Review Article

Markerless 3D motion capture in return to sport decision making for ACL injured high level athletes: a narrative review with proposed clinical implementation pathway

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Background and Objective: Anterior cruciate ligament (ACL) injury remains a career-defining event for high-level athletes, and current return to sport (RTS) criteria often fail to detect residual neuromuscular deficits that drive graft failure and contralateral tears. Three-dimensional (3D) markerless motion capture has emerged as a scalable technology that may address these gaps by quantifying movement quality during sport-specific tasks. The objective of this narrative review is to summarize the current evidence on markerless 3D motion capture in ACL rehabilitation and RTS decision-making, with a specific focus on clinical implementation pathways for high-level athletes.

Methods: A comprehensive literature search was conducted across PubMed/MEDLINE, Embase, and the Cochrane Library from January 2005 through May 2025 using terms related to markerless motion capture, biomechanical analysis, ACL reconstruction, and RTS. English-language original research, systematic reviews, validation studies, and clinical commentaries were considered. Reference lists of included articles were hand-searched to identify additional relevant publications.

Key Content and Findings: Traditional biomechanical tools, including dual fluoroscopy, marker-based motion capture, and inertial measurement units, have advanced understanding of ACL injury mechanisms but face practical barriers limiting routine clinical use. Markerless systems use computer vision and machine learning to generate joint kinematics and, when integrated with force plates or pressure insoles, kinetics during sport-specific tasks. Platforms such as OpenCap expand access for research and large-scale field testing, whereas clinical systems such as Theia3D demonstrate the strongest current evidence for clinical integration, with validation studies showing acceptable sagittal-plane accuracy but less mature evidence for dynamic, multiplanar RTS movements. A structured RTS pathway incorporating serial biomechanical testing, parameter-specific clearance thresholds, and longitudinal monitoring is proposed. Remaining challenges include limited validation samples, incomplete evidence for sport-specific multiplanar tasks, and sparse prospective data linking markerless-derived metrics with clinically meaningful outcomes.

Conclusions: Markerless motion capture is positioned to become a valuable component of RTS decision-making by providing scalable, objective, and ecologically valid assessment of movement quality. Future work should prioritize standardized capture protocols, multicenter normative datasets stratified by sport and sex, and prospective studies connecting markerless-derived metrics with reinjury and performance outcomes.

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Introduction

For high-level athletes, defined here as individuals competing at the collegiate, professional, or national or international level where sport is a primary occupation or major commitment, an anterior cruciate ligament (ACL) tear is not just an injury; it is often a career-defining event with long-term consequences. In elite sports, where performance, contractual obligations, and competitive expectations are paramount, ACL injuries can derail seasons and shorten careers. More than 200,000 ACL injuries occur annually in the United States (1), affecting over 3% of athletes within four years of sports participation, and incidence rates continue to rise across all levels of competition despite decades of research in ACL and return to sport (RTS) (2). Beyond the initial injury burden, graft reinjury and contralateral ACL tears remain substantial, amplifying the challenge of safe RTS (3).

Traditional RTS criteria, including time from surgery, limb strength symmetry, and hop distance tests, are useful but often fail to detect residual neuromuscular deficits, asymmetries, and compensatory movement patterns that elevate reinjury risk (4). High-level athletes are particularly vulnerable, as even subtle deficits can alter performance or elevate injury risk. Studies have shown that athletes who satisfy standard RTS benchmarks may still demonstrate poor landing mechanics, altered trunk and hip control, or kinetic asymmetries associated with secondary ACL injury (5-8). Compounding these challenges is the lack of baseline biomechanical data in most athletes (9). Without preinjury reference values, clinicians are often uncertain what normal movement to restore, defaulting to normative data, often from nonelite athletes, which makes any target imperfect and impersonal. To deliver truly personalized care and improve outcomes, more sensitive and comprehensive measurement tools are needed.

Three-dimensional (3D) motion capture has long offered a promising route to narrow this gap. By capturing both kinematic and kinetic data during sport-specific tasks, motion capture can reveal movement quality and loading asymmetries that traditional benchmarks cannot. Traditional motion capture technologies, including marker-based motion capture and wearable sensor systems, have advanced our understanding of ACL injury mechanisms such as dynamic valgus, abnormal trunk lean, and limited knee flexion; however, their widespread use has been limited by practical barriers (10). Marker-based motion capture is constrained by high cost, lengthy setup, specialized expertise, and confinement to laboratory environments. Inertial measurement unit (IMU)-based systems are more portable but are limited by reduced accuracy for complex, multi-degree of freedom movements, signal drift and magnetic interference, frequent calibration requirements, finite battery life, and reliance on skilled collection and interpretation (11). These barriers have historically restricted both approaches from widespread clinical adoption.

