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The use of wearable technology as an assessment tool to identify between-limb differences during functional tasks following ACL reconstruction. A scoping review

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Abstract

Objective: To report how wearable sensors have been used to identify between-limb deficits during functional tasks following ACL reconstruction and critically examine the methods used.

Methods: We performed a scoping review of studies including participants with ACL reconstruction as the primary surgical procedure, who were assessed using wearable sensors during functional movement tasks (e.g., balance, walking or running, jumping and landing) at all postsurgical time frames.

Results: Eleven studies met the inclusion criteria. The majority examined jumping-landing tasks and reported kinematic and kinetic differences between limbs (involved vs.

unninvolved) and groups (injured vs. controls). Excellent reliability and moderate-strong agreement with laboratory protocols was indicated, with IMU sensors providing an accurate estimation of kinetics, but the number of studies and range of tasks used were limited. Methodological differences were present including, sensor placement, sampling rate, time post-surgery and type of assessment which appear to affect the outcome.

Conclusions: Wearable sensors consistently identified between-limb and group deficits following ACL reconstruction. Preliminary evidence suggests these technologies could be used to monitor knee function during rehabilitation, but further research is needed including, validation against criterion measures. Practitioners should also consider how the methods used can affect the accuracy of the outcome.

Keywords:
ACL
Wearables
Functional movement

1. Introduction

Anterior cruciate ligament (ACL) injuries frequently occur in sports involving landing, change of direction, and pivoting movements (Myklebust & Bahr, 2005). Despite the relative frequency and success of surgical repair, return to sport (RTS) at the same level is not guaranteed (Ardern et al., 2014). Individuals often display residual movement impairments (Decker et al., 2002; Goerger et al., 2015; Lee et al., 2014; Stearns & Pollard, 2013), and significant biomechanical between-limb differences (de Fontenay et al., 2014; King et al., 2018; Paterno et al., 2007; Welling et al., 2018). These can persist even at the time of return to sport (Stearns & Pollard, 2013) (King et al., 2018), and for several years after surgery (Lee et al., 2014) (Paterno et al., 2007). Such alterations have been identified primarily during functional tasks (e.g. landing (Decker et al., 2002), jumping (Goerger et al., 2015) (de Fontenay et al., 2014) (Paterno et al., 2007) (Welling et al., 2018), and cutting (Lee et al., 2014) (Stearns & Pollard, 2013) (King et al., 2018)), and display prospective associations with an elevated risk of second ACL injury (Paterno et al., 2015) (Paterno et al., 2010).

The majority of ACL research has been performed in a laboratory setting. These procedures have provided extensive insights but can constrain the movement task, reducing the ecological validity. Laboratory methods also involve time consuming protocols, complex analysis and expensive technical equipment. This may limit adoption by clinicians involved in the rehabilitation of ACL reconstructed (ACLR) athletes. Field-based functional assessments have been proposed as a more realistic approach. However, research indicates that metrics such as hop distance (Davies et al., 2020), and change of direction time (Marques et al., 2020) are not sensitive enough to identify deficits in knee function when biomechanical alterations exist. Given these limitations, objective and practically viable measures to quