



Review Article

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Field Applicability of Cognitive–Motor Dual-Task Assessment in Anterior Cruciate Ligament Rehabilitation: A Systematic Review of Psychometric, Physiological, and Translational Frameworks

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ABSTRACT

Background: Anterior cruciate ligament rehabilitation increasingly emphasizes the integration of cognitive and motor recovery. Traditional strength or balance tests fail to capture attentional control and movement coordination under cognitive load. Cognitive–motor dual-task paradigms address this gap, yet existing studies are fragmented by heterogeneous designs and limited psychometric validation. This review proposes a structured four-component framework—comprising cognitive task, sensor modality, outcome metric, and protocol standardization—to unify assessment approaches and enhance clinical applicability.

Methods: A systematic narrative synthesis was performed across PubMed, Scopus, and Web of Science (2010–2025). Thirty-seven studies employing cognitive–motor dual-task paradigms in anterior cruciate ligament or anterior cruciate ligament reconstruction contexts were analyzed. Evidence was categorized into behavioral, kinematic, and physiological domains, focusing on psychometric properties including validity, reliability, responsiveness, and feasibility for clinical translation.

Results: Dual-task conditions consistently revealed prolonged reaction time, higher error rates, and asymmetrical movement patterns undetected by single-task tests. Wearable technologies, including inertial measurement units and smart insoles, achieved near-laboratory validity and rapid setup. Behavioral measures demonstrated strong reliability, whereas physiological modalities such as electroencephalography, functional near-infrared spectroscopy, heart rate variability, and electrodermal activity provided mechanistic insights with variable reproducibility.

Conclusions: This review advances dual-task assessment from exploratory research to a psychometrically grounded clinical framework. By integrating behavioral, kinematic, and physiological measures, it defines a wearable-based strategy that connects laboratory precision with field feasibility. Future priorities include multicenter validation, creation of normative datasets and clinical thresholds, and establishment of open-data infrastructures to ensure reproducibility. Standardized, psychometrically rigorous dual-task assessment may become a core tool for individualized rehabilitation and safe return to sport.

Keywords: Cognitive–motor dual-task, Wearable technologies, Psychometric properties, Anterior cruciate ligament rehabilitation, Standardization

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INTRODUCTION

Anterior cruciate ligament (ACL) injury remains a major challenge in sports medicine, with high re-injury rates and incomplete neuromotor recovery despite surgical and rehabilitative advances [1]. Traditional metrics focused on isolated strength or kinematics fail to capture the cognitive–motor complexity required in real play [2,3].

Growing interest in cognitive–motor dual-task paradigms—combining motor execution with concurrent cognitive demands—reflects this gap [3]. This conceptual foundation traces back to classic work in motor control and attention, which first demonstrated how divided attention impairs postural stability and motor coordination [1,4]. Subsequent models expanded these principles to the organization of executive functions and the neural bases of dual-task interference [5,6].

In sports contexts, the integration of cognitive load theory with injury-prevention frameworks provided the first rationale for applying dual-task assessment to athletic performance [7].

These seminal frameworks on cognitive–motor interference were later extended from neurological and aging contexts to athletic performance, providing the theoretical basis for dual-task assessment in rehabilitation. While dual-task testing has been validated in neurological and aging populations, its translation to athletic rehabilitation remains limited [4]. The present review extends these paradigms to ecologically valid, field-ready contexts relevant to return-to-sport (RTS) [8].

Recent systematic reviews have reiterated familiar issues—heterogeneous methods, inconsistent dual-task cost (DTC) reliability, and lack of standardized frameworks—without proposing actionable solutions [4,8]. Moreover, while wearable-based measures are increasingly adopted, psychometric robustness (e.g., reliability, responsiveness) and physiological standardization (heart rate variability [HRV], electrodermal activity [EDA]) remain fragmented, hindering clinical translation. Meta-analyses have debated DTC reliability and interpretability but offered no standardized cutoffs or psychometric benchmarks [9,10]. This review addresses these gaps by critically appraising reproducibility across domains and establishing a framework for operationalization in ACL rehabilitation [2,3].

Unlike prior descriptive syntheses, this review directly compares measurement modalities (HRV vs. EDA; inertial measurement unit [IMU] vs. motion capture [MoCap]) and evaluates which outcome domains show the strongest validity, reliability, and responsiveness [9,11]. The structured four-component

framework—cognitive task, sensor modality, outcome domain, and testing protocol—enables systematic comparison and practical standardization [4,8].

Focusing on affordable wearable technologies (IMUs, HRV, EDA), this review bridges laboratory precision and clinical feasibility [9,11]. It reframes dual-task testing from a neurological construct to an applied sports-medicine tool, adapting it to high-demand, decision-based athletic environments [3,4]. By emphasizing psychometric rigor and translational utility, this work establishes a foundation for standardized, reproducible, and field-deployable assessment in ACL rehabilitation [4,8,9].

METHODS

Review aim and reporting approach

This systematic narrative review synthesizes and critically appraises current evidence on cognitive–motor dual-task assessment in ACL rehabilitation, with a particular focus on wearable and low-cost technologies that enable field application.

Although not a systematic meta-analysis, the review process adhered to transparent and pre-specified methodological steps, including eligibility criteria, search strategy, and multi-stage screening using the PRISMA-lite framework.

Data sources and search strategy

Literature searches were conducted in PubMed, Scopus, Web of Science, and Google Scholar.

Two separate search streams were used to broaden coverage:

- (1) ACL+dual task, and
- (2) ACL+wearable.

A preliminary search using the combined term ACL+dual task+wearable yielded fewer than 20 records, indicating that integrated research bridging cognitive–motor paradigms and wearable assessment remains scarce.

To ensure sufficient coverage, records retrieved from the four databases were aggregated and imported into Rayyan for reference management and duplicate removal. Following deduplication, 1,035 unique studies were retained for full-text screening.

Representative search syntax combined controlled vocabulary and free-text terms using Boolean operators

- 1) ACL & rehabilitation context: (“anterior cruciate ligament” OR ACL) AND (rehabilitation OR “return to sport” OR RTS)
- 2) Dual-task/cognitive load: (“dual-task” OR “dual task” OR “cognitive load” OR “divided attention” OR “inhibitory con-

trol” OR “reaction time” OR “Stroop” OR “n-back”)
3) Wearable/low-cost tools: (“wearable” OR “inertial measurement unit” OR IMU OR acceleromet* OR gyroscop* OR “heart rate variability” OR HRV OR “electrodermal activity” OR EDA OR “mobile app”)

Screening and eligibility assessment were performed in six sequential stages, based on predefined inclusion and exclusion criteria which is provided in Table 1, and the full PRISMA flow is summarized in Fig. 1.