Recent advances in computer vision and artificial intelligence have led to the development of markerless motion capture technologies that reduce barriers related to cost, setup, specialized expertise, and environmental constraints (12). These technologies enable biomechanical assessment outside the confines of the laboratory with a simpler, faster setup, making clinical use more feasible. Professional sports organizations and healthcare systems in the United States are already integrating both traditional marker-based and newer markerless systems to monitor performance, guide rehabilitation and support return-to-play decisions (13,14). This review focuses on the role of markerless 3D motion capture in biomechanics and RTS decision-making for ACL-injured athletes, with an explicit emphasis on clinical implementation, summarizing validation evidence, biomechanical insights, and a proposed structured RTS pathway applicable in real-world sports medicine settings. Although the present emphasis is on elite athletes, these technologies are poised to expand into broader athletic and clinical populations, ultimately democratizing access to advanced biomechanical insights. We present this article in accordance with the Narrative Review reporting checklist (available at https://aoj.amegroups.com/article/view/10.21037/aoj-2025-1-95/rc).

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Table 1 The search strategy summary

Items	Specification
Date of search	January 2025 (updated May 2025)
Databases and other sources searched	PubMed/MEDLINE, Embase, Cochrane Library; hand-searching of reference lists
Search terms used	(markerless OR "computer vision" OR "pose estimation" OR Theia3D OR OpenCap) AND (kinematics OR kinetics OR biomechanics OR "ground reaction force" OR "motion capture") AND ("anterior cruciate ligament" OR ACL OR "ACL reconstruction") AND ("return to sport" OR "return to play" OR rehabilitation OR "sport readiness")
Timeframe	January 2005 to May 2025
Inclusion and exclusion criteria	Inclusion criteria: English-language original research, systematic reviews, meta-analyses, validation studies, clinical commentaries, and clinical practice guidelines addressing biomechanical motion capture technologies and/or return-to-sport assessment in ACL-injured or reconstructed athletes
	Exclusion criteria: conference abstracts, non-English-language publications, purely technical computer science papers without clinical relevance
Selection process	Conducted by A.T.D. with review and input from L.M. and J.M.B.; not conducted as a systematic review

ACL, anterior cruciate ligament.

Methods

A literature search was performed in PubMed/MEDLINE, Embase, and the Cochrane Library for articles published between January 2005 and May 2025. The search strategy combined terms related to markerless motion capture (e.g., "markerless", "computer vision", "pose estimation", "Theia3D", "OpenCap"), biomechanical analysis (e.g., "kinematics", "kinetics", "ground reaction force"), ACL injury and reconstruction (e.g., "anterior cruciate ligament", "ACL reconstruction"), and RTS (e.g., "return to sport", "return to play", "sport readiness"). English-language original research articles, systematic reviews, meta-analyses, validation studies, clinical commentaries, and relevant clinical practice guidelines were included. Conference abstracts, non-English-language publications, and purely technical computer science papers without clinical application were excluded. Reference lists of identified articles were hand-searched to capture additional relevant publications. Because this is a narrative review rather than a systematic review, the search strategy is intended for transparent reporting rather than exhaustive retrieval. The search strategy summary is presented in *Table 1*.

Biomechanical analysis

Biomechanical analyses provide a systematic approach to understanding how the body generates, transfers, and absorbs forces during movement. By quantifying joint angles, segment velocities, ground reaction forces, and muscle activation patterns, these analyses allow researchers and clinicians to evaluate both the quality and efficiency of movement (15). Historically, biomechanical studies have sought to identify injury mechanisms as well as to assess athletic performance variables (16). Modern approaches extend beyond isolated joint measures to consider the body as an integrated system, recognizing that deficits in one region (e.g., hip strength) can manifest as compensatory strategies elsewhere (e.g., knee valgus) (17). This systems-level perspective makes biomechanics uniquely valuable in the context of ACL injury, where subtle asymmetries or altered loading strategies, including reduced knee-flexion moments, dynamic valgus, and hip-abductor weakness, can help predict reinjury risk and influence RTS outcomes (7,17).

Traditional biomechanics tools

Several traditional biomechanical analysis tools have shaped our understanding of ACL injury mechanisms and RTS considerations. Each has contributed valuable insights but faces practical barriers to routine clinical use. Together, they highlight the need for scalable and clinically feasible approaches that maintain accuracy while broadening accessibility.

