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SCOPING REVIEW

Force and Power Testing in Anterior Cruciate Ligament Reconstruction Literature: A Scoping Review

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Abstract

Background Force and power testing has been recognised as a key aspect of anterior cruciate ligament reconstruction anterior cruciate ligament reconstruction (ACLR) rehabilitation. However, a literature synthesis is required to examine how these physical characteristics have been assessed due to pronounced heterogeneity in the methods used.

Objectives To synthesise and describe the existing literature on force and power testing post-ACLR.

Methods A scoping review of the electronic databases MEDLINE (PubMed), SPORTDiscus, Cochrane Library and PEDro was conducted including studies adopting at least one force or power test in patients post-ACLR. The search methodology followed the Joanna Briggs Institute Manual for evidence synthesis and included the Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR).

Results In total, 1625 studies fulfilled the inclusion criteria. Seven main device categories were identified, with different rates of implementation over the years (1981–2023) and throughout the recovery process: (1) isokinetic dynamometry (IKD; 64.9%), (2) jump (without force platform; 32.2%), (3) force platform (28.0%), (4) traditional gym equipment and bodyweight exercises (6.2%), (5) hand-held dynamometry (4.0%), (6) manual muscle testing (1.5%) and (7) other devices (5.5%). Studies used 1.42 ± 0.62 devices, with 45 different combinations recorded. Various tests were conducted using different devices, ranging from 8 to 72 recorded tests per category. Only force plate assessments showed a linear increment in implementation from the surgical procedure ($r = 0.86$, $p = 0.012$).

Conclusions Significant heterogeneity in assessment device selection, metrics analysed, test implementation and protocols was observed. Most studies included a single device category to examine force and power characteristics of patients post-ACLR. The IKD remains the most adopted testing device in research, but current assessment practices are more varied than in the past.

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Key Points

Substantial heterogeneity was present in the literature regarding device implementation, test selection, adopted metrics and device combinations when evaluating post-ACLR force and power.

Most studies relied on a single device category (1.42 ± 0.62), with multiple force and power technologies infrequently combined in the included studies.

In recent years, devices implemented have primarily consisted of isokinetic dynamometers, force plates and those which examine jump and hop displacement.

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1 Introduction

Anterior cruciate ligament (ACL) ruptures and subsequent anterior cruciate ligament reconstructions (ACLRs) are high burden injuries [1–9]. Return to sport (RTS) post-ACLR is a lengthy process, generally requiring 8–12 months, with some patients needing even longer [3, 4, 6, 10]. Despite ACLR and extensive rehabilitation, patients still often display poor knee function [11], early onset of knee osteoarthritis [12], suboptimal RTS rates [9, 13–15], high re-injury incidence [7, 8, 10], reduced performance [3, 16], decreased career longevity [3, 17] and reduced quality of life [18–20]. Current practice-based guidelines recommend a stage-based, criteria-driven approach to rehabilitation and RTS [21–30], with progression determined upon achieving specific criteria. However, guidelines around testing and monitoring remain unclear.

Restoring neuromuscular performance, defined as 'an umbrella term including maximal muscle strength, muscle endurance, power, rate of force development (RFD) and stretch–shortening cycle (SSC) function, as well as kinetic outputs during functional tasks' [31], has been identified as an important factor to support progression and optimise outcomes post-ACLR [10, 32–37]. Objective assessment of these qualities post-ACLR has a long history, with the implementation of the isokinetic dynamometer (IKD) and hop testing dating back to the 1980s. However, a more recent renewed emphasis on objective assessment practices, alongside advances in technology and commercially affordable testing devices, have increased test accessibility. Whether and how these changes have been reflected in research currently remains unknown. Therefore, there is a need for a literature synthesis to be conducted to identify devices, tests, metrics and assessment time points implemented across the entire ACLR rehabilitation pathway and inform practice.

The aims of this scoping review were (1) to report the most implemented assessment devices throughout the years (1980–2023), (2) to analyse the adopted metrics per each device, (3) to explore the most performed tests with each device and (4) to report when different devices are implemented during the recovery process.

2 Methods

A scoping review was selected due to the exploratory nature of our research question and study aims which included mapping the cumulated literature on force and power testing post-ACLR. This methodology also allowed us to critically analyse and highlight gaps in the vast published literature [38–40]. We conducted this scoping review following the Joanna Briggs Institute Manual for evidence synthesis [41], including the implementation of the Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR). Considering the exploratory nature of scoping reviews and the performed descriptive analysis of several variables encountered in the included studies, study quality and risk of bias assessments were not conducted as they do not influence study outcomes [38].

2.1 Inclusion Criteria

The following inclusion criteria were applied for this scoping review.

2.1.1 Study Types

We included original research studies, prospective, retrospective and observational in nature, case studies and case series published in English [42]. Reviews (systematic, narrative, meta-analysis, etc.), guidelines, conference abstracts and non-peer-reviewed studies were not included.

2.1.2 Participants

Patients post-ACL rupture with or without additional knee injuries and treated with ACLR implementing any graft type and additional procedures were included. We did not include studies in which patients were managed non-surgically and with previous ACLR treated for a different condition sustained after the reconstruction (e.g. patellar tendon repair after previous ACLR). In the case of mixed population, for instance, half of the cohort underwent ACLR and the other half was treated non-surgically, the study was included, and only information relative to the ACLR cohort was extracted. Patients of any age and activity level were included to map the whole published literature on force and power testing post-ACLR.

2.1.3 Intervention

We included studies that implemented at least one force and/or power test. For eligibility purposes, force testing was defined as any assessment aimed at evaluating the force produced by the athlete either via instrumented methods (e.g. IKD, hand-held dynamometer [HHD], etc.) or clinician rated assessment (e.g. manual muscle testing [MMT]). This included traditional strength metrics such as peak force and peak torque, alongside other metrics derived from it, including RFD, rate of torque development (RTD), impulse and work. Power tests, defined according to the mechanical definition as the rate at which work is performed and calculated as the product of force and velocity, were included in the review and recognised as an important quality to monitor

and restore post-ACLR [43, 44]. Jump and hop performance assessments, quantified either via force plates or other displacement-based devices, such as tape, Vertec, wall reach, etc., were also included. Their inclusion was justified by the association between jump–hop performance and lower limb strength ($R^2 = 0.49$–0.57) [45, 46], their dependence on power production capacities [47] (even if not equivalent [48]) and by their extensive implementation in clinical practice [31, 49]. Finally, all post-surgical time frames were included, with no limitations on the year of publication of the study.

2.2 Study Identification and Selection

As detailed in the Joanna Briggs Institute Manual for evidence synthesis [41], the implemented search strategy followed a three-step approach.

2.2.1 Step 1: Initial Limited Search

An initial limited search was conducted in MEDLINE and SPORTDiscus in October 2023. The implemented search terms were anterior cruciate ligament reconstruction, force, power and test. These terms were combined as follows: 'Anterior Cruciate Ligament Reconstruction' AND ('force' OR 'power') AND 'test'. Titles, abstracts and index terms used in the collected studies were analysed with the goal of identifying keywords to refine the following search strategy (Appendix A).

2.2.2 Step 2: Refined In-Depth Search

Based on the detected keywords from the initial search, a second, more refined search was conducted across four different databases, MEDLINE (PubMed), SPORTDiscus, Cochrane Library and PEDro, in November 2023 (Appendix B).