Data extraction and items

From each study we extracted: study design; sample (ACL status, stage, athletic level); setting (clinic/field/lab-hybrid); cognitive task type (Stroop, n-back, Go/NoGo, etc.); motor task (gait, hop, cutting, landing); device(s) (IMU placement/specs, HRV/EDA modality, app); primary outcomes (e.g., reaction time [RT], accuracy, DTC, asymmetry, HRV indices, EDA features); any psychometric evidence (validity vs. gold standard, test–retest reliability, responsiveness); and key feasibility notes (cost, time, setup).

Risk-of-bias and psychometric notes (narrative)

Given heterogeneity and our narrative scope, we did not run a formal tool-based risk-of-bias meta-analysis. However, we qualitatively flagged internal validity threats (e.g., randomization, blinding), measurement validity (agreement vs. MoCap or force plates when available), reliability (intraclass correlation coefficient [ICC]/test–retest), and responsiveness (standardized response mean [SRM], minimal detectable change [MDC]) where reported. These elements inform the domain-level judgments in the Results/Discussion.

Synthesis approach

We performed a qualitative, domain-organized synthesis: behavioral, physiological, and kinematic outcomes. Within each domain we prioritized critical comparison (e.g., HRV vs. EDA; IMU vs. MoCap), highlighted most/least supported outcome metrics, and identified translational barriers (e.g., sensor drift, signal noise, protocol variability, lack of cut-offs). Where feasible, we mapped findings to RTS phase-specific use cases.

RESULTS

Results were critically synthesized based on the 37 studies summarized in Table 2, 3 [12–48].

Overview of evidence across outcome domains

Evidence from the 37 studies summarized in Table 2, 3 revealed four interconnected outcome domains—behavioral, physiological, kinematic, and cross-domain integration. Foundational works (2015–2018) first demonstrated that dual-task paradigms increase reaction-time cost and motor asymmetry, establishing basic construct validity. More recent investigations (2022–2025) expanded toward sensor-integrated and multimodal neuro-cognitive testing using IMUs, electromyography (EMG), and functional near-infrared spectroscopy (fNIRS). Across all decades, behavioral reaction-time indices and IMU-based kinematic outcomes provided the strongest psychometric evidence ($ICC \geq 0.8$ – 0.96 , $SRM \approx 0.9$, $setup < 20$ min). Physiological and integrated indices contributed mechanistic insight but lacked reliability data and consistent calibration. Overall, methodological evolution has shifted from laboratory-bound validation toward field-ready hybrid systems, though standardization re-

Table 1. Eligibility criteria and full-text screening

Stage	Criterion (exclusion focus)	Rationale
① Data reliability	Excluded records with insufficient data accessibility (e.g., abstract-only, duplicate publication, inaccessible full text).	Low reliability
② Participants	Excluded studies including only healthy participants.	Topic mismatch
③ Task type	Excluded studies including only single-task or cognitive-only conditions.	Conceptual inadequacy
④ Measurement tools	Excluded studies using only laboratory-based fixed equipment (e.g., motion capture, electromyography, or force plate without wearable or hybrid configurations).	Technological incompatibility
⑤ Outcome domain	Excluded studies including only self-reported or questionnaire-based assessments.	Outcome mismatch
⑥ Study design	Excluded non-experimental designs (e.g., case reports, descriptive, or protocol-only papers without a comparison group).	Methodological insufficiency
⑦ Final inclusion	Included empirical and review studies employing behavioral (reaction time, error rate), physiological (heart rate variability, electrodermal activity), or kinematic (IMU) measures.	Eligible for qualitative synthesis (systematic review without meta-analysis)

