0.125, 95% CI: -0.18 to 0.043) to substantial (kappa = 0.737, no 95% CI: 0.51–0.97) inter rater reliability.[52] Additionally, Parry et al.[52] found perfect to excellent intra-rater reliability (90-100% percent of exact agreement) for the SL landing task, however inter-rater reliability ranged from slight agreement (kappa: 0.03, 95% CI -0.07 - 0.13) to fair agreement (κ: 0.29, 95% CI -0.17 - 0.43). For a hopping task, Epstein et al.[53] utilized the QASLS tool to assess 20 subjects (60% female, 16.5 $\pm$ 1.6 years) during the final landing of a triple hop for distance. Intra-rater reliability ranged from moderate (ICC: 0.747; 95%CI 0.471-0.891) and excellent (ICC: 0.917; 95%CI 0.803-0.966) within each of the five raters and moderate (ICC: 0.703; 95%CI 0.510-0.852) inter-rater reliability was found.[53] These findings suggest that the QASLS is a valid and reliable tool to assess SL tasks (i.e. squat, landing, and hopping tasks), but clinicians may benefit from training sessions to improve ratings between practitioners for more complex and dynamic tasks.

TOOLS TO ASSESS CHANGE OF DIRECTION

Change-of-direction (COD) assessments are a clinically relevant approach to evaluating movement quality during high-demand tasks that more closely resemble the mechanical and neuromuscular challenges faced in sport. As rehabilitation progresses into later phases and patients post-ACLR prepare to RTS, COD tasks provide insight into multiplanar control, deceleration strategies, and trunk and lower extremity coordination. Although qualitative COD assessments are not analogous to using 3D motion capture, standardized COD protocols have been shown to reveal meaningful movement patterns associated with injury risk and performance.[54,55] This section summarizes currently published tools designed to assess movement quality during COD tasks, including their scoring approaches, psychometric properties, recommended users, and clinical applicability across pediatric and adolescent athletic populations. Table 3 and Appendix A summarize the task set-up, instructions, scoring methods, reliability and validity evidence, recommended scorers, and populations for each change of direction assessment.

EXPANDED CUTTING ALIGNMENT SCORING TOOL (E-CAST)

The Expanded Cutting Alignment Scoring Tool (E-CAST) is a 2D video-based clinical screening tool designed to evaluate trunk and lower-extremity alignment during a standardized 45-degree sidestep cut. It was developed by Butler