2.2.3 Step 3: Reference List Review

An additional search of several reference lists was finally performed to identify additional sources potentially missed in the first two steps. All the retrieved sources were downloaded and uploaded into Covidence systematic review software (Covidence, Veritas Health Innovation, Melbourne, Australia – available at www.covidence.org), and duplicates deleted through the software function prior to applying the selection criteria. Two independent reviewers (A.C. and G.O.) screened the sources for eligibility based on title and abstract and then the full text for inclusion. Disagreements were resolved through discussion or via the inclusion of a third reviewer (M.B.).

2.3 Data Management

A descriptive synthesis was implemented to map and summarise the findings from the literature. To answer the research questions, several categories were created a priori and presented as headings in Sect. 3 (e.g. patient characteristics, device implementation, metrics utilisation, etc.), inspired by previously published work [50] and existing scoping methodologies [40]. The descriptive synthesis was performed by extracting data from each study based on the implemented assessment devices. Categories created a priori were then improved iteratively throughout the extraction process to capture the variability of assessment protocols. Categories were created to enhance clarity and replication of the findings. Based on device implementation practices, we established seven different categories: (1) IKD, (2) jump (without force platform), (3) force platform, (4) traditional gym equipment and bodyweight exercises, (5) HHD, (6) MMT and (7) other devices. These categories followed a clinically relevant grouping structure, reflecting the most implemented assessment devices in the literature, allowing for analysis of specific tests and metrics adopted within. We grouped all the devices used to assess jump and hops (displacement-based devices such as use of tape, Vertec, wall reach, etc.), excluding the use of force platform, which constitutes a separate category. Tests performed without force platforms provide derived performance outcomes, such as flight time, displacement or estimated jump height, without considering the kinetic component of the task, available through force platform technology.

Data were extracted and imported into a customised Excel spreadsheet (Microsoft Corp, Redmond, WA, USA) by a reviewer (A.C.) and verified by a second reviewer (G.O.). Disagreements were resolved through a consensus or the inclusion of a third reviewer (M.B.). Data were analysed through descriptive statistics and summarised as frequencies and arithmetic means. Device implementation frequencies were reported, together with the number of different tests performed with each device, their specific utilisation rate and the implemented metric categories. Device implementation was also binned by year of study publication from 1981 to 2023 and graphically presented as a relative proportion of all devices reported in each year [50]. To investigate the device implementation trends over time post-ACLR, further analysis was conducted on SPSS Version 24.0 (IBM Corporation, Armonk, NY) via Pearson's correlation coefficients analysis. Finally, data were imported into Matlab (vR2023b, The MathWorks, Natick, USA) to analyse the combined use of assessment devices. A co-activation network chart was constructed based on the recorded device categories and their interaction with node size representing how frequently a device category activates overall, node colour indicating how many other devices a category co-activates with, line

thickness describing how strongly the devices are linked and number of lines specifying the precise number of co-activations between devices.

3 Results

The electronic database search yielded a total of 8349 studies, with 6724 excluded and 1625 included in the review (Appendix C), as detailed in the PRISMA-ScR reported as Fig. 1.

3.1 Studies' and Participants' Characteristics

Overall, 54 different countries contributed to the publication of the 1625 included studies, with the USA (n = 628/1625, 38.6%), Japan (n = 110/1625, 6.8%) and Australia (n = 108/1625, 6.6%) contributing the most frequently. Collectively, this scoping review summarised the force and power testing practices of over 130,000 patients post-ACLR. When considering the studies that reported participants' sex (n = 1532/1625, 94.3%), 1025 studies (n = 1025/1532, 66.9%) had a greater number of men included, with the aggregate proportion including all the studies being exactly 60% male and 40% female. A total of 1007 studies (62.0%) implemented scales that include information on the patients' activity level or activity-related function, with over 30 different scales identified. The Tegner Activity Scale (TAS), which specifically grades activity level, was the most frequently used in this context (n = 584/1007, 58.0%). The International Knee Documentation Committee (IKDC) form (n = 582/1007, 57.8%), and Knee injury and Osteoarthritis Outcome Score (KOOS; n = 229/1007, 22.7%), which provide information

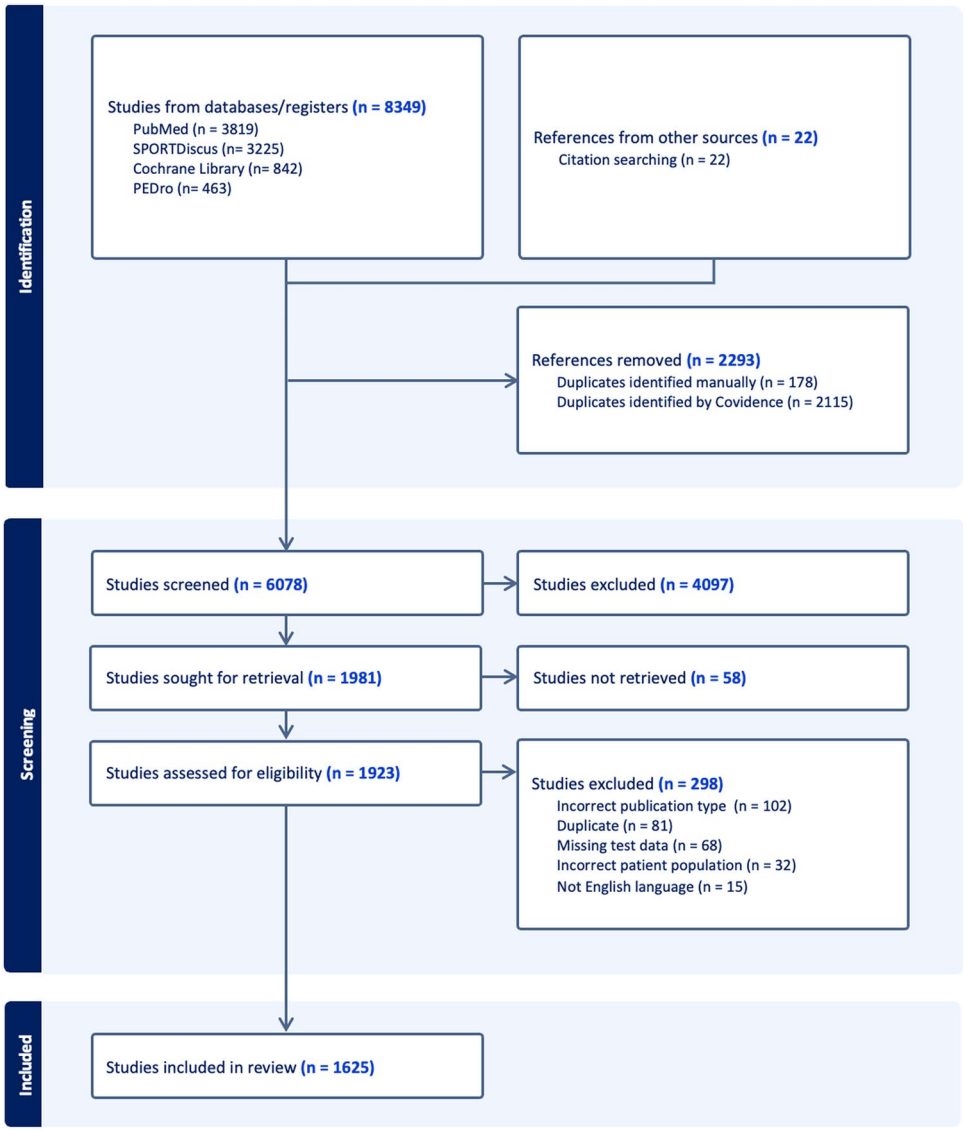


Fig. 1 PRISMA-ScR flow diagram of study selection. PRISMA-ScR, Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews

on the activity and sport related function, were also frequently implemented. Information on the sports were available in only 238 studies (14.6%), with soccer (n = 164/238, 68.9%) and basketball (n = 117/238, 49.2%) being the most reported.