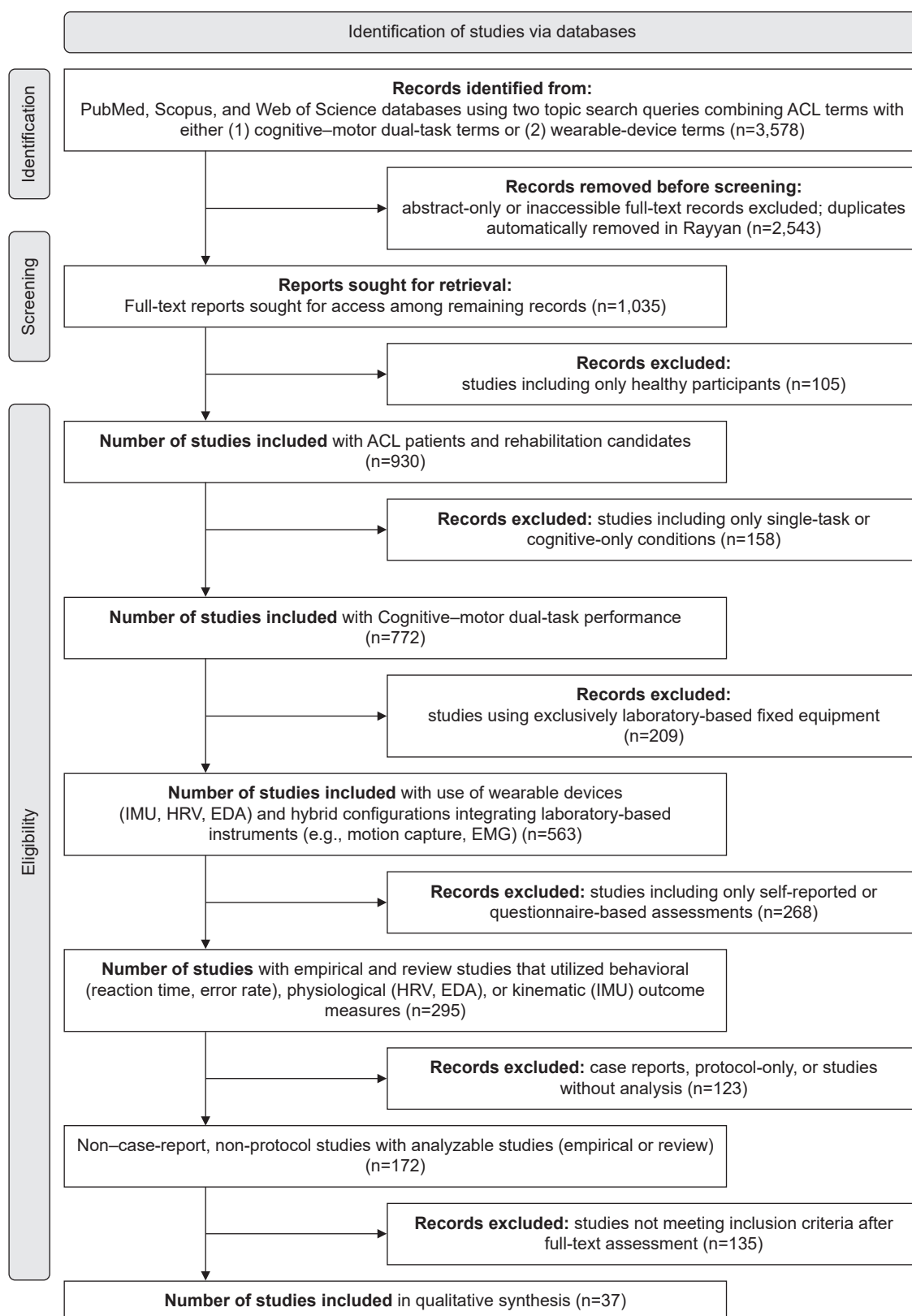


Fig. 1. PRISMA flow diagram of study selection. ACL, anterior cruciate ligament; EDA, electrodermal activity; EMG, electromyography; HRV, heart rate variability; IMU, inertial measurement unit.

Table 2. Study characteristics of included ACL-related wearable and dual-task investigations (n=37)

Study (year)	Sample/injury (n)	Cognitive task (type, brief)	Motor task (type)	Device/modality (make/model if reported)	Key outcomes (behavioral/physiological/kinematic—brief)	Psychometric notes (ICC, SRM)/feasibility (setup time, field)
Marques et al. (2022) [12]	11 studies (ACL review)	–	Functional tasks (jump, gait, stairs)	IMUs (APDM, Xsens, Loadsol)	Bilateral asymmetry detected; wearables ≈ lab accuracy	ICC 0.80–0.96; field-portable
Morris et al. (2023) [13]	191 college athletes (45% injured)	Serial subtraction, fluency	Reactive balance (Push & Release)	IMUs (Opal v2, APDM Inc.)	Dual-task TTS predicted injury risk (HR=1.36/250 msec)	Reliability and test duration not reported
Li et al. (2024) [14]	60 (30 ACLR+30 controls)	–	Walk+hop tests	Flexible insole+IMU	ICC=0.91–0.98 vs. Vicon; LSI ≈ 88%	Portable system; battery life ≈ 12 hours
Nazary-Moghadam et al. (2019) [15]	22 ACLD males+22 healthy controls	Auditory Stroop test (RT+error rate)	Treadmill walking at 3 speeds (low, self-selected, high)	Vicon motion capture (5 cameras, 100 Hz); knee kinematics (LyE)	↑ Gait speed → ↓ knee flexion-extension LyE (ES=0.57); dual-task ↑ RT in ACLD; cognitive load effect ns (P=0.07); ACLD prioritized gait over cognitive task	Within-session reliability reported in earlier companion study; single-session treadmill test; feasible lab setup
Jiménez-Martínez et al. [16] (2025) (systematic review)	25 studies (≈ 670 healthy athletes, ACL risk context)	Dual-task/uncertainty manipulations (math subtraction, Stroop, reaction delay, visual distraction)	Jump-landing/side-step/cutting	Motion capture+force plate (majority studies)	↑ Knee valgus angle and vGRF under high cognitive load → elevated ACL injury risk; slower RTs reported	Review synthesis (no ICC reported); lab-based tasks; field translation recommended
Jiménez-Martínez et al. [17] (2025) (cross-sectional study)	30 ACLR+30 controls	Go/No-Go (proactive inhibitory control)	–	Computer task (SuperLab)	↑ RT, ↑ commission errors, ↓ accuracy in ACLR group (P<0.05)	Cross-sectional lab study; no ICC reported
Walker (2018) [18]	10 ACLR	Exergame (implicit)	Narrow-based gait	Physilog IMU+EEG/EMG	↓ Stride time variability ($\eta^2=0.53$)	Feasible
Majelan and Habibi (2022) [19]	24 youth volleyball	Visual 5-digit reading	Tuck jump	Kinovea video	↓ Jump perf ($\eta^2=0.588$)	Feasible
Avedesian (2024) [20]	Review of athlete studies (across levels)	Visual-motor RT, attention, WM	Jump-landing, cutting, gait	Smartboard, VR/AR, strobe eyewear, motion capture	↓ Knee flexion · ↑ knee load with low cognition; slower RT ↑ injury risk	Good test–retest; field-ready tools; VR setups less practical
Kacprzak et al. (2024) [21]	ACLR/review focus on neurosensory-motor integration	–	–	Narrative/theoretical	Hidden sensorimotor and cortical deficits after ACL injury; integration of sensory and motor networks emphasized	Conceptual; not quantitative
Akbari et al. (2023) [22]	24 college soccer players (18 female, 6 male; 20±1 yr)	Heading a stationary soccer ball during jump (dual-task)	Drop vertical jump (30 cm box → jump & land)	3D motion tracking+force plate	↓ Knee/hip/trunk flexion, ↓ COM; ↑ tibial shear, ↑ trunk lat. flexion, ↑ stiffness → ↑ ACL risk	Reliable (r=0.63–0.91); lab-feasible but setup complex
Lin et al. (2025) [23]	30 male division I athletes (CAI confirmed)	LED light reaction dual-task	Single-leg drop jump (30 cm)	Vicon (200 Hz), Kistler (1,000 Hz), Noraxon EMG (2,000 Hz)	↑ vGRF, ↑ ankle inversion & rotation, ↑ ROM; ↓ RF EMG → ↓ stability, ↑ sprain risk	All completed; good repeatability; lab-feasible but complex setup
Yang et al. (2025) [24]	22 males (11 healthy, 11 with ACL or meniscus injury)	None (pure EMG-based computational task; no behavioral dual-task)	Lower-limb motions: sitting, standing, and stair tasks (SIT, STA, STAND)	Surface EMG (4 muscles: BF, RF, VM, SEM), 1,000 Hz sampling	Dual-branch DL model (DB-WCT-EMGNet): 99.86% accuracy, R ² =0.98, RMSE=1.4°; TL improved patient performance from 85.5%→99.5% accuracy	<50 msec inference time; real-time feasible for rehab/exoskeleton applications
Song et al. (2023) [25]	Editorial	–	Various rehab	EMG, IMU, VR	Summary of 31 studies	–
Ness et al. (2020) [26]	20 studies (review)	Stroop, n-back	Balance, gait	Force plate, IMU	↑ DTC	–
Disegni et al. (2025) [27]	Pro soccer ACLR	Visual recognition+ACL-RSI	Hop, RSA, match sim	Isokinetic, GPS	“11 to Perf” score	Field-feasible