Dual fluoroscopy

Dual fluoroscopy combines synchronized X-ray imaging

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with 3D bone models to capture in vivo joint kinematics at sub-millimeter precision (18). Validation studies demonstrate translation errors of less than 0.3 mm and rotation errors under 0.5°, making it the most accurate method available for skeletal motion analysis. This precision eliminates soft tissue artifact that can compromise marker-based systems and has been critical in studying graft function and cartilage loading after ACL reconstruction. Despite its accuracy, dual fluoroscopy is limited by radiation exposure, high costs, and ecological constraints, confining its role to controlled laboratory research rather than large-scale or longitudinal athlete monitoring (18).

Marker-based motion capture

Marker-based optical motion capture has been the laboratory gold standard for decades and underpins much of the foundational work linking biomechanics to ACL injury risk, including dynamic valgus, reduced knee flexion, and abnormal trunk positioning (13,19). Under controlled conditions, marker tracking accuracy is typically <2 mm, but joint kinematic accuracy is compromised by skin movement artifact, which can introduce up to 10° to 15° of error at the knee during high-load tasks (20). Validation against imaging methods demonstrates strong criterion validity and test-retest reliability for sagittal-plane kinematics; however, both validity and reliability are reduced in the frontal and transverse planes, where soft-tissue artifact and marker placement error introduce larger systematic offsets (21). Despite its central role in advancing ACL biomechanics research, limitations including lengthy setup, high equipment costs, and reliance on skilled operators have restricted its translation into routine RTS assessment (19).

IMUs

IMUs use accelerometers, gyroscopes, and sometimes magnetometers to capture segment orientation and acceleration (11). They offer portability and the ability to monitor athletes outside the laboratory, and have been applied to longitudinal tracking of load, asymmetry, and stabilization after ACL injury (22). Validation studies indicate typical orientation errors of 2° to 5° root mean square (RMS) for simple, single joint motions, with accuracy declining for complex multi-degree-of-freedom tasks such as cutting or pivoting because of drift and sensor-fusion limitations (23). Additional challenges include magnetometer interference, frequent calibration, finite battery life, and the need for skilled interpretation (24). While IMUs extend biomechanics into field settings, these limitations reduce their reliability for high-stakes RTS decision-making.

Markerless motion capture: an emerging biomechanics technology

Markerless motion capture has accelerated in recent years thanks to advances in computer vision, camera quality, and program-based joint kinematic analysis (25). By reconstructing a virtual 3D skeletal model from synchronized video, these systems quantify joint kinematics without reflective markers. The result is faster setup, reduced operator burden, and ecological validity for use in clinics, training facilities, and even on-field RTS testing.

OpenCap represents the research-focused end of this spectrum (*Figure 1*). Using two or more iOS devices and a laptop, it provides a portable and affordable (<$1,000) platform, with data processed in the cloud to generate 3D kinematics (26). Validation studies show mixed accuracy: knee kinematics within 3° to 10° and frontal-plane hip measures within 6°, but sagittal-plane hip angles with errors exceeding 10° (14). It has demonstrated strong agreement in ACL-relevant tasks such as hopping and sit-to-stand, with setup times ~80% faster than marker-based systems and strong feasibility for large-scale, field-based studies (27). However, reliance on cloud processing introduces efficiency and privacy concerns; calibration is sensitive to the environment, and accuracy remains insufficient for high-stakes clinical decisions. OpenCap is therefore best positioned for education, pilot research, and large-scale data collection, rather than RTS clearance.

Theia3D, in contrast, has emerged as the leading clinical candidate among currently available markerless systems. This commercial system uses synchronized video cameras and deep learning to estimate joint centers and segment orientations. Validation studies demonstrate strong agreement with marker-based capture for sagittal plane movements such as walking, squatting, and running, with errors typically within 2° to 6°; larger discrepancies remain in frontal and transverse planes (19). Theia3D has also demonstrated concurrent validity for knee flexion-extension kinematics during selected dynamic athletic tasks, including landing, cutting, and change of direction drills, when compared with established marker-based systems (10,13). Reliability is encouraging but should be interpreted narrowly: intersession studies report intraclass correlation coefficients greater than 0.85 for sagittal plane kinematics during gait, supporting longitudinal monitoring for gait-

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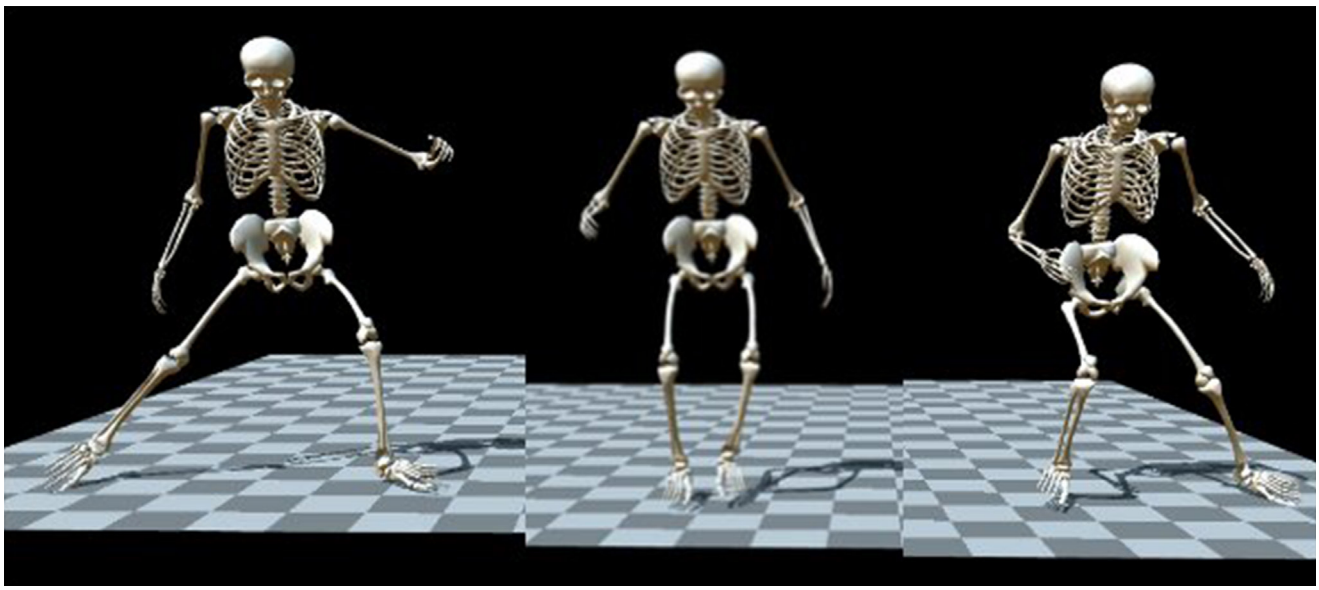


Figure 1 Three-dimensional skeletal model displayed in Visual3D software (C-Motion, Inc.) during a shuffle step on a basketball court, illustrating the type of markerless pose estimation output used in biomechanical analysis. Images are from the authors' original data collection.

based measures; however, reliability for sport-specific cutting, landing, and change of direction movements most relevant to ACL RTS assessment has not yet been fully established (20). Clinically, Theia3D has been applied in select sports medicine and rehabilitation settings to quantify hop asymmetries, altered trunk and hip control, and compensatory strategies in ACL-injured athletes, providing faster and less intrusive assessments than marker-based systems while preserving ecological validity. When paired with embedded force plates or instrumented insoles, kinetic parameters, including vertical ground reaction force symmetry and knee extension moment, can also be captured, providing a fuller picture of movement quality than kinematics alone. Limitations include higher costs than consumer-based platforms and reduced accuracy for transverse plane and frontal plane motions, but its reproducibility, resolution, and growing adoption in professional sports and health systems make it the current frontrunner for clinical integration.

With validation increasingly established for gait and simple functional tasks, though less so for dynamic, sport-specific, and multiplanar movements most relevant to RTS clearance, the next challenge is implementation. Markerless systems produce outputs directly relevant to RTS decision-making: joint angles, segment velocities, spatiotemporal measures, and, when paired with force plates or pressure insoles, joint kinetics (*Figure 2*) (12). These align with clinical priorities such as detecting landing asymmetries, quantifying knee flexion deficits, and monitoring trunk and hip mechanics. Pilot implementations from Ito *et al.* confirm feasibility in ACL RTS testing, though systematic offsets and reduced accuracy in multi-planar motions remain important limitations (28).

The greatest value of markerless systems lies in their ability to extend beyond traditional RTS benchmarks. Conventional criteria like hop distance or isokinetic strength symmetry provide only partial insight into recovery. By quantifying movement quality, markerless tools can identify compensatory strategies that persist even when athletes meet standard thresholds, such as reduced knee flexion, asymmetric loading, or abnormal trunk positioning (29). This additional layer of information enables more nuanced RTS decision-making, shifting the paradigm from a narrow focus on symmetry toward a multidimensional understanding of recovery.

Moreover, markerless systems support longitudinal tracking in ecologically valid environments. By deploying Theia3D in clinics or training facilities, ideally integrated with embedded force plates or instrumented insoles to capture kinetic data alongside kinematics, clinicians can follow an athlete's progress across rehabilitation phases without the burden of repeated laboratory visits.