Table 3. Change of direction tasks

Task	Set-Up & Equipment	Instructions	Scoring Method	Reliability Evidence	Validity Evidence	Recommended Scorer	Populations Studied
Expanded Cutting Alignment Scoring Tool (E-CAST)	45° sidestep cut course, COD target/ cone, 2 cameras or smartphone (frontal & sagittal views).	Run forward to the cone, plant your foot, slow down, and cut at a 45-degree angle in the direction instructed. Perform the movement the same way each trial.	Dichotomous checklist of movement faults; present = 1, absent = 0; higher score = more faults/poorer movement quality.	Intra-rater ICC = 0.78; Interrater ICC = 0.71; item kappa values ranged from slight to almost perfect.	Concurrent validity supported vs 3D motion capture; AUC = 0.67–0.91 for 5/6 variables; sensitivity 70–85%, specificity 55–89%.	Trained physical therapists, sports medicine clinicians using slowed video review and standardized scoring images.	Adolescent female athletes in cutting/ pivoting sports; late-stage rehab, RTS, and injury-risk screening populations.
Cutting Movement Assessment Score (CMAS)	Sidestep cutting task (30°–90° COD), frontal and sagittal cameras; optional diagonal view.	Run forward and perform a side-step cut in the direction instructed. Move naturally and at game-like speed while we record from the front and side.	9-item rubric; 7 dichotomous items plus multi-category scoring for trunk position and lateral leg plant distance; higher score = poorer movement quality/higher knee-loading risk.	Intra- and inter-rater ICC/kappa typically 0.69–0.95; cross-profession agreement kappa = 0.63–0.84; inter-rater reliability more variable with minimal training.	Strong association with peak KAM on 3D analysis ($r = 0.80$, $p < 0.001$); distinguishes higher- vs lower-risk cutting strategies; detects differences between anticipated and unanticipated cutting.	Sports physical therapists, athletic trainers, strength and conditioning coaches, and sports scientists with structured scoring training.	Athletic populations performing cutting tasks; evidence includes female footballers and other field/court sport athletes.
Deceleration Task Assessment	Sprint lane, marked deceleration zone, frontal and sagittal video cameras.	Sprint forward as fast as you can. When you reach the marked area, slow down quickly and stop by planting on one leg.	Qualitative scoring of limb stability, pelvis stability, trunk stability, shock absorption, and movement strategy; summed composite score; higher score = safer/more controlled mechanics.	Excellent reliability; intra- and inter-rater ICCs > 0.94 across scoring criteria.	Concurrent validity supported vs 3D motion capture; lower qualitative scores were associated with greater peak knee valgus moments.	Clinicians or researchers trained in qualitative 2D video analysis of deceleration mechanics.	Sport athletes performing high-speed braking tasks; especially relevant to football/soccer-style deceleration demands.
Run-Plant Task Assessment	Run-up lane, target planting zone, 2 synchronized cameras (frontal & sagittal).	Run forward to the marked area, plant your foot in the box, then quickly change direction and backpedal to the start. Perform each trial with good effort and control.	Dichotomous checklist of movement faults during plant phase; includes trunk lean, dynamic knee valgus, sagittal trunk-tibia alignment, foot position, and preparatory deceleration strategy; higher score = more faults.	Intra-rater ICC approximately 0.43–0.54; Interrater ICC 0.32–0.66; some individual items showed moderate-good reliability, but total score reliability was limited.	Validity evidence was not clearly established in the provided summary; authors recommended further refinement before stand-alone clinical use.	Clinicians using standard video recordings, though tool refinement is needed before independent clinical decision-making.	Adolescent female athletes performing rapid deceleration and 180° change-of-direction tasks.

COD = Change of direction, ICC= Intraclass correlation coefficient, AUC= Area under the curve, KAM = Knee abduction moment

and colleagues as an expansion of the original Cutting Alignment Scoring Tool (CAST) to better capture sagittal-plane movement patterns associated with ACL loading.[20] Athletes perform a planned cutting maneuver toward a COD target, such as an "opponent cone," decelerate on the plant limb, and cut along a 45-degree trajectory. Video is recorded in the frontal and sagittal planes using standard 2D video cameras, or a smartphone. The tool is intended to identify movement strategies that have been associated with elevated ACL injury risk, including trunk lean, cut width, knee valgus, knee flexion, and ankle plantarflexion.[21] Suboptimal movement strategies are identified and scored as present or not present, with present faults awarded a score of one. Higher scores indicate poorer performance. Butler et al.[21] recommends post hoc scoring from a slowed video by trained physical therapists or sports medicine clinicians using standardized camera placement and reference images to improve consistency. The tool has been developed and validated specifically in adolescent female athletes involved in cutting and pivoting sports, making it most appropriate for late-stage rehabilitation, RTS assessment, and injury-risk screening in this population rather than for early rehabilitation.[21]

RELIABILITY & VALIDITY

Butler et al.[20] first established the reliability of the E-CAST in adolescent female athletes participating in cutting and pivoting sports.[20] It was reported that cumulative intra-rater reliability was good (ICC = 0.78, 95% CI 0.59-0.96) and inter-rater reliability was moderate (ICC = 0.71, 95% CI 0.50-0.91) for the total E-CAST score, with kappa values for individual items ranging from slight to almost perfect depending on the variable. A subsequent study by Butler et al.[21] evaluated concurrent validity of the E-CAST against 3D motion capture in a similar adolescent female athlete population.[21] Receiver operating characteristic analyses demonstrated acceptable to outstanding discrimination (AUC = 0.67-0.91) for five of the six movement variables, with sensitivity ranging from 70-85% and specificity from 55-89%, indicating that the E-CAST can identify athletes exhibiting high-risk trunk, knee, and ankle mechanics during cutting when compared with 3D biomechanics. Butler et al.[21] further reported that a quantitative 2D kinematic version of E-CAST did not significantly improve reliability over the original qualitative scoring, supporting the clinical feasibility of visual scoring without specialized motion-analysis software.[21]