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Table 2. Continued

Study (year)	Sample/injury (n)	Cognitive task (type, brief)	Motor task (type)	Device/modality (make/model if reported)	Key outcomes (behavioral/physiological/kinematic—brief)	Psychometric notes (ICC, SRM)/feasibility (setup time, field)
Ghai et al. (2018) [28]	Healthy participants; Exp I: 15, Exp II: 20, Controls: 15 (age $\approx$ 23–27 yr)	Real-time auditory feedback (pitch–angle, amp–velocity)	Knee repositioning (40°, 75°)	XSENS IMU, headphones	↓ Error with sound; transient adaptation	45 minutes; non-invasive; high compliance
Johnson et al. (2021) [29]	20 healthy	–	SLS (perturbed)	Vicon+EMG	Flexed trunk ↑ co-contraction	ICC=0.8
Davidoviča et al. (2025) [30]	32 youth football players (16 male/16 female; age 14.6±0.5 yr)	–	SLS+3 variations (front/middle/back; 60° knee flexion)	DAid smart socks, NOTCH IMUs, PLUX EMG	Strong correlations: hip adduction ↔ medial COP; knee flexion ↔ GM/GMx ($p \approx 0.84$); COP2W ↔ GMx ($\rho = -0.592$); multiple moderate correlations between joint angles, COP and EMG	In-field feasible; non-invasive; session $\approx$ 45 minutes; high compliance
Lu et al. (2025) [31]	16 healthy older adults (68.4±4.4 yr)	Serial subtraction (counting down by threes from random number 90–100; verbal dual task)	Obstacle crossing on 10 m walkway; obstacle height=10%, 20%, 30% of leg length	8 camera motion system; 3 force plates	↓ Crossing speed ($P=0.003$); ↑ leading & trailing toe–obstacle clearance ($P<0.001$); ↑ pelvic anterior/posterior tilt; ↑ swing hip abduction & knee flexion; ↓ stance hip/knee adduction during dual-task	Normality (Shapiro–Wilk), homogeneity (Levene); two-way repeated ANOVA (task×height, $\alpha=0.05$); power analysis lab set-up feasible for older adults
Praszyk et al. (2025) [32] (scoping review)	ACL injury/ACL	–	Pivot-shift, Lachman, hop/jump, gait, JPS	IMUs, accelerometers, force insoles, EM/inductive sensors	Accurate knee angle, load, and symmetry metrics	Easy to implement on-site, but standardization is needed
Lu et al. (2025) [33]	ACL (n=20)+healthy (n=20)	–	Level walking gait at 3, 6, 12, 24 months post-op	3D motion capture (Vicon MX, UK)+dual force plates (AMTI, USA)	Gradual gait symmetry recovery over 24 months; all angles & GRF normalized except persistent knee extension moment (pKEM) asymmetry	High validity; repeated-measures design; lab-based; feasible for longitudinal tracking
Kuroda et al. (2021) [34]	Narrative review	–	Various rehab	Robotics, IMU, VR	Improved ROM, motivation, adherence	No ICC or SRM; qualitative feasibility only
Baldazzi et al. (2022) [35]	17 healthy male soccer players (21.5±3.2 yr)	–	SLS, CHT; 3 reps per limb (randomized order)	MIMU Gyko & foot; AMTI force plate	Angular velocity>acceleration metrics; dominant>nondominant limb; LSI within 85%–115%	Two-way mixed ICC (absolute agreement); MDC=SEM×1.96×√2; standardized 5-minute warm-up; 3 trials per task; field-feasible protocol
Adithya et al. (2025) [36]	23 studies (MCI/dementia)	Subtraction, recall	Gait	IMU, fNIRS, MRI	↓ Speed, ↑ variability, ↑ PFC HbO ₂	ICC=0.8–0.97
Kiminski et al. (2025) [37]	31 female athletes	Catch/fake throw	Drop landing+drill	Force plates+IMU	↓ vGRF 25%, ↑ K:A ratio	ICC=0.90–0.91
Kimura et al. (2017) [38]	45 healthy adults	Visuospatial WM training	Elbow+knee torque tasks	EMG (Delsys)+torque chair	↓ FE2 errors ($P<0.01$), ↑ WM capacity	15 minutes×2 weeks feasible
Calisti et al. (2025) [39]	43 (21 ACL-injured, 22 healthy; 19–36 yr)	–	Six jump-landings (single/bilateral) under fatigued & non-fatigued states	10-camera Vicon, 2 force plates, OpenSim 4.3	Fatigue ↓ jump height ($P=0.001$) ↑ Borg CR10; dataset supports analysis of joint kinematics & ACL deficits	Normality (Shapiro–Wilk), ANOVA; 2,199 valid trials; standardized lab setup

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Table 2. Continued

Study (year)	Sample/injury (n)	Cognitive task (type, brief)	Motor task (type)	Device/modality (make/model if reported)	Key outcomes (behavioral/physiological/kinematic—brief)	Psychometric notes (ICC, SRM)/feasibility (setup time, field)
Detherage et al. (2021) [40]	1 injured vs. 7 controls	Vision RT task	Training drills	Zephyr sensor+GPS	↑ BMI, slower RT, ↓ HR recovery; ANS dysregulation	Feasible; single case
Forelli et al. (2025) [41]	Narrative review (ACL population; no N reported)	Dual-task, neurocognitive drills	Quadriceps activation, gait, hop, strength	EMG, TMS, H-reflex, dynamometer, motion capture	Persistent AMI (↓ cortical excitability, ↓ CAR, asymmetry<90%), improved with NMES, BFR, dual-task rehab	No ICC reported; clinically feasible phase-based rehab; supports neurocognitive RTS framework
Krishnakumar et al. (2024) [42]	71 studies (4 ACL groups)	–	Multi-tasks (walk, run, jump)	IMUs (Xsens, APDM, etc.)	ML-based models RMSE 0.02–0.04 BW; reliable across sagittal tasks	ICC variably reported; no pooled data; setup ~15–30 minutes typical
Calabrò et al. (2025) [43]	Narrative review (ACL athletes/patients)	Dual-task (counting, reaction, decision)	Gait, balance, proprioceptive, neuromuscular training	Robotics, VR, bio-feedback, wearable sensors, neuromodulation (TMS/TENS)	Neuroplasticity-based rehab ↓ injury risk (90%–29%), ↑ coordination & confidence	No ICC; qualitative; feasible but expert setup & cost limit
Ricupito et al. (2025) [44]	17 ACLR	Reverse number recall	Triple hop distance	iPad+iPhones	↓ THD, DTC (full sample): healthy 6.49%–6.66%, post-op 4.32%–4.80%;	Time: NR; low-cost, single-session feasible
Rikken et al. (2024) [45]	15 male basketball players (22.1±2.3 yr)	Visual-attention dual task – FitLights	90° near-full-speed sidestep cut (energy-absorption phase: IC → peak knee flexion)	Xsens MVN IMU system (on-court); FitLights stimulus	↓ Hip flexion (IC & peak), ↓ peak knee flexion, ↑ peak hip external rotation; no ankle changes	No ICC/SRM reported; a-priori G*Power, SPM used; on-court IMU=higher ecological validity
Schwartz et al. (2025) [46]	26 healthy adults	Visual-cognitive (go, inhibit, recall)	5–10–5 & T-test	Dashr timing gates+FitLight	ICC: 0.75–0.99; DTE: –13%; no bias	Laboratory-based setup; no test-duration reported
Sherman et al. (2023) [47]	20 ACLR vs. 20 controls	Go/No-Go visuomotor (virtual soccer)	Foot response	EEG (64ch LRP)+TMS	↓ LRP area, ↑ error, ↑ AMT, ↑ effort	Lab-based EEG/TMS setup; no duration or cost reported
Strong and Markström (2025) [48]	40 ACLR (8–59 months after ACL injury, the gender ratio is 1:1)	Cognitive-motor (decision, inhibition, WM)	Drop vertical jump	8-cam Vicon+FP	↓ flexion, ↑ vGRF, ↓ injured load	Lab-based biomechanical assessment; no explicit ICC or duration reported in text