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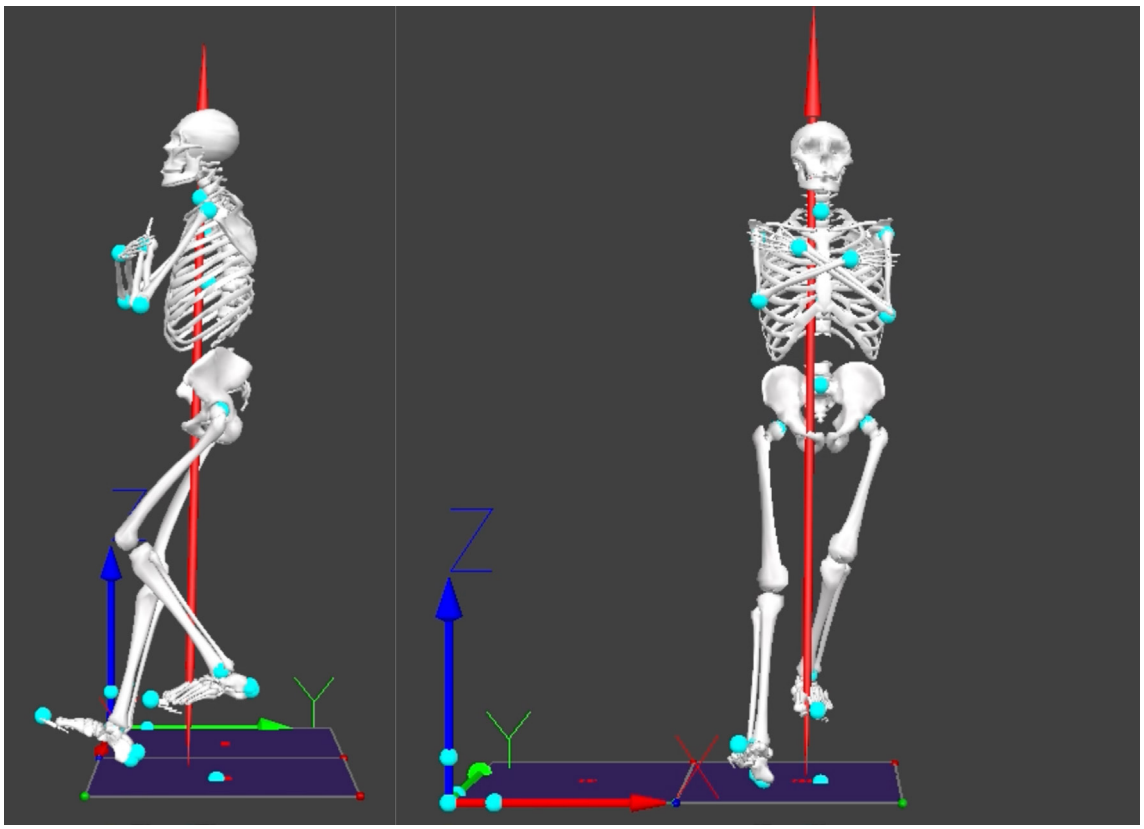


Figure 2 Theia3D skeletal display during a single leg step down test. The ground reaction force from the force plate is shown as a red vector and key points are shown as teal spheres. Images are from the authors' original data collection.

This continuity improves detection of subtle changes, helps distinguish genuine recovery from compensatory adaptation, and allows interventions to be tailored in real time. Looking forward, widespread adoption may also enable the creation of large-scale normative databases stratified by sport, sex, and competition level, addressing the long-standing gap of missing individualized baseline data. Integration with machine learning could further refine RTS decision-making, though predictive accuracy remains modest at present [area under the curve (AUC) ~0.63 in elite athletes] (30).

Markerless motion capture is no longer just a research tool but an emerging clinical solution. OpenCap expands access for research, education, and large-scale field testing, while Theia3D currently leads in clinical integration. Critically, clinicians must be aware that OpenCap's reported sagittal plane hip angle errors exceeding 10° represent a clinically meaningful limitation for ACL populations, given the central role of trunk and hip control in ACL injury mechanics and rehabilitation; use of OpenCap for high stakes hip kinematics assessment should therefore be approached with caution until accuracy is further improved. As validation improves and datasets mature, markerless motion capture is positioned to become a future standard in RTS decision-making for ACL-injured athletes, bridging the gap between biomechanics research and everyday clinical practice.

Clinical implementation pathways

Markerless motion capture is most powerful when translated into clinically actionable workflows. Theia3D is currently the stronger candidate for high-fidelity clinical integration, whereas OpenCap remains best suited for education, pilot research, and large-scale field testing because of its lower cost, portability, and cloud-based workflow. This distinction should not be interpreted as a definitive hierarchy; rather, it reflects the different tradeoffs between accessibility, measurement resolution, privacy considerations, and clinical infrastructure. Implementation requires clarity on which

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biomechanical parameters provide the most value, how they can be monitored during rehabilitation, and how they should be incorporated into RTS clearance decisions.