3.2 Devices Implemented in the Literature

Device implementation percentages, assessed anatomical areas, test frequency, post-ACLR assessment time-points, test types, metrics and number of different tests recorded per device are detailed in Table 1. Seven main categories of devices were identified (Fig. 2). Further information on the adopted metrics is reported in Fig. 3.

3.2.1 Isokinetic Dynamometer

The IKD was the most implemented device, used in 64.9% of studies (n = 1054/1625), primarily for the knee (knee: n = 1043/1054, 99.0%; hip: n = 18/1054, 1.7%; ankle: n = 9/1054, 0.9%; closed kinetic chain [CKC]: n = 4/1054, 0.4%). Four contraction modes were identified: isokinetic concentric (n = 840/1054, 79.7%), isometric (n = 309/1054, 29.3%), isokinetic eccentric (n = 78/1054, 7.4%) and isotonic (n = 1/1054, 0.1%). Overall, 24 different contraction angular velocities (in addition to 0°/s isometric testing) were adopted, with 60°/s (43.1%) and 90°/s (8.5%) being the most implemented 'slow-speed' contractions and 180°/s (24.6%) and 240°/s (5.9%) being the most common 'high-speed' contractions. There were 58 test variations recorded, with reciprocal isokinetic-concentric knee flexion–extension (n = 660/1054, 62.6%), isolated isometric knee extension (n = 282/1054, 26.8%) and isokinetic-concentric knee extension (n = 135/1054, 12.8%) contractions being most common.

3.2.2 Jumps and Hops (No Force Platform)

Aside from the universally implemented tape measure to document vertical or horizontal displacement, additional devices grouped in this category include those which measure flight time (e.g. contact mat, infrared lights), manual vertical displacement (e.g. wall reach, Vertec), software-based vertical displacement (e.g. camera and markers) and acceleration(inertial sensor units). Approximately three quarters of the studies included in this category (n = 397/524, 75.8%) implemented jumps or hops in only one direction, irrespective of the task configuration (e.g. unilateral and bilateral), with horizontal (anterior) implemented most (n = 488/524, 93.1%), followed by vertical (n = 110/524, 21.0%), medio-lateral (n = 65/524, 12.4%),

Table 1 Implemented device and test specifics reported in descending order of utilisation from left to right. Body areas, frequency, post-ACLR assessment time points, test types and summary of the implemented metrics are reported for comparison between instruments. Colours span from red to green representing the percentage of implementation of the equipment from 0 to 100%, respectively

Implemented devices specifics

Parameter		Isokinetic dynamometer	Jumps and hops (no force plate)	Force Plates	Gym equipment and bodyweight	Hand-held dynamometer	Manual muscle testing
Device usage across 1625 studies		64.9%	32.2%	28.1%	6.2%	4.0%	1.5%
Body Areas	*Knee complex*	99.0%	-	0.0%	18.8%	83.1%	83.3%
	Hip complex	1.7%	-	0.0%	1.0%	46.2%	25.0%
	Ankle complex	0.9%	-	0.0%	2.0%	3.1%	4.2%
	CKC and functional tasks	0.4%	100.0%	100.0%	84.2%	-	-
	Core and spine	0.0%	-	0.0%	5.0%	4.6%	0.0%
Frequency	*>1 time*	42.0%	31.5%	28.7%	39.4%	32.5%	45.2%
	≥3 times	20.7%	13.2%	13.1%	14.1%	18.5%	26.2%
	≥5 times	4.0%	1.8%	1.7%	2.8%	1.9%	7.1%
Time-points	*Pre-surgery*	11.9%	7.0%	5.8%	7.6%	6.1%	7.4%
	0-3 months	13.3%	2.0%	9.7%	20.1%	21.5%	61.8%
	3.1-6 months	22.3%	20.5%	12.7%	19.2%	13.8%	11.8%
	6.1-9 months	11.0%	18.8%	16.2%	15.2%	22.8%	8.8%
	9.1-12 months	13.0%	17.8%	15.5%	10.7%	14.2%	0.0%
	12.1-24 months	10.1%	15.5%	12.4%	5.8%	8.9%	4.4%
	24+ months	13.7%	13.3%	19.9%	12.9%	10.6%	5.9%
Test types (same device)	*Only 1 type of test*	78.1%	42.9%	77.4%	75.2%	30.8%	41.7%
	≥ 2 types of tests	21.9%	57.1%	22.6%	24.8%	69.2%	58.3%
	≥ 3 types of tests	7.2%	40.5%	8.3%	13.9%	35.4%	12.5%
Metrics	*Torque and Moment*	97.0%	-	63.4%	-	23.1%	-
	Force	1.2%	1.5%	56.8%	-	75.4%	100%
	Time	2.7%	30.9%	12.1%	8.9%	-	-
	Power	3.7%	1.7%	10.7%	10.9%	-	-
	Displacement	-	98.1%	22.6%	55.4%	-	-
	Repetition Number	-	11.3%	-	17.8%	-	-
	Work	9.1%	-	4.8%	-	-	-
	Impulse	-	1.0%	12.5%	-	-	-
	RFD / RTD	4.2%	-	2.9%	-	-	-
Test Variations per assessment category		58	39	72	21	13	8

ACLR, anterior cruciate ligament reconstruction; CKC, closed kinetic chain; RFD, rate of force development; RTD, rate of torque development

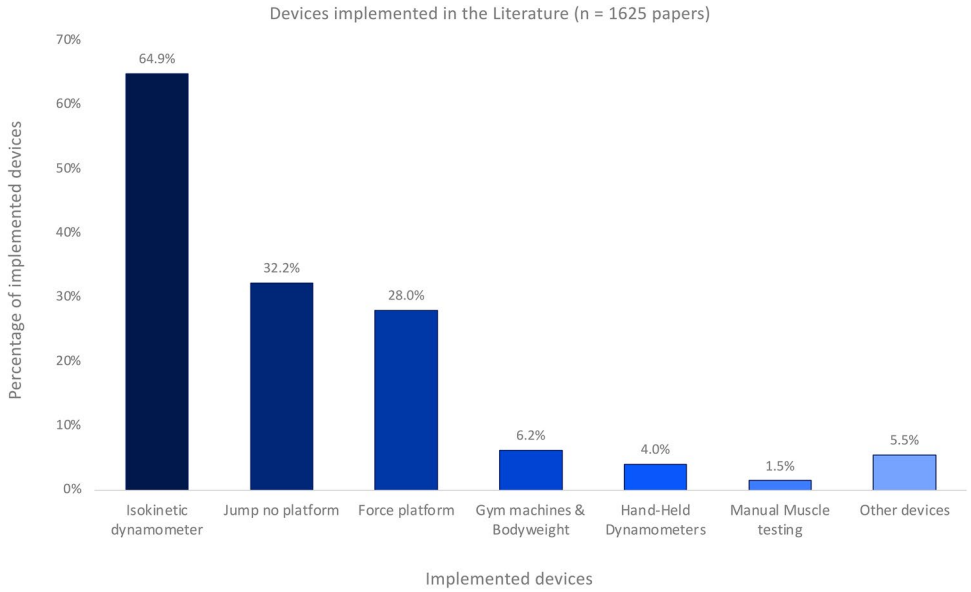


Fig. 2 Devices implemented by different authors post-ACLR to assess force and power, reported in descending order from left to right. ACLR, anterior cruciate ligament reconstruction

combined (n = 33/524, 6.3%) and rotational directions (n = 2/524, 0.4%). There were 39 test variations recorded with single hop for distance (SHD; n = 458/524, 87.4%), triple hop for distance (THD; n = 191/524, 36.5%) and triple cross-over hop for distance (CHD; n = 150/524, 28.6%) most common.