CUTTING MOVEMENT ASSESSMENT SCORE (CMAS)

The Cutting Movement Assessment Score (CMAS) is a similar field-based qualitative screening tool designed to evaluate movement quality during side-step cutting.[55,56] The CMAS assesses trunk, hip, knee, and foot mechanics during a sidestep cut (often 30° - 90° COD), with a specific focus on both the penultimate foot contact and the final plant step. Athletes perform a cutting maneuver while recorded from the frontal and sagittal views. An additional, optional diagonal view has also been reported. Trials are analyzed retrospectively using slowed video. The CMAS uses a nine-item rubric scored from video analysis, capturing postures and movement strategies that are known to be associated with peak KAM.[55,56] Seven items are scored dichotomously (1 = movement fault observed, 0 = not observed), while lateral leg plant distance and trunk position use non-binary classifications (3 and 4 classifications, respectively). Scores are summed for a total CMAS score, with higher scores indicating poorer movement quality and greater knee-joint loading risk.[56] Notably, the CMAS has been shown to detect meaningful differences between anticipated and unanticipated cutting, supporting its relevance to sport-specific injury-risk screening.[55] The tool was designed for use by sports physical therapists, athletic trainers, strength and conditioning coaches, and sports scientists following structured training in item definitions and scoring procedures.

RELIABILITY & VALIDITY

Reliability and validity of CMAS have been established through a series of laboratory- and field-based studies.[57,58] In the original validation study, a strong correlation was observed between CMAS score and peak KAM measured using 3D motion analysis (r = 0.80, p < 0.001), and athletes in the highest CMAS tertile exhibited significantly greater knee abduction angles, lateral foot plant distances, internal foot progression angles, and multiplanar knee joint moments than those in the lowest tertile. Additionally, moderate-to-excellent intra- and inter-rater reliability for CMAS total score and individual items (ICC and kappa values typically 0.69-0.95) were reported when scored by trained raters using standardized video protocols.[55] More recently, Jones et al.[57] reported that the CMAS maintains good-to-excellent agreement across practitioners from different professional backgrounds (kappa = 0.63-0.84) and that comparable scores can be obtained using two camera views (including sagittal) compared with three, supporting its field-based feasibility.[57] Field-based studies in female footballers have shown more variable inter-rater reliability when minimal rater training is used, but consistently moderate-to-good intra-rater reliability for most CMAS items, reinforcing the importance of standardized rater preparation.[58]

DECELERATION TASK ASSESSMENT

A qualitative 2D video-analysis method has been described to evaluate movement quality during a sport-specific deceleration task.[17] In the standard protocol, athletes perform a maximal forward sprint followed by rapid deceleration and a single-leg plant on the stance limb, sometimes followed by a backward acceleration (e.g., backpedal) depending on the testing context. The deceleration task is evaluated using a qualitative scoring framework that is based on observable joint kinematics from frontal and sagittal video recordings. The scoring criteria have been previously reported as they were originally developed for a 90° cutting maneuver by Della Villa et al.[59]This scoring system involves the evaluation of several movement domains, such as limb stability, pelvis stability, trunk stability, shock absorption, and

movement strategy. Each criterion is assigned a score ranging from inadequate to optimal movement execution. Individual sub scores are summed to produce a composite movement-quality score, with higher values indicating safer or more controlled mechanics. The evaluation focuses on the frame of maximal knee flexion following foot contact, when frontal-plane knee motion and trunk control are most apparent. This deceleration movement represents a common sport scenario, particularly in football/soccer pressing actions, and has been identified as a situational pattern frequently associated with ACL injury mechanisms.