Dynamic knee valgus, reduced knee-flexion excursion, and excessive lateral trunk lean remain the three kinematic "red flags" after ACL reconstruction (31). King *et al.* demonstrated that athletes nine months post-op still showed significant between-limb differences in knee-abduction moments (a kinetic measure) and kinematic variables including internal rotation and flexion angles during change-of-direction tasks, while Poston *et al.* showed that combining trunk lean with knee valgus angle (both kinematic measures) improved the prospective identification of graft ruptures, with each additional 5° of combined motion nearly halving the risk (32,33). These subtle kinematic deviations are not captured by strength symmetry or hop-distance testing, yet they represent persistent neuromuscular deficits with direct clinical relevance that standard RTS criteria fail to detect (8).

Kinetics add a complementary dimension by quantifying how much load each limb bears. Wren *et al.* reported that athletes often mask deficits by unloading the surgical limb by 8% to 15% during hop tests, either favoring the non-operative side or underperforming bilaterally to appear symmetrical (8). High-speed motion capture paired with force plates has consistently shown reductions in peak knee-extension and abduction moments, implicating both quadriceps avoidance and frontal-plane motor-control deficits. Bjornsen *et al.* further demonstrated that vertical ground reaction force monitoring can guide athletes to restore symmetrical loading, underscoring how kinetic data complement kinematic assessment in providing a complete picture of limb-loading recovery (15).

Recovery timelines further complicate decision-making. While quadriceps strength symmetry may normalize between 6 and 12 months post-ACLR, kinematic and kinetic recovery follows a slower and variable trajectory. Dynamic valgus often plateaus at nine months, whereas knee-moment symmetry may lag another six months. Bakal *et al.* showed that even athletes seven months post-ACLR demonstrated reduced ground reaction forces and eccentric impulses in the reconstructed limb compared to the non-operative limb, indicating persistent offloading and asymmetric loading strategies that persist beyond traditional RTS milestones (34). These findings support the need for serial biomechanical testing rather than fixed-time benchmarks.

Thresholds for clearance are also evolving. The traditional ≤10% cutoff for limb symmetry has been shown to be overly simplistic, with studies linking quadriceps weakness and vertical ground reaction force asymmetries to functional deficits even when hop distance symmetry is achieved. Parameter-specific cutoffs have been proposed, including ≤10% for vertical ground reaction force (vGRF) and knee flexion moment, ≤5° for knee valgus, and ≤10% for muscle strength symmetry, to provide more precise and individualized decision-making metrics. It is important to acknowledge, however, that most of these thresholds were derived from general or recreational athlete populations; their direct applicability to high-level athletes, who may exhibit compensatory strategies at much finer margins and for whom the consequences of reinjury are particularly severe, requires further validation in elite-specific cohorts. In the absence of preinjury baseline data, which most athletes lack, these normative thresholds serve as approximate guides rather than definitive clearance criteria, and individual clinical judgment remains essential (35-37).

The future feedback potential of markerless systems extends their use beyond diagnostics into therapy (*Figure 3*). It is important to clarify that neither Theia3D nor OpenCap currently incorporates real-time biofeedback as a built-in feature. However, the evidence base for motion capture-guided feedback, established primarily with marker-based systems, provides conceptual support for integrating such capabilities into markerless workflows as the technology matures. Vasquez *et al.*, using marker-based motion capture, demonstrated that overlaying joint angle data during squats and drop jumps improved limb loading symmetry by 11% and knee flexion excursion by approximately 6° after only four sessions, while Calabrò *et al.* showed that projecting ground reaction force data allowed athletes to self-correct loading asymmetries within a single session (2,5). This type of immediate feedback may accelerate motor learning and increase athlete engagement by gamifying rehabilitation, but current evidence primarily reflects immediate within-session performance improvements. Long-term retention of these neuromuscular corrections through motor learning consolidation has not yet been rigorously established and represents an important direction for future research.

Longitudinal tracking also enables clinicians to identify when athletes plateau. Kinematic asymmetries often stabilize around nine months, but kinetic deficits may persist well beyond standard RTS milestones (32,34). Weekly or monthly monitoring can flag stalled progress, prompting targeted interventions such as velocity-based or multiplanar training to re-challenge the neuromuscular

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Figure 3 Example of a Theia3D markerless motion capture clinical setup with a skeleton overlay displayed on the subject. This figure illustrates the type of visual output that could support future feedback capable workflows, although Theia3D does not currently provide built-in real-time biofeedback.

system. This kind of objective, longitudinal biomechanical feedback replaces guesswork with data-driven progress tracking (28,29).