3.2.3 Force Platforms

Force plates were used in 28.0% (n = 455/1625) of studies with 76.7% (n = 349/455) utilising only a single test. A simultaneous kinematic analysis was implemented in 75.4% of the studies (n = 343/455). Jump assessment was the most implemented test type (n = 234/455, 51.4%), primarily vertical (n = 156/234, 66.7%) and horizontal (n = 73/234, 31.2%). Walking assessment was implemented in a third of the studies (n = 151/455, 33.2%), and foundational tasks such as double leg squat, lunge, and step-up were used in 12.3% of the studies (n = 56/455). Cutting tasks, isometric assessments (both yielding and overcoming) and deceleration tests were scarcely adopted, with a 7.3%, 1.5% and 0.2% rate of implementation, respectively. There were 72 different tests recorded with walking (n = 151/455, 33.2%), SHD (n = 61/455, 13.4%) and running (n = 38/455, 8.4%) being most common.

3.2.4 Other Assessments

Gym equipment and bodyweight exercises, HHD and MMT were adopted less frequently, with 6.2% (n = 101/1625), 4.0% (n = 65/1625) and 1.5% (n = 24/1625) of the included studies adopting them, respectively. Gym equipment and bodyweight exercises were primarily implemented to assess functional and CKC capacities (n = 85/101, 84.2%) with isotonic testing being the most represented contraction modality (n = 99/101, 98.0%). Both the HHD and MMT were used in the assessment of a variety of body areas, such as knees, hip and ankle complex; however, they were both primarily implemented in testing knee spanning muscles (HHD, n = 54/65, 83.1%; MMT, n = 20/24, 83.3%). HHD was predominantly used under isometric conditions (n = 63/65, 96.9%).

3.3 Time Trends in Device Implementation Over the Years

From 1981 to 1991, the IKD was almost the only implemented device in the assessment of force and power in patients post-ACLR (Fig. 4). In the last decade, the IKD remains the most implemented device (42%), followed by force platforms (23%), jump/hop displacement devices (22%), traditional gym equipment and bodyweight (5%), HHD (3%), MMT (1%) and other devices (4%) (Fig. 4).

3.4 Time Trends in Device Implementation Post-ACLR

Variation in the rate of implementation of different devices in the time post-ACLR was evident (Fig. 5). When investigating the linear relationship between time and device implementation, only force plates recorded a statistically significant positive correlation (r = 0.86, p = 0.012), indicating their increased adoption over time post-ACLR (Table 2).

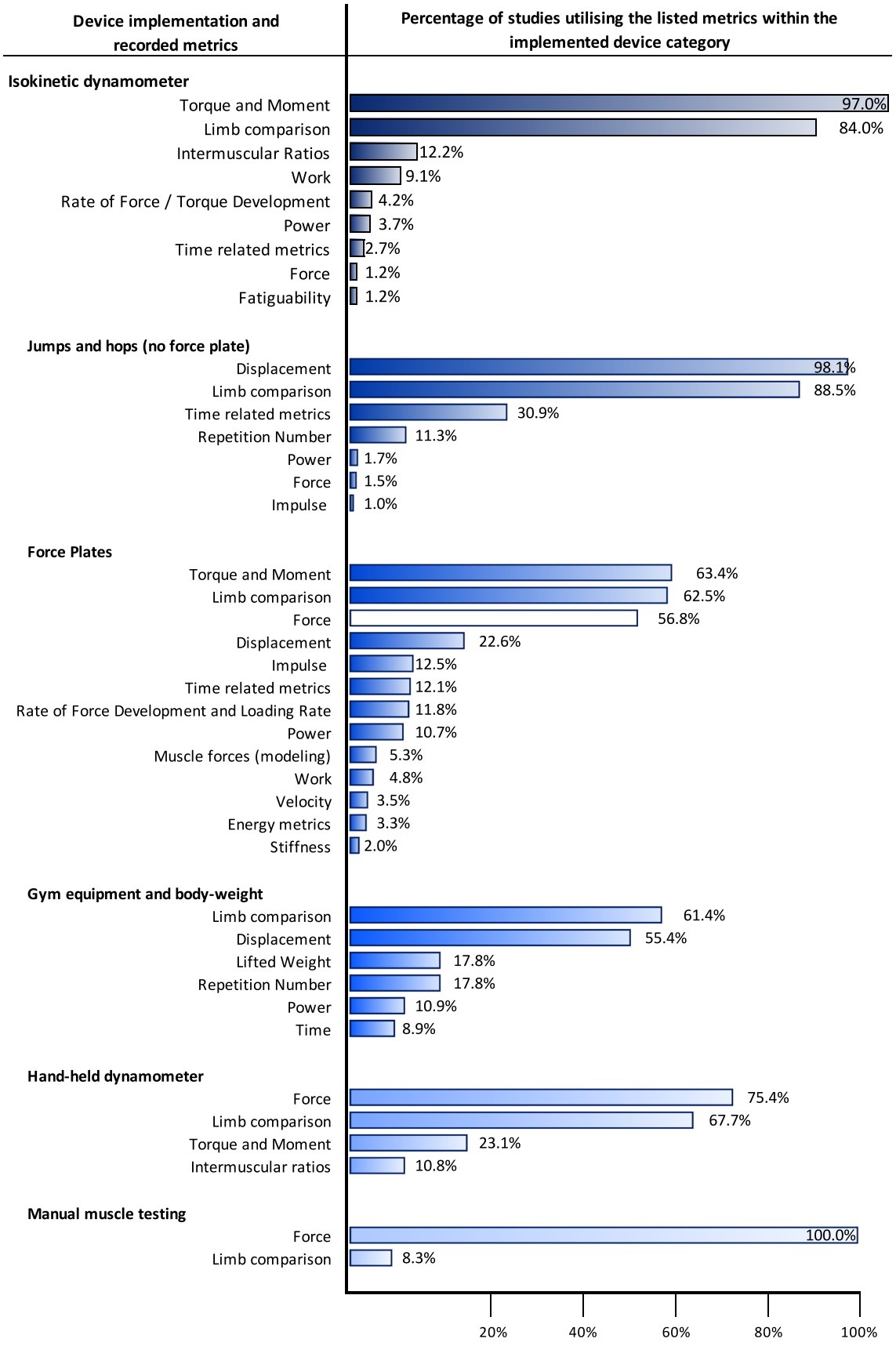


Fig. 3 Analysed metrics based on the implemented assessment device with relative percentage of usage

3.5 Device Combinations

When investigating how studies integrated different device categories into the testing process (including non-instrumented jump testing performed with tape, wall reach, etc.), 45 combinations were recorded. Most studies implemented a single assessment category ($n = 1037/1625$, 63.8%) with a mean of 1.42 ± 0.62 device categories per study (range: 1–5). The co-activation network provides information on the relationship among the assessment categories (Fig. 6). Jump and hop displacement devices were included in 51% of the combinations and, together with gym equipment and bodyweight testing, were the only ones connected with every other category. The most frequent combinations included jump and hops with (a) gym equipment and bodyweight ($n = 11$), (b) IKD ($n = 9$) and (c) HHD ($n = 9$).