RELIABILITY & VALIDITY

Di Paolo et al.[17] investigated the reliability and biomechanical validity of this qualitative 2D deceleration assessment by comparing the video-based scores with 3D motion capture.[17] The qualitative scoring system demonstrated excellent reliability, with both intra-rater and inter-rater intraclass correlation coefficients exceeding 0.94 across all scoring criteria. Notably, lower qualitative scores, reflecting poorer movement quality, were associated with significantly greater peak knee valgus moments. These findings support the concurrent validity of the qualitative deceleration task assessment as a clinically feasible method for identifying athletes who demonstrate higher knee joint loading during high-speed braking tasks.

RUN-PLANT TASK ASSESSMENT

The run-plant task is a two-dimensional video-based qualitative assessment designed to evaluate trunk and lower-extremity alignment during rapid deceleration and a 180° directional change.[60] Athletes are asked to run forward toward a target zone, plant the stance limb within a designated area, and then reverse direction by backpedaling to the starting position. Two synchronized cameras positioned in the frontal and sagittal planes record the movement to allow visual assessment of movement quality during the final plant step. Movement quality during the run-plant task is evaluated using a qualitative checklist that identifies observable movement faults during the plant phase of the task.[60] The assessment includes criteria related to trunk lean, dynamic knee valgus, sagittal trunk-tibia alignment, foot position, and preparatory deceleration strategy. Each criterion is scored dichotomously based on whether a movement fault is present, and the individual item scores are summed to produce a total score representing overall movement quality. Higher scores reflect a greater number of movement faults and therefore poorer movement control during the deceleration task. The tool is intended as a practical screening approach that clinicians can apply using standard video recordings to identify athletes who may demonstrate suboptimal trunk or lower-extremity alignment during dynamic deceleration tasks. However, given overall reliability of the total score was limited in the initial study, Butler et al.[60] recommend that the tool be further refined and validated before used as a standalone injury risk screening or return-to-sport assessment.[60]

RELIABILITY & VALIDITY

Butler et al.[60] examined the reliability of this qualitative assessment tool in a cohort of adolescent female athletes performing the run-plant task.[60] Overall, reliability for the total score ranged from poor to moderate across raters and scoring rounds, with intra-rater ICC values ranging approximately from 0.43 to 0.54 and inter-rater ICC values from 0.32 to 0.66. Individual scoring items demonstrated variable reliability. Sagittal alignment and medial foot position showed moderate to good reliability, whereas other criteria such as dynamic valgus and preparatory deceleration steps demonstrated limited variability across participants, which reduced the interpretability of ICC estimates despite high percent agreement between raters. Based on these findings, the authors concluded that refinement of several scoring definitions is necessary before the tool can be confidently used for independent clinical decision-making. Despite these findings, the tool represents one of the few attempts to provide clinicians with a framework to assess trunk and lower limb alignment during a deceleration task, an important but understudied area. As such, this tool should not yet be used for clinical assessment but rather serve as a guide to inform clinicians of movement patterns that may be considered during a deceleration task.

INTERPRETATION AND INTERVENTIONS

To reduce the risk of second ACL injury after primary ACLR, it is essential to identify movement impairments and implement targeted interventions to address them. Movement assessment should be individualized, considering all relevant factors. The clinician should perform additional tests, beyond quality of movement assessment, that aim to identify factors that may be contributing to the aberrant movement patterns observed.[61] A thorough assessment should incorporate objective testing across multiple joints to identify all potential contributors of the movement impairment. For example, concluding that a frontal plane impairment is solely due to a deficit in the same plane can be misleading. For instance, knee valgus during an anterior step-down may be a "movement solution" for multiple underlying issues, including weakness in the lateral hip muscles,[62-64] limited eccentric quadriceps strength,[12] and/or restricted closed-chain ankle dorsiflexion.[65] Without a detailed analysis of all contributing factors, identifying the root cause may be challenging and can lead to incorrect assumptions. Table 4 summarizes common movement impairments associated with an increased risk for non-contact knee injuries, potential contributing factors, and suggested interventions. The authors recommend using a combination of targeted strength training, plyometrics, and neuromuscular training to enhance movement quality during various tasks. Neuromuscular training programs are widely recommended for preventing such injuries.[66-69] The effectiveness of these programs can be further enhanced by tailoring the training to address the specific deficits identified during the quality of movement assessment. Furthermore, it is recommended that athletes with movement impair-

Table 4. Common movement impairments associated with an increased risk for non-contact knee injuries, potential contributing factors, and suggested interventions.