At Ochsner Health, a large, multi-site academic health system based in New Orleans, Louisiana, with dedicated sports medicine and orthopedic surgery programs, a structured Theia3D based RTS pathway has been implemented within a purpose-configured biomechanics laboratory. The setup consists of eight synchronized high-definition cameras using the Theia3D system arranged to capture a calibrated volume encompassing common sport-specific tasks, integrated with an embedded in-floor force plate to enable concurrent kinematic and kinetic analysis. This pathway combines clinical examination, strength testing, balance, and biomechanical assessments at 3, 6, 9, and 12 months (*Figure 4*). Tasks include squats, depth drops, countermovement jumps, and cutting drills. The protocol also incorporates sport-specific agility challenges, including the Vail Sports Cord Test, a resisted agility drill assessing dynamic cutting and deceleration mechanics, and the Reactive Balance Drill, which evaluates single-limb stabilization under perturbation conditions; both are designed to expose residual neuromuscular deficits not apparent during more controlled bilateral tasks. Clearance to the next stage of participation is contingent on parameter-specific cutoffs. Importantly, the process is continually reviewed and remains a work in progress; as more data are collected, both protocols and decision rules are refined. Patient-reported outcomes and tracking of reinjury and contralateral injury rates are integrated into this framework to ensure that biomechanical improvements translate into meaningful reductions in clinical risk and better long-term outcomes (*Figure 5*).

Looking ahead, widespread adoption of markerless systems could enable the creation of normative datasets stratified by sport, sex, and competitive level, filling the gap created by the absence of individualized baseline data. Integration with machine learning could further enhance the prediction of reinjury or performance outcomes, although current models remain modest in accuracy. As validation improves and datasets expand, markerless capture is poised to become not just a supplement but a cornerstone of RTS decision-making.

Challenges and limitations

Despite the promise of markerless motion capture technologies, several barriers remain before widespread

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Figure 4 Integration of Theia3D markerless motion capture into the clinical environment.

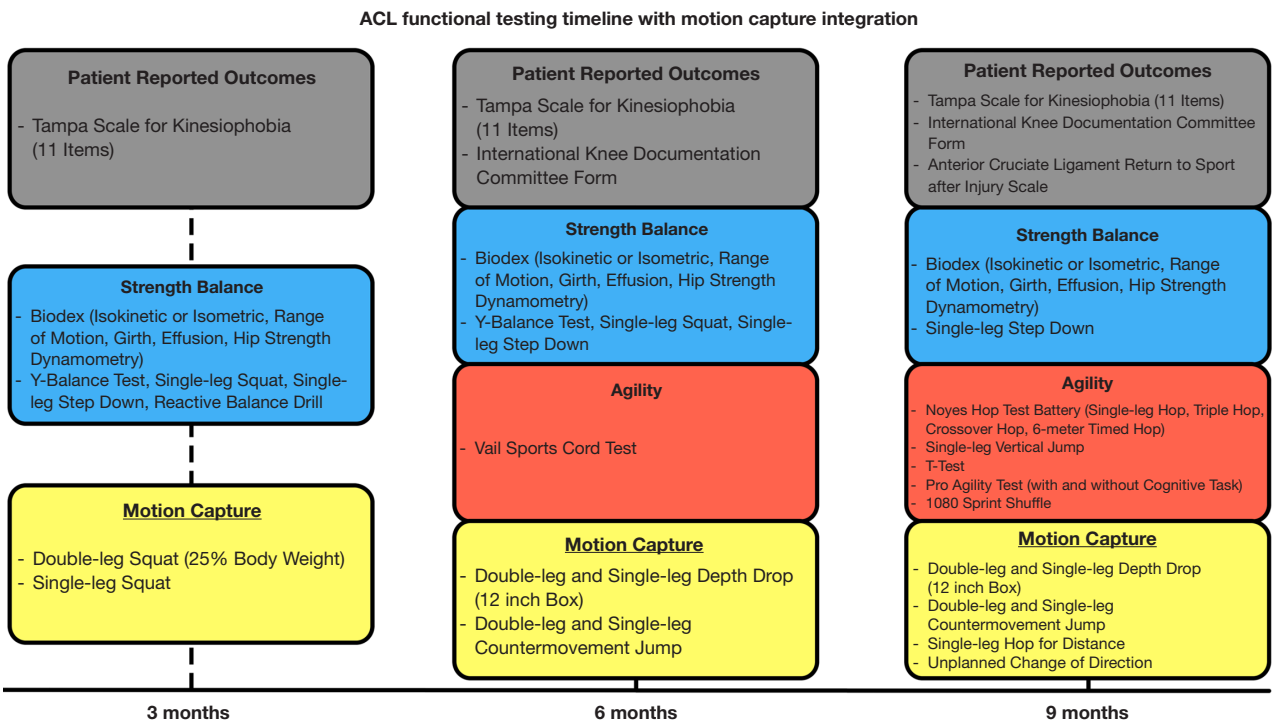


Figure 5 Clinical RTS workflow example. ACL, anterior cruciate ligament; RTS, return to sport.