4 Discussion

This scoping review, which summarises 1625 studies, maps the past and present of force and power testing post-ACL injury and reconstruction.

4.1 Device Implementation Evolution

Over decades, force and power assessment practices have profoundly changed (Fig. 4). Firstly, introduced in the 1980s [51], IKD was the most implemented mode of force and power assessment, included in approximately 70–100% of ACLR studies published. Jump testing, also introduced in the 1980s with the use of the SHD as a measure of lower limb function [52–55], became more frequently implemented from the 1990s onwards, along with the THD, CHD and 6 m timed hop (T6H) [52, 55]. Force plate assessment was first featured in the late 1980s in an ACL-injured [56] and ACLR population [57], with its utilisation displaying a considerable increment in recent years. HHD, gym equipment and bodyweight exercises have also emerged as additional testing approaches, supporting the assessment of multiple body areas. Collectively, these data show that the IKD remains the preferred device in force and power testing post-ACLR. However, its relative contribution to all the reported assessment categories changed over time, from 100% in 1981 to 42% in 2023. Several factors may have contributed to this diversification, such as an increased emphasis on criteria-based rehabilitation, recommendations

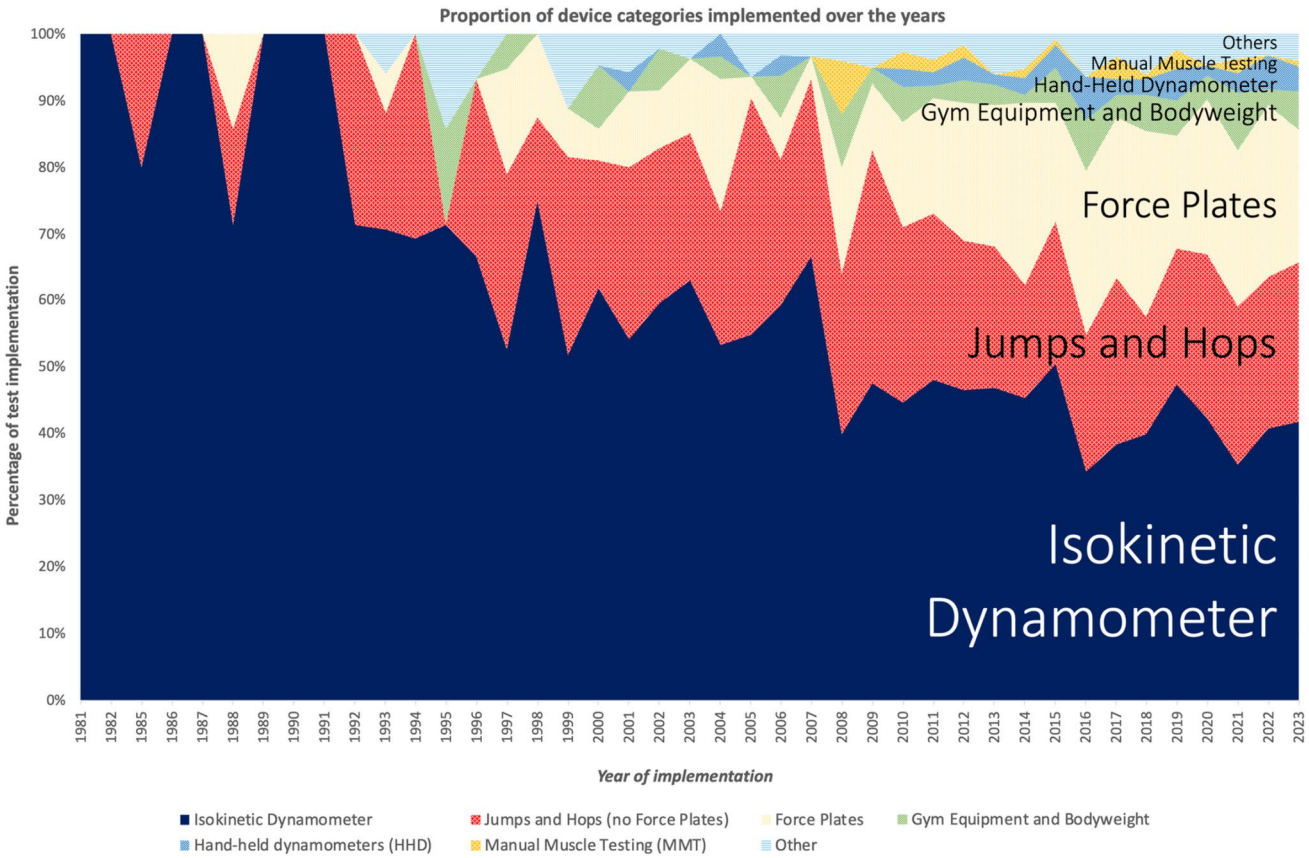


Fig. 4 Relative proportion of implemented devices on the total of performed tests to assess force and power in a given year from 1981 to 2023

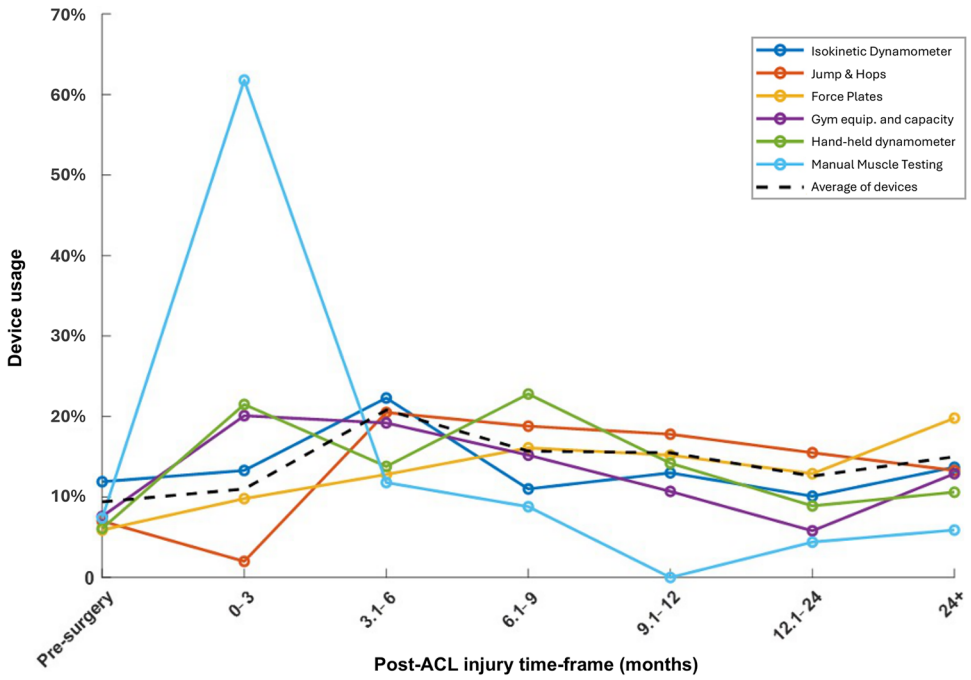


Fig. 5 Force and power device implementation from ACL injury over time. ACL, anterior cruciate ligament; equip, equipment