Identified 2D Fault	Contributing Factor(s)	Suggested Exercise / Intervention	Clinical Reasoning
Dynamic Knee Valgus	Weak gluteus medius/ minimus; restricted ankle dorsiflexion.	Lateral band walks, Hip clocks, Hip abduction wall press, Single leg deadlifts, dorsiflexion stretches, FIFA 11+ drills.	Improve frontal plane femoral control and sagittal ankle range of motion.[70, 71]
Knee Extensor Bias	Upright trunk; reliance on quads for deceleration.	Forward trunk lean squats, Romanian deadlifts, glute-dominant landing drills.	Shifting center of mass forward engages hip extensors and reduces ACL strain.[72]
Stiff / Upright Landing	Quadriceps weakness; fear of loading (kinesiophobia).	Eccentric leg press, Step down progression, Box jumps, Depth jumps (focus on silent landing)	Improve energy absorption and eccentric quadriceps confidence.[73,74]
Lateral Trunk Lean	Poor core stability; weak lumbopelvic stabilizers.	Side planks, Pallof press, perturbation training (ball tossing).	Enhance the trunk's ability to resist lateral forces and maintain center of mass.[75]
Sub-optimal Penultimate Step	Poor deceleration strategy.	Progressive deceleration drills; "penultimate step" focus cues.	Dissipate force before the final plant step to reduce peak knee abduction moment.[54]

ACL= Anterior cruciate ligament

ments follow a progression to restore movement quality with basic tasks such as step downs and single leg squats prior to advancing to more dynamic activities such as hopping and cutting tasks.[37]

FEASIBILITY IN CLINICAL PRACTICE

When implementing quality of movement assessment tools into clinical practice there are several factors that need to be considered to maximize efficiency and effectiveness. While most of the tools discussed involve no equipment, some do require a 12-inch box which ranges in cost from $50- $300. Similarly, the reliability and validity of many of the tools were established using 2D video recording, allowing the clinician to slow down the video and re-watch several times to assess quality of movement.[20,21,26,34,38,51,52,76,77]

This requires the use of one or more video recording devices such as smartphones, tablets, digital cameras, or webcams which also result in added costs for clinics that do not already have these devices. Further, if more than one camera view is needed, this will either require additional staff members to manage the recording devices, or the use of tripods to hold the devices and allow for video recording with one clinician. Despite these financial considerations, the cost to use 2D video capture in the clinic is substantially less than that of 3D motion capture. When using these tools in the clinic, clinicians should also consider their available space. Smaller spaces are suitable for the double leg and single leg tasks; however, the change of direction and deceleration tasks require larger facilities. Additionally, performing these more rapid movements on certain floor types (e.g. tile, carpet) may not be ideal. Finally, the reliability of each assessment tool is dependent on the standardization of each task, and on the quality of clinician training provided. It is recommended that standard operating procedures are followed for each task to maintain consistency and ensure reliable and valid outcomes. If using an electronic medical record, the standard patient instructions and set up can be included in the documentation template to guide clinicians in accurate implementation. Each clinician should be trained to administer each task and utilize the quality of movement assessment tool. The training should be developed and implemented across clinic sites to ensure standardization and reliability between clinicians. Despite these considerations, implementing quality of movement assessments in clinical practice remains a low-cost and relatively simple way to objectively evaluate human movement.