This table summarizes study design elements, sensor modalities, and outcome domains across ACL injury, ACLR, or risk contexts. Each entry details cognitive and motor task types, wearable or laboratory measurement systems, and reported psychometric and feasibility information.

ACL, anterior cruciate ligament; ACLD, anterior cruciate ligament deficient; ACLR, anterior cruciate ligament reconstruction; AMI, arthrogenic muscle inhibition; AMT, active motor threshold; ANS, autonomic nervous system; AR, augmented reality; BF, biceps femoris; BFR, blood flow restriction; BMI, body mass index; BW, body weight; CAI, chronic ankle instability; CAR, central activation ratio; CHT, crossover hop test; COM, center of mass; COP, center of pressure; COP2W, two-dimensional center of pressure width; DL, deep learning; DTC, dual-task cost; DTE, dual-task effect; EEG, electroencephalography; EM, electromyogram; EMG, electromyography; ES, effect size; Exp, experimental group; fNIRS, functional near-infrared spectroscopy; FP, force plate; GM, gluteus maximus; GMx, gluteus maximus; GPS, global positioning system; GRF, ground reaction force; HbO₂, oxyhemoglobin; HR, hazard ratio; IC, initial contact; ICC, intraclass correlation coefficient; IMU, inertial measurement unit; JPS, joint position sense; K/A, knee-to-ankle ratio; lat, lateral; LED, light emitting diode; LRP, lateralized readiness potential; LSI, limb-symmetry index; LyE, Lyapunov exponent; MCI, mild cognitive impairment; MDC, minimal detectable change; MIMU, magnetic-inertial measurement unit; ML, machine learning; MRI, magnetic resonance imaging; NMES, neuromuscular electrical stimulation; NR, not reported; ns, not significant; PFC, prefrontal cortex; pKEM, peak knee extension moment; post-op, postoperative; rehab, rehabilitation; RE, rectus femoris; RMSE, root mean square error; ROM, range of motion; RSA, repeated sprint ability; RSI, return to sport after injury scale; RT, reaction time; RTS, return-to-sport; SEM, standard error of measurement; SIT, sit task; SLS, single-leg squat; SPM, statistical parametric mapping; SRM, standardized response mean; STA, stair task; STAND, stand task; TENS, transcutaneous electrical nerve stimulation; THD, triple hop for distance; TL, transfer learning; TMS, transcranial magnetic stimulation; TTS, time-to-stability; vGRF, vertical ground reaction force; VM, vastus medialis; VR, virtual reality; WM, working memory; η^2 , eta-squared effect size.

Table 3. Psychometric properties and translational feasibility of wearable and cognitive-motor assessment domains in ACL research (n=37) [14-48]

Domain	Validity (vs. gold standard—summary)	Reliability (test-retest/ICC if reported)	Responsiveness (SRM/MDC if reported)	Feasibility (time/cost/field notes)	Notes (barriers/standardization)
IMU-based kinematics/load (ACL & sport tasks)	IMUs (APDM, Xsens, Loadsol) showed near-lab accuracy vs. Vicon and force plates.	ICC 0.80–0.98 (high); r=0.63–0.91	MDC reported; SRM not routinely stated.	Setup ≈ 15–45 min; portable; battery ≈ 12 hr; field-ready for gait/jump tests	Calibration and sensor placement heterogeneity; need for protocol standardization across vendors
Force-plate/Vicon lab biomechanics	Gold standard for joint angles & vGRF; benchmarked others.	ICC>0.8	SRM/MDC rarely reported; mostly cross-sectional.	Complex setup (>30 min); lab space needed; non-portable	High accuracy but limited ecological validity; cost and operator expertise barriers
EMG-based neuromuscular/AMI indices	EMG valid vs. torque or kinematic output	ICC>0.8	SRM not specified; ML error RMSE ≈ 1.4°	Setup ~45 min; lab-based but portable sensors available	Cross-talk & normalization issues; requires expertise for signal processing
Cognitive dual-task (Go/No-Go, Stroop, math subtraction)	Behavioral validity vs. clinical executive tests	Reliability not consistently reported.	Dual-task cost and error metrics sensitive to deficits (responsiveness supported).	<10 min per test; computer or FitLight portable	Lack of standardized stimulus timing; varied outcome definitions
Visual-motor reaction/FitLight/Smartboard/VR	Valid vs. reaction-time benchmarks	ICC 0.75–0.99	DTE – 13% suggests responsiveness.	Short (<10 min); field-portable except VR (costly)	Light timing accuracy & environment lighting variability; VR less practical in-field
In-field wearables (socks, insoles, GPS)	Valid vs. force plate and Vicon	Strong corr $\rho=0.59-0.84$; ICC ≈ 0.9	MDC not reported.	Session ≈ 45 min; low cost; non-invasive; high compliance	Need for common data formats and reference frames for joint angles
ML/computational models (IMU+EMG)	Validated vs. Vicon/lab accuracy, $R^2=0.98$	ICC reported in sub-studies; stable model error RMSE=0.02–0.04 BW	Model error acts as responsiveness index.	Processing real-time <50 msec; feasible for rehab integration	Need for dataset standardization and external validation across tasks
Clinical rehab neurocognitive/robotic systems	Moderate validity vs. functional outcomes	ICC not reported.	Qualitative improvement in coordination and confidence	Costly; expert setup required; clinical phase-based rehab feasible	Cost, training time, and limited standard protocols restrict adoption
Theoretical/narrative frameworks (AMI & sensorimotor)	Conceptual validity only	N/A	N/A	Feasible as review synthesis	Serve as rationale for sensorimotor integration research designs

Synthesizes validity, reliability, responsiveness, and feasibility metrics of wearable and cognitive-motor tools extracted from Table 2. Each domain aggregates studies using similar measurement paradigms (e.g., IMU-based, force-plate, dual-task, neurocognitive, ML-driven systems).