Table 2 Time and device implementation linear relationship analysis assessed via Pearson correlation coefficient (*r*). Bolded values indicate a statistically significant relationship

Time post-ACLR and device implementation		
Device	*r*	*p*-Value
Isokinetic dynamometer	– 0.2	0.673
Jump and hop	0.49	0.261
Force plates	**0.86**	**0.012**
Gym equipment and bodyweight	– 0.3	0.515
Hand-held dynamometer	– 0.14	0.765
Manual muscle testing	– 0.48	0.281

to expand the assessment 'beyond the knee joint' and growing evidence on the importance of restoring muscle capacity of adjacent joints and functional performance (e.g. jump and hop performance) [23–28, 58–60]. Furthermore, advances in device affordability, identified as a key barrier in clinical practice [31], portability and data processing may have enhanced the accessibility of objective testing.

From a clinical and research perspective, this diversification may represent a positive evolution, provided that the implemented tests are valid, are aligned with evidence-based practice recommendations and are performed as complementary assessments, to enhance the depth of the data collected or to extend the accessibility of objective testing in clinical practice. Evidence-based recommendations in ACLR rehabilitation highlight the critical importance of assessing isolated knee extensor and flexor strength [10, 33, 34, 36, 59, 61–63], which continues to be primarily performed via IKD or appropriately validated dynamometers. Replacing analytic assessment with functional testing alone may lead to the inability to detect specific strength deficits, which violates evidence-based recommendations, and should be discouraged [64–66]. Instead, testing practices should be complementary, with the introduction of functional assessment alongside analytic strength evaluation [24, 25, 28, 59, 60], with the reported diversification reflecting this development via the integration of jump and hop and force plates assessment categories. Advances in technology may also augment the depth of the collected objective data. For example, practitioners may continue assessing functional performance via jump and hop testing, shifting, where feasible, from the use of displacement-based assessments (e.g. tape, Vertec or wall reach) to more advanced devices capable of quantifying in-depth force–time data such as force plates. Increased device affordability may support reliable data collection by providing clinicians with more accessible alternatives to previously cost-prohibitive lab-based instruments. For instance, although not able to reproduce all IKD contraction modes and derived metrics, appropriately validated and more affordable dynamometers (e.g. HHD and inline dynamometers) may represent a clinically feasible alternative to strength assessment, making data collection more accessible [67, 68]. Finally, greater availability of objective devices and metrics does not necessarily imply improved data quality collection, better decision-making process or enhanced rehabilitation outcomes. Therefore, this diversification in testing practices may also present as a weakness when tests are performed redundantly just for the sake of collecting data or when non-valid or less reliable assessment

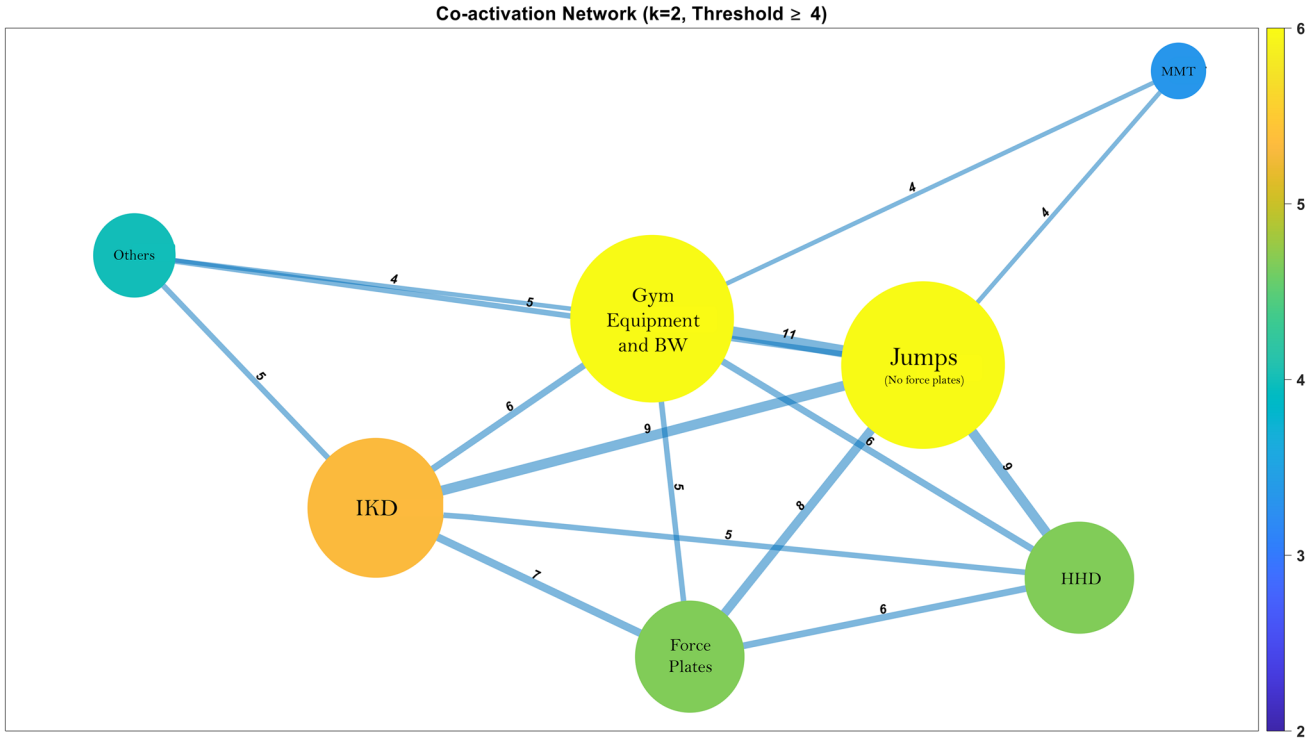


Fig. 6 Co-activation network graph representing the interactions between different test categories. Note: node size represents how frequently a device category activates overall, node colour indicates how many other devices a category co-activates with, line thickness describes how strongly the devices are linked, and number of lines specifies the precise number of co-activations between devices. MMT, manual muscle testing; IKD, isokinetic dynamometer, HHD, hand-held dynamometer; BW, bodyweight

strategies are implemented as alternatives to previously validated methodologies.