RECOMMENDATIONS FOR CLINICAL PRACTICE

It should be noted that quality of movement assessments should not be performed in isolation. When making decisions related to progression in the rehabilitation program or clearance to RTS, a holistic approach should be used. It is recommended to include quantitative measures such as strength, hop distance, limb symmetry index, and knee range of motion, as well as psychological assessments, including measures of psychological readiness to RTS or kinesiophobia, alongside qualitative assessments.[78] There is currently insufficient evidence to suggest specific quality of movement assessments or reference values for interpretation based on patient age or stage of maturation. As such, it is the author's opinion that movement competency should guide test selection and implementation. For example, individuals should demonstrate mastery of the task prior to the performance of the quality of movement assessment. If task mastery has not been achieved, the quality of movement assessment may not provide reliable data due to increased performance variability.[79] Once the athlete becomes proficient with the task, movement variability should decrease.[79] At that point, quality of movement assessments should be chosen strategically based on the performance variables being assessed and the athlete's needs analysis. Selecting a combination of assessment tools that collectively evaluate a well-rounded set of performance qualities will improve the efficiency and the specificity of

Table 5. Performance variables by task

Task	Performance Variables Assessed
Single hop for distance Triple hop for distance Triple crossover hop for distance	Single limb horizontal force production and load acceptance
Landing Error Scoring System Drop Vertical Jump	Double limb vertical load acceptance and force production
Single leg drop land	Single limb vertical load acceptance
Single leg squat	Single limb slow controlled movement
Overhead squat	Double limb slow controlled movement
Tuck Jump	Double limb repetitive plyometric ability
Expanded Cutting Alignment Scoring Tool Cutting Movement Assessment Score Cutting tool by Weir et al[76]	Change of direction

the test battery. For example, the single hop for distance, triple hop for distance, and triple crossover hop for distance, all assess horizontal force production and load acceptance on one limb, while the LESS and DVJ evaluate double limb vertical load acceptance and force production. Table 5 describes the performance variables assessed by each task. From a time efficiency standpoint, it may not be feasible or necessary to administer each one of these tests. Instead, the clinician can select one representative tool per performance attribute. For example, a battery might include: the triple hop for distance to assess horizontal force production and load acceptance, the single leg drop land to examine single leg vertical load acceptance, the single leg squat to assess a slow controlled movement, and the ECAST to evaluate change of direction technique. Similarly, a test battery can be designed based on the athlete's needs. For example, for a basketball player whose primary deficits include force production and load acceptance during landings, as well as change of direction mechanics, the clinician may choose to administer the DVJ to assess vertical force production and load acceptance, the single hop for distance to examine horizontal force production and load acceptance, and the CMAS to evaluate change of direction technique. The intentional selection of assessments when building a test battery is critical to maximizing both efficiency and clinical utility. Finally, it should be noted that pre-adolescent athletes may demonstrate greater movement variability in general, due to both physical and neuromuscular immaturity.[79] As such, it is recommended to implement a greater number of test trials for pre-adolescent athletes to ensure an accurate representation of the athlete's movement.[79]

CAUTIONS

When implementing quality of movement assessment tools into RTS decision-making after ACLR, the clinician should be aware that there is limited evidence related to the ability of qualitative assessments to predict second ACL injury. One study found an association between quality of movement during a change of direction task and second ACL injury risk in youth athletes.[25] Specifically, the authors reported that athletes who demonstrated dynamic knee valgus, identified with the E-CAST, were approximately 4.6 times more likely to suffer a second ACL injury.[25] Similarly, another study that used 2D video to evaluate a combination of single limb, double limb and change of direction tasks, also reported a relationship with second ACL injury risk.[72] This study, instead of using a binary qualitative checklist, used a composite score of various biomechanical metrics such as joint angles, joint moments, and ground reaction forces.[72] To validate and enhance the clinical utility of these tools as part of RTS decision making after ACLR, more empirical evidence is needed. In addition to the validity, the reliability of the quality of movement assessment tool needs to be critically assessed. Clinicians need to be aware that tool consistency directly impacts the RTS decision-making process; and thus, need to approach cautiously.

SUMMARY

Quality of movement assessment tools provide low-cost, easily accessible methods to evaluate trunk and lower extremity movement patterns during rehabilitation and RTS after ACLR. Valid and reliable tools can be applied to double-leg, single-leg, and change of direction tasks, allowing clinicians to progressively assess movement quality as the athlete advances through rehabilitation and RTS training. With adequate practitioner training and practice, these tools can provide a consistent method for identifying suboptimal movement patterns and guiding treatment interventions.

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SUPPLEMENTARY MATERIALS

Appendix

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