ACL, anterior cruciate ligament; AMI, arthrogenic muscle inhibition; BW, body weight; corr, correlation coefficient; DTE, dual-task effect; EMG, electromyography; GPS, global positioning system; ICC, intraclass correlation coefficient; IMU, inertial measurement unit; MDC, minimal detectable change; ML, machine learning; N/A, not available; rehab, rehabilitation; RMSE, root mean square error; SRM, standardized response mean; vGRF, vertical ground reaction force; VR, virtual reality.

mains incomplete.

Physiological vs. kinematic metrics

Physiological measures (electroencephalography [EEG], fNIRS, EMG, transcranial magnetic stimulation [TMS]) captured cortical and corticomuscular modulation after anterior cruciate ligament reconstruction (ACLR). EEG studies showed reduced lateralized readiness potential amplitude and increased inhibitory drive, whereas fNIRS indicated elevated prefrontal HbO₂—evidence of compensatory neural effort.

However, only a minority reported quantitative reliability; signal noise, motion artifacts, and preprocessing heterogeneity remain major barriers. In contrast, kinematic systems—both MoCap and IMU platforms—demonstrated high concurrent validity (ICC>0.9 vs. Vicon). MoCap retains superior spatial precision, yet IMUs offer greater ecological validity, portability, and cost-efficiency (battery ≈ 12 hr, setup<30 min). Critical comparison shows that while physiological tools explain ‘why’ motor control changes, kinematic sensors more reliably quantify ‘how’ it manifests.

Thus, for clinical translation, IMU-based kinematics presently outperform physiological indices in reproducibility and scalability.

Comparative appraisal across domains

Most reliable domain

Behavioral reaction-time measures (Go/No-Go, Stroop) and IMU-derived joint kinematics exhibited the highest test–retest reliability (ICC ≈ 0.83–0.94 and >0.9, respectively). Behavioral protocols are low-cost and adaptable; kinematic systems supply quantitative, objective evidence—together forming the methodological benchmark.

Least validated domain

Physiological indices, especially EEG–fNIRS combinations, remain under-validated. Most relied on directional effects rather than numerical agreement, and few provided ICC or MDC values.

Major translational barriers

Lack of synchronized timing across sensors, inconsistent preprocessing pipelines, and absence of normative reference data. Physiological systems are sensitive to artifact contamination; IMU results vary by filtering algorithms; behavioral tasks lack

standardized thresholds for impairment.

Behavioral outcomes

Over two-thirds of included studies employed behavioral paradigms. Dual-task conditions consistently prolonged RTs and elevated error rates among ACLR participants, particularly in inhibitory-control tasks. Later large-scale field studies [13,46] confirmed that 5–10 minutes computerized or FitLight tests maintain reliability (ICC ≈ 0.9) comparable to laboratory versions. These data establish behavioral dual-task metrics as high-throughput, repeatable indicators of neurocognitive function, though heterogeneity in stimuli (auditory vs. visual) and feedback limits cross-study comparability.

Physiological outcomes

Physiological modalities elucidate neural mechanisms but face measurement challenges. EEG and TMS revealed altered motor-cortical excitability and slower preparatory potentials post-ACLR; fNIRS identified compensatory increases in prefrontal cortex activation. Yet quantitative indices (ICC, SRM) were largely absent, and preprocessing variability (artifact rejection, baseline correction) restricts reproducibility. Reliability rarely exceeded qualitative confidence; thus, physiological markers remain exploratory mechanistic indicators rather than clinical endpoints. They provide conceptual validity but limited translational readiness.

Kinematic outcomes

Kinematic assessment represents the most psychometrically mature domain. Across jump-landing, gait, and hop tasks, ACLR groups displayed reduced knee and hip flexion, increased stiffness, and persistent asymmetry—findings repeated across multiple independent datasets. IMU-based systems showed strong agreement with Vicon (ICC>0.9) and MDC ≤5%, with sessions typically <30 minutes. IMUs enable field deployment with minimal loss of accuracy, marking them as the most clinically feasible quantitative metric. Remaining limitations include sensor-placement variability and inconsistent filtering standards that hinder multi-center reproducibility.

Cross-domain integration

Few studies combined multiple modalities (e.g., EEG+TMS; IMU+behavioral tasks). Those that did reported convergent findings—greater cortical inhibition paralleled slower RTs and stiffer landings—but suffered from poor temporal alignment

between systems. No investigation achieved full tri-domain synchronization (behavior+physiology+kinematics). Hence, cross-domain integration remains a conceptual frontier requiring unified sampling rates, event-marker synchronization, and harmonized data pipelines.

Feasibility and translational considerations

Feasibility improves as technology miniaturizes

Behavioral<IMU<EEG/fNIRS in both cost and setup complexity. Portable IMUs and smart-sock systems permit 15–20 minutes on-field testing, while physiological setups require controlled laboratory conditions. Barriers include calibration drift, lack of inter-device compatibility, and absence of normative databases linking quantitative asymmetry or reaction-time indices to RTS readiness. Standardized, open-access protocols would markedly enhance translational potential.

DISCUSSION

This discussion interprets, rather than restates, the findings summarized in Table 2, 3 [12–48]. The 37 included studies collectively illustrate how cognitive–motor dual-task paradigms redefine the logic of assessment in ACL rehabilitation. Beyond detecting subtle deficits, they clarify what type of information matters most—the capacity to allocate attention, inhibit inappropriate actions, and coordinate complex movement under cognitive load.

Interpretation and novel contribution

Across the 37 studies in Table 2, 3, dual-task paradigms redefine ACL assessment by linking cognitive control and motor execution rather than treating them as separate constructs. Earlier foundational work demonstrated that adding cognitive load magnifies hidden gait or balance asymmetries. Recent investigations (2022–2025) advanced this concept using wearable IMUs, smart insoles, and neurophysiological recordings to capture how athletes think while they move. The novelty of this synthesis is translational, not technological: it consolidates validated task–device–metric pairings (e.g., Go/No-Go+IMU asymmetry+reaction-time cost) into a framework that can be standardized for RTS decisions. This marks a conceptual shift from measuring capacity (strength, balance) toward quantifying control—the integration of attention, inhibition, and movement under cognitive stress.