4.2 What Type of Testing is Performed Post-ACLR and How?

Previous scoping reviews examining criteria for returning to run and sport post-ACLR reported time as the main criterion for progression, with strength often not considered in the decision-making process (15–41%) [50, 69]. These literature syntheses reported IKD use in less than a quarter of the included studies (6–24%) [50, 69], while our review recorded IKD as the most implemented device across the whole ACLR literature. The use of the IKD is aligned with previously published literature [70, 71]. As per our review, concentric mode was the most adopted contraction type (70–80%) of the included studies [70, 71], followed by isometric and eccentric. We observed 25 different angular velocities with 60°/s and 180°/s confirmed as being the most common [70, 71]. Aside from the traditionally implemented peak and mean torque values [70, 71], the IKD also provides practitioners with additional metrics to characterise knee function such as work, RTD and power [72]. Surprisingly, their implementation has been confirmed as low (see Fig. 2) [70, 71]. In addition, residual torque–angle deficits are common following ACLR [73] and warrant inclusion when using an IKD. Finally, the knee flexion to extension ratio, more commonly defined as hamstrings to quadriceps ratio, was only reported in 12.2% of studies despite its previously reported association with ACL re-injuries [33]. Nearly all studies that did report this ratio (96.9%) utilised the traditional ratio (concentric knee flexion: concentric knee extension); however, only 11.6% utilised the dynamic control ratio (DCR; eccentric knee flexion: concentric knee extension), with 7.8% using both ratios. Even if scarcely utilised, the DCR has been advocated as a metric of interest in IKD testing to assess the agonist–antagonist joint balance [74–76], as it relates eccentric hamstrings capacity to concentric quadriceps capacity. In dynamic actions, the knee flexors have the important function of acting eccentrically as brakes to decelerate the knee movement generated by the concentric quadriceps contraction [77], opposing the anterior tibial translation and shearing forces, hence contributing to dynamic knee stability. However, when evaluating this metric, it is important to not only consider the peak torque proportion but also its ratios at specific knee angles, which often requires dedicated software and may limit its implementation [73]. Cumulatively, this suggests the utilisation of the IKD can be improved to optimise its effectiveness.

Current clinical practice guidelines and recent research underlined the importance of assessing neuromuscular performance [25, 78, 79]. Due to its simplicity, cost-effectiveness and accessibility [80], hop testing is often implemented in clinical practice [31, 49, 81] and research [10, 82, 83] as a surrogate of lower limb power [80]. Davies et al. (2020) reported the most frequently used hop test battery at the time of RTS, including the SHD, THD, CHD and T6H [80]. The current review confirms these findings. Importantly, not all jump tests measure the same neuromuscular construct, especially when considering the hop direction [84]. Knee, hip and ankle do not contribute equally to horizontal and vertical jumps, with vertical jumps deemed more appropriate because of significantly higher contribution of the knee in the propulsion phase [85]. The implementation of force plates has enabled the collection of additional neuromuscular metrics that further support the understanding of jump kinetics, strategy and asymmetries [86–91]. In our review, the use of force plates appears to increase progressively throughout the rehabilitation process. This is important, especially towards the final stages of rehabilitation and RTS, because despite the restoration of global performance metrics, including jump height and hop distance, residual kinetic deficits may still be detected via this technology [65, 90].

Traditional gym equipment and bodyweight exercises were rarely used in research (6.2%), primarily being utilised to assess functional performance using the reach test, leg extension, leg press and leg curl device. Despite being considered a sufficiently valid and reliable low-cost device to assess muscle strength [67, 92–94], less than 5% of the studies adopted the HHD in our review. When interested in assessing knee-spanning muscle strength, the HHD and inline dynamometry showed excellent reliability [67, 92–94] and moderate to excellent validity [94] when compared with the IKD.

The importance of assessing adjacent joint strength, primarily hip and ankle, has been underlined by several authors [95–99]. The hip muscle complex plays a vital role in supporting knee biomechanics [100], load distribution [77] and functioning [96], with decreased strength post-ACLR identified as a contributor to knee symptoms [101] and reduced hop performance [96]. Additionally, the role of the calf complex in absorbing forces and decreasing ACL strain (particularly the soleus) has been underlined in recent years [77, 102]. Currently, assessment of proximal and distal joints is poorly represented in the literature, with only 4% of all the studies included in this review assessing the hip or ankle complex. Aligned with a recent systematic review and meta-analysis on hip and calf muscle strength post-ACLR [103], our findings confirm that hip strength is most assessed using HHD, followed by IKD, whereas the ankle complex is primarily evaluated via IKD.

Despite still being implemented by professionals in clinical practice (11.3–33%) [81, 104, 105], MMT has been discouraged, owing to its low sensitivity to elucidate minor asymmetries [Medical Research Council (MRC) scale ≤ 3] [106, 107]. Aligned with other reviews [50, 69], our work confirms its low implementation in research (1.5%), and it appears that assessment takes place primarily in the early stages post-ACLR. With the increased practical utility of HHD and inline dynamometry, clinicians are encouraged to adopt this more objective-based approach to increase validity and reliability.

Finally, our review highlights the requirement for more longitudinal studies to characterise the recovery trajectories post-ACLR [43, 108, 109]. In our review, across all the assessment categories, we observed repeated testing only in 30–45% of the studies. Future longitudinal studies should implement repeated stage-based assessment across key recovery time points, for example, at approximately 3, 6, 9 and 12 months, with pre-surgical baseline and longer-term follow-up included where feasible [108]. By clearly defining the recovery trajectories of different neuromuscular qualities (e.g. strength, RFD and power) and relating them to the recovery stages post-ACLR (e.g. mid- to late-stage progression) and functional tasks introduction (e.g. running, jumping), it may be possible to establish stage-specific reference values and progression criteria to inform safe progression and RTS decision-making [25–28, 59, 79].

4.3 Methodological Heterogeneity in Testing

Accurate assessment of muscle function post-ACLR is the foundation for clinical decision-making and criterion-based rehabilitation progression. Recent literature has concluded that isokinetic concentric extensor and flexor strength tests typically demonstrate acceptable intra-rater reliability (albeit low-certainty evidence) and moderate construct validity, whereas isometric tests lack sufficient validity [110–112]. However, procedural heterogeneity in IKD assessment, encompassing variations in testing mode (e.g. 60°/s versus 180°/s), joint angle stabilisation, lever arm calibration and warm-up protocols, collectively undermines inter-clinician comparability [111]. Moreover, isolated strength and power metrics fail to account for neuromuscular adaptations, such as altered electromyographic activation patterns, increased musculotendinous stiffness and compensatory movement strategies, that had been documented postoperatively [113–115].

Hop tests are commonly utilised to examine single limb power and neuromuscular adaptations [80] and are considered a reliable and valid performance-based outcome measure [116]. However, hop performance outcomes should be considered as the result of the complex interaction between physical and psychological factors, including knee stability,

confidence, cognitive load and physical demands associated with the task execution itself, particularly on the landing phase, where knee contribution is substantial [65, 117–119]. Together with the multi-joint nature of jumping and hopping and the potential for alterations in movement strategy (e.g. hip or ankle dominance patterns), diagnostic accuracy can be affected [65, 80]. Furthermore, solely considering hop distance symmetry may mask lower limb biomechanics deficits [65], supporting the notion that hop tests should not be used in isolation [120, 121]. Hop test methodology is often poorly reported [122], and procedural heterogeneity, encompassing variations in familiarisation, numbers of trials, hand position standardisation, landing technique and general instructions, can impact outcomes and limit inter-study comparability [120].