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clinical adoption is feasible. Optical marker-based motion capture systems such as Vicon or Qualisys continue to represent the gold standard for accuracy, but installation, cameras, force plates, and software can exceed $150,000 to 250,000. This price is prohibitive for most clinics and community health systems. Markerless platforms dramatically reduce costs, with systems ranging from <$10,000 for smartphone-based setups to more comprehensive multi-camera solutions at higher price points. However, ongoing cloud-processing and licensing fees may accumulate over time, complicating long-term affordability.

Even simplified markerless systems demand technical expertise, including camera calibration, spatial stabilization of the capture volume, model scaling to individual body segments, and troubleshooting of occlusion or tracking failures. Early validation studies have shown that new users may require 30 to 60 minutes per athlete to set up and postprocess data (28). Interoperator variability can introduce errors of up to ±3° in joint angle kinematics, arising primarily from inconsistencies in camera placement and calibration, variability in subject positioning within the capture volume, and differences in operator-defined anatomical scaling of the skeletal model. These steps still rely on user judgment in current markerless pipelines despite increasing automation. Although training courses exist, onboarding requires substantial clinician time and can compete with busy clinical schedules.

Most validation studies to date involve small samples of healthy male athletes, limiting generalizability to higher-risk groups such as females, adolescents, and elite athletes. Larger, more inclusive datasets are beginning to emerge, but the field requires multicenter trials and broader representation before findings can be confidently applied across populations. Marker-based systems often require 20 to 30 minutes of data processing per athlete, while cloud-based markerless tools are faster but still limited by network speed. Clinics handling large athlete volumes may face bottlenecks, and cloud workflows raise concerns about compliance with the Health Insurance Portability and Accountability Act (HIPAA), the United States federal law governing the privacy and security of protected health information, as well as data de-identification and encryption standards.

Future directions

Several developments are poised to expand the clinical utility of markerless motion capture in ACL rehabilitation and RTS decision-making. Advances in deep learning now enable reconstruction of 3D joint kinematics and estimation of kinetics from as few as two smartphone cameras. For example, Turner *et al.* demonstrated a sagittal-plane knee-flexion error of ~4°, highlighting the feasibility of rapid, low-cost data collection (38). As algorithms mature, these pipelines may support scalable testing protocols that integrate directly into clinical practice. Commercial systems such as Theia3D continue to expand capabilities for multiplanar, high-speed movements in ecologically valid settings, bridging the gap between laboratory precision and real-world applicability.

Large-scale initiatives are a critical next step. Multi-site collaborations are being assembled to link markerless-derived kinematics and kinetics with reinjury and contralateral injury outcomes, alongside patient-reported outcomes, so that movement metrics can be tied to endpoints athletes and clinicians actually care about. As these datasets mature, software models should become more robust, enabling stronger links between movement profiles, reinjury risk, and performance. In parallel, community efforts to standardize capture protocols, reporting conventions, and deidentified data pipelines will improve cross-institution comparability and accelerate translation into RTS decision-making.

Conclusions

RTS decision making has shifted from subjective observation to multidimensional assessments integrating strength, movement quality, and neuromuscular control. While marker-based motion capture remains the gold standard, its prohibitive cost and technical burden limit accessibility. Markerless systems represent an important next frontier, offering improved feasibility, scalability, and integration into rehabilitation settings. Challenges remain, including cost, technical learning curves, limited validation in diverse populations, incomplete validation for sport-specific multiplanar tasks, and data processing inefficiencies. Yet these gaps are narrowing as technology evolves.

Future progress depends on standardizing capture and analysis protocols, broadening study populations, and linking biomechanical metrics to patient-reported outcomes and reinjury rates. Ultimately, markerless motion capture holds the potential to transform RTS decision-making. By providing objective, repeatable, and ecologically valid assessments, these technologies can move clinical practice

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closer to the goal of safe, individualized, and data-driven return to play pathways for athletes recovering from ACL injury.

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Footnote

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Ethical Statement: The authors are accountable for all aspects of the work in ensuring that questions related to the accuracy or integrity of any part of the work are appropriately investigated and resolved.

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