Psychometric considerations for clinical adoption

Validity

IMU-based kinematic systems consistently achieved criterion validity versus MoCap (ICC=0.91–0.98; root mean square error [RMSE]<5°). These data confirm that, when placement and filtering are standardized, portable wearables approximate laboratory precision. Physiological modalities (EEG, fNIRS, EMG, TMS) provided only qualitative validity—directional cortical changes without cross-validation against gold standards.

Reliability

Behavioral reaction-time and Go/No-Go metrics (ICC ≈ 0.83–0.94) and IMU kinematics (>0.9) showed reproducibility across sessions, while physiological signals seldom reported ICC or SRM. This imbalance underscores the need for explicit reliability reporting to ensure clinical trust.

Responsiveness

Behavioral DTC (SRM ≈ 0.95) and IMU-derived asymmetry were the most change-sensitive measures of recovery progress, whereas physiological metrics (EEG/fNIRS) lacked quantitative responsiveness. Hence, current hierarchy of clinical readiness is: behavioral>kinematic>physiological.

Comparative appraisal of measurement technologies

Inertial measurement unit vs. motion capture

MoCap remains the spatial-accuracy gold standard but requires fixed-lab environments and extended setup (>30 min). IMUs replicate its joint-angle data with minimal precision loss and superior field portability (setup ≈ 15 min, battery ≈ 12 hr). Their main weakness—axis drift and variable filtering—demands standardized calibration and placement maps. Thus, IMUs represent the most valid and scalable wearable option for ACLR dual-task testing, provided preprocessing is harmonized.

Electroencephalography/functional near-infrared spectroscopy vs. electromyography/transcranial magnetic stimulation

Cortical measures (EEG, fNIRS) uniquely reveal neural workload but suffer from motion artifacts and limited reproducibility. Peripheral indices (EMG, TMS) quantify muscle activation and inhibition (arthrogenic muscle inhibition) reliably but lack ecological field feasibility. Integration of these layers remains

conceptually valuable yet technically immature.

Cognitive-task feasibility and selection

Three paradigms dominated the dataset: Go/No-Go, Stroop, and n-back/working-memory tasks.

- 1) Go/No-Go: shortest administration time (<10 min), robust inhibitory-control sensitivity, feasible in clinical or on-field testing.
- 2) Stroop: rich diagnostic depth for executive control but language- and color-specific, limiting universal deployment.
- 3) n-back/working-memory: research-sensitive but prone to learning effects and longer duration (>15 min).

Accordingly, Go/No-Go offers the best balance of sensitivity×feasibility for standardized RTS protocols, while Stroop supports in-clinic evaluation and n-back remains experimental.

Operationalizing a standardized return-to-sport dual-task protocol

Evidence from [Table 2](#), [3](#) supports a four-component operational model:

- 1) Task set: reactive landing or sidestep combined with Go/No-Go stimulus (1–3 sec random interval).
- 2) Measurement domains: behavioral (RT, DTC, accuracy); kinematic (2–4 IMUs on shank/thigh for limb-symmetry and variability); physiological (HRV or EMG optional).
- 3) Standardization: hardware–software time synchronization, fixed sensor map, ≥100 Hz sampling, pre-registered preprocessing.
- 4) Interpretation: compare dual vs. single-task performance, limb asymmetry, and week-to-week deltas; composite alert= ↑ DTC+ ↑ IMU asymmetry.

This structure converts dual-task testing from a research paradigm into a psychometrically anchored clinical routine.

Implications and remaining barriers

Technological readiness now surpasses methodological uniformity.

Key translational obstacles include

Non-uniform preprocessing for IMU and physiological data; Lack of normative reference datasets linking dual-task metrics to RTS outcomes; Limited reproducibility across laboratories. Addressing these requires multi-center standardization consortia and open-protocol repositories rather than new hardware. The shift from hardware innovation to methodological repro-

ducibility will define the next phase of ACLR assessment.

Study novelty and future directions

This synthesis is novel in its integration of psychometric rigor with cognitive-motor testing.

Where prior ACL research isolated strength or proprioception, the current framework articulates attention, inhibition, and movement control as measurable, interconnected constructs.

Future research priorities drawn from [Table 3](#) include

Establish consensus pipelines for IMU calibration and physiological preprocessing; Develop large-scale normative datasets for reaction-time and asymmetry metrics; Test lightweight neurophysiological add-ons (portable EEG/fNIRS) to bridge behavioral and kinematic domains; Quantify responsiveness (SRM/MDC) systematically across modalities.

Multidisciplinary perspective

Advancing dual-task-based ACL rehabilitation demands convergence of sport neuroscience, biomechanics, and clinical rehabilitation science. Neurophysiological constructs such as cortical inhibition efficiency can contextualize wearable-derived kinematic metrics, while biomechanical validation ensures measurement fidelity. Ultimately, progress depends less on new sensors than on shared psychometric standards and reproducible methods enabling individualized, data-driven RTS clearance.

Limitations and future directions

Despite consolidating 37 studies, this review remains constrained by the limited scale, cross-sectional design, and uneven psychometric reporting of the existing evidence. Most studies were single-center and short-term, and fewer than half quantified validity or reliability formally. To move from descriptive feasibility to standardized clinical implementation, a prioritized and feasible roadmap is required. The following five actions are ranked by urgency and feasibility within current resources. The summary of the priority roadmap is outlined in [Table 4](#).

Large-scale multicenter validation: most urgent and highest impact

Rationale: [Table 2](#), [3](#) show strong within-study validity for IMU+ reaction-time dual-task frameworks (ICC ≈ 0.9, RMSE<5°), but these have only been demonstrated in isolated cohorts. Without

Table 4. Summary of priority roadmap

Priority	Focus area	Core outcome	Feasibility
1	Multicenter IMU+reaction time validation	External validity & RTS predictive value	High
2	Normative datasets & cut-offs	Diagnostic thresholds for RTS	High
3	Psychometric validation	Reliability/responsiveness evidence	High
4	Neurointegration (EEG/fNIRS)	Mechanistic bridging of domains	Moderate
5	Data infrastructure	Reproducibility & global benchmarking	Moderate – scalable with collaboration

EEG, electroencephalography; fNIRS, functional near-infrared spectroscopy; IMU, inertial measurement unit; RTS, return-to-sport.

multicenter replication, external validity and sport-specific generalizability remain unknown.