4.4 General Methodological Considerations for Test Standardisation

To enhance methodological rigor in typical clinical settings, practitioners should standardise test procedures adopting the following strategies:

1. Standardise the warm-up*:* use the same protocol to minimise performance variability by controlling the post-activation potentiation effect and fatigue [123, 124] (e.g. 5 min stationary bike + three submaximal practice trials).
2. Be consistent: select a test battery and ensure consistent set-up procedures, equipment choice, speed, range of motion and instructions across all the assessments. A standardised procedure providing instructions and cues to the patient should be agreed upon by practitioners beforehand and implemented consistently [125–127]. When a test battery is implemented, test order should be organised according to the targeted physiological energy systems, progressing from the least to the most physiologically demanding [120].
3. Practice before the test: ensure patients have been exposed to practical trials (2–3 sessions) to allow for familiarisation and mitigate the learning effect [128].
4. Periodically evaluate reliability and measurement error: assess both absolute reliability (e.g. coefficient of variation, aiming for $\leq$ 10%) and relative reliability (test–retest intra-class correlation coefficients, with $\geq$ 0.75 considered acceptable), and calculate the minimal detectable change when testing with the same clinician or across different evaluators [129–132].
5. Document patient-reported effort and pain: using a simple visual analogue or numeric rating scale (1–10) to monitor pain [27] and effort [133] during the test can be helpful in interpreting fluctuations in performance and progression throughout the recovery process.

These steps, which can be executed with minimal additional time or resources, help improve test reliability, validity and responsiveness, ensuring better-informed rehabilitation decisions and safer RTS outcomes [134]. Moreover, it is recommended that hop tests should not be completed in isolation [120, 121]. Inclusion of kinetic and kinematic measures, and a comprehensive assessment of the strength characteristics at the ankle, knee and hip can further enhance diagnostic accuracy and the potential to identify residual deficits.

4.5 Something is Missing—Where Are the Gaps?

Despite deceleration and change of direction (COD) tasks being considered ‘at risk’ movements for ACL injury [135], kinetic assessment of these tasks was only included in 2.1% of the studies in this review. This is likely due to cost, equipment, time and practical constraints. When strength deficits are present, the insufficient neuromuscular capacity to absorb loads during high-load tasks typically leads to greater reliance on the passive system, constituted by joint structures, ligaments and tendons [136, 137]. The combination of poor neuromuscular readiness coupled with sub-optimal biomechanics contributes to ACL loading, and the study of kinetics and its determinants during decelerative and COD tasks has been recommended [28, 136].

Based on our review and previous reviews [50, 69], analytic assessment of quadriceps and hamstrings are common practices in the realm of strength assessment. Only 6% of the studies utilised a CKC assessment (including capacity tests, step-up/down, sit-to-stand task, etc.), and only 2.3% included a test of strength (e.g. loaded leg press, isometric leg press with mounted force plate, isometric belt squat on force plates, etc.). CKC strength measures, such as dynamic or isometric maximal strength, assessed during squat or mid-thigh pull and expressed relative to body mass, have been reported to be an important determinant of acceleration, COD, maximal speed and jump performance [138], indicative of sporting performance. Additionally, greater maximal strength (e.g. squat 1-repetition maximum [RM]) relative to body mass is associated with reduced risk of lower limb injury [139, 140]. Including these data can further inform the lower limb strength and asymmetry profile and rehabilitation progression [136].

Finally, the inclusion of RFD measurement has been recommended by different authors in clinical practice [109, 141, 142]. In their recent systematic review and meta-analysis, Turpeinen et al. [142] reported a sustained suppression of RFD capacity for knee extensors and flexors when compared with the contralateral limb. Similarly, Angelozzi et al. [109] reported that despite patients fully restoring CKC strength at 6 months post-ACLR, moderate to large deficits in RFD were still evident. In our scoping review, knee flexor and extensor RFD was assessed in only 4.2% of the studies.

This suggests further research to examine RFD throughout the rehabilitation process is warranted.

4.6 'Must-Haves' and 'Nice-to-Haves' in Clinical Practice

'Must-haves' refer primarily to the domains that should be assessed rather than the specific implemented device, whose availability may be influenced by several socio-economic factors [31]. Current recommendations suggest practitioners should incorporate longitudinal measurement of lower limb strength [43, 108, 109], primarily knee extensors and flexors [10, 33, 34, 36, 59, 61–63], alongside, at least, a functional jump or hop test [24, 25, 28, 59] to guide the recovery process. Although RFD is considered an important metric to investigate throughout the rehabilitation and RTS process [109, 141, 142], rigorous methodological considerations are required to ensure reliable outcomes [143]. Alongside the absence of widely accepted rehabilitation-specific RFD thresholds and the cost of the appropriate instrumentation, these methodological requirements may limit its implementation in clinical practice, making RFD assessment a 'nice-to-have'.

When assessing knee-spanning muscle strength, the IKD has been considered the preferred option in both research and practice [72, 144]. However, due to cost implications, this may not often be practically viable [31, 49, 81]. For most clinicians, measurements of lower limb strength can be reliably conducted using inline HHD [67, 92–94]. Alternatively, concentric strength can be assessed with traditional gym equipment and/or free weights using repetition-based tests; however, should practitioners adopt these devices, more stringent symmetry cut-offs (~ 5–10% higher than standard) are recommended, as isoinertial assessments tend to overestimate symmetry and may lack sensitivity in identifying clinically relevant deficits [92, 136].

An additional 'nice-to-have' includes the strength assessment of adjacent joints, primarily the ankle and hip complex. These should be assessed either via HHD [94], fixed dynamometers [145, 146] or force plates [147]. Further practically viable approaches include traditional gym equipment, free weights and capacity tests [26–28, 136, 148]. Functional performance should be assessed by including at least one jump or hop task [80], preferably a vertical one [85, 89], using a contact mat, wall reach or mobile application as a baseline requirement. When possible, the inclusion of both a slow SSC (> 250 ms ground contact time, e.g. a countermovement jump) and fast SSC (< 250 ms, e.g. a drop jump) in the patient assessment may be considered as a 'nice-to-have'. When available, force plates should be included as a 'nice-to-have' to augment the analysis [49, 81], including further kinetic- and strategy-based metrics [85, 89, 90].

Finally, appropriate data interpretation should be considered a 'must-have' and should not be based on symmetry values alone. As a 'nice-to-have', practitioners should further contextualise the collected data by considering: (a) pre-injury/operative values, as the status of the contralateral limb may change throughout the recovery process [149, 150]; (b) absolute and relative (body mass-normalised) values, particularly when evaluating a patient's capacity and contrasting it with functional task demands (e.g. running, jumping); and (c) normative values based on the patient's sex, sport and activity level, as they can provide more information on their readiness within the sport context.

4.7 Strengths and Limitations

This is the largest review examining strength and power assessment post-ACLR to date. The focus was on device implementation and thus, information detailing how tests were conducted and how different testing processes impact patients' future outcomes was not investigated. Future research should more clearly elucidate each implemented device category, providing information on the specifics of each adopted test and how they impact the progression throughout the recovery process. Finally, to meet the inclusion criteria of this review, studies had to be peer-reviewed and written in English, leading to the possibility of publication bias.

5 Conclusions

This scoping review included 1625 studies, mapping the literature on force and power testing from 1981 to 2023. Significant heterogeneity in assessment device selection, test implementation and protocols was observed. Most studies still rely on a single device to assess patients post-ACLR. The IKD is the most adopted testing device in research, but more recently, force plate analysis has increased, and current assessment practices are more varied. This likely underlines the need for a more comprehensive approach to ACLR testing due to the potential for sub-optimal outcomes, and future research should focus on providing guidance and clarity on how and when to assess force and power in patients post-ACLR.

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Availability of Data and Material Data available upon request.

Artificial Intelligence Use No AI tools were used.

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