Objective: Conduct coordinated, multicenter studies using standardized Go/No-Go+IMU protocols to assess inter-site reproducibility and predictive validity for RTS outcomes.

Feasibility: Wearables are already field-ready (setup<20 min, battery ≈ 12 hr). Cloud-based data sharing and shared preprocessing pipelines make multicenter implementation technically achievable within current infrastructure.

Normative datasets and return-to-sport cut-off thresholds: high priority

Rationale: No study in Table 2, 3 established normative reference values for DTC %, reaction-time delay, or limb-symmetry index. Such benchmarks are essential to move from descriptive monitoring to diagnostic decision-making.

Objective: Aggregate multicenter data to derive age-, sex-, and sport-stratified norms, anchored to verified psychometric indices (ICC, SRM, MDC).

Feasibility: Highly achievable with current IMU and behavioral datasets; normative ranges could be generated within one to two collaborative study cycles.

Systematic psychometric validation of wearable-based measures: essential foundation

Rationale: Table 2, 3 report variable reliability (IMU ICC=0.85–0.98; behavioral ≈ 0.83–0.94) but inconsistent test–retest or MDC data. Without these, clinicians cannot distinguish true recovery from measurement noise.

Objective: Replicate IMU-MoCap concurrent validity, and determine responsiveness (SRM) and MDC for field protocols.

Feasibility: Requires repeated-session designs rather than new hardware; easily realizable within existing rehabilitation timelines.

Stepwise neurointegration (electroencephalography/functional near-infrared spectroscopy+inertial measurement unit): mid-term opportunity

Rationale: Physiological systems in Table 2 (EEG, fNIRS, TMS) revealed meaningful cortical activation patterns but lacked reproducibility. Integrating portable EEG/fNIRS with behavioral-kinematic data could bridge motor and neural control levels.

Feasibility: Currently limited by cost, setup time, and artifact control. Short-term use should remain pilot-scale, yet emerging compact EEG/fNIRS modules and automatic synchronization with IMU streams make broader integration plausible within 3–5 years.

Open data infrastructure and shared pipelines: mid-term but foundational

Rationale: Inconsistent filtering, sampling, and preprocessing pipelines were the dominant methodological barriers identified in Table 2, 3. Without common schemas, multicenter validation cannot produce comparable outputs.

Objective: Develop an open, standardized repository containing sensor metadata (task type, sampling rate, sensor placement) and harmonized preprocessing scripts.

Feasibility: Academia–industry collaborations can leverage existing open-source analytics; implementation is realistic within current technical ecosystems.

Overall synthesis

The most urgent need is multicenter replication of the validated IMU+reaction-time dual-task paradigm, immediately followed by the creation of normative datasets and psychometric reliability frameworks. Neurointegration and open-data infrastructure represent the next strategic phase, enabling mechanistic insight and cross-laboratory reproducibility. Advancing along this sequence will convert current heterogeneous dual-task studies into a standardized, evidence-anchored clinical system for ACL rehabilitation and RTS decision-making.

CONCLUSION

Cognitive–motor dual-task assessment marks a conceptual and methodological shift in ACL rehabilitation—from isolated biomechanical or strength evaluations to ecologically valid testing that mirrors the cognitive–motor demands of real-sport environments. Evidence synthesized from the 37 studies in Table 1, 2 demonstrates that when behavioral, kinematic, and physiological indices are combined, clinicians can detect residual neurocognitive-motor deficits that conventional single-task tests overlook.

Integrated evidence and clinical meaning

Behavioral reaction-time and accuracy metrics showed excellent reproducibility ($ICC \approx 0.83$ – 0.94), while IMU-based kinematics achieved near-laboratory validity versus MoCap ($ICC > 0.9$, $RMSE < 5^\circ$). These complementary domains—attention control and movement symmetry—form the most psychometrically mature foundation for clinical translation. Physiological measures (EEG, fNIRS, HRV) provided mechanistic insight but remain limited by preprocessing heterogeneity and insufficient test–retest data. Thus, dual-task assessment now offers a structured, evidence-anchored framework capable of quantifying how athletes allocate attention, inhibit actions, and coordinate movement under cognitive load.

Novel contribution

The novelty of this synthesis lies not in proposing new sensors, but in unifying validated task–device–metric combinations—such as Go/No-Go tasks coupled with IMU-derived asymmetry and reaction-time cost—into a standardized, psychometrically grounded template. By embedding validity, reliability, and responsiveness within each measurement domain, the review advances dual-task testing from experimental feasibility toward clinical actionability for RTS decisions. This transition reframes cognitive–motor assessment as an applied, data-driven component of individualized ACL rehabilitation.

Strategic priorities for continued development

Progress toward full clinical deployment depends on sequential, feasible steps grounded in the current evidence base:

1) Multicenter validation of the IMU+reaction-time framework (most urgent)

Large-scale trials across rehabilitation centers should verify reproducibility and external validity of standardized dual-task

protocols.

2) Normative datasets and RTS cut-off thresholds (high priority)

Pooling multicenter data will enable creation of reference ranges and cut-offs for DTC and reaction-time delay, allowing objective RTS classification by age, sex, sport, and graft type.

3) Comprehensive psychometric validation (essential foundation)

Systematic evaluation of test–retest reliability, sensitivity to change, and MDC will distinguish true recovery from measurement noise.

Mid-term opportunities

Incremental neurointegration-linking portable EEG or fNIRS with behavioral-kinematic data—offers deeper insight into cortical mechanisms of motor control, though short-term feasibility remains limited by cost and setup demands. Parallel development of open, standardized data infrastructures for pre-processing, metadata exchange, and cloud-based sharing will enhance reproducibility, accelerate meta-analyses, and enable global benchmarking across laboratories.

Translational outlook

Wearable-enabled dual-task assessment now bridges the gap between high-precision laboratory systems and field-ready clinical applications. With continued standardization, multicenter collaboration, and psychometric rigor, dual-task testing is poised to become a cornerstone of personalized, evidence-based ACL rehabilitation, transforming cognitive–motor assessment from a research innovation into a clinically validated, globally scalable standard that improves both safety and effectiveness in modern sports medicine.

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AUTHOR CONTRIBUTIONS

Jun Woo KWON had full access to all of the data in the study and takes responsibility for the integrity of the data and the accuracy of the data analysis. Author reviewed this manuscript and agreed to individual contributions.

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CONFLICTS OF INTEREST

No existing or potential conflict of interest relevant to this article was reported.

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DATA AVAILABILITY

The data presented in this study are available upon reasonable request from the corresponding author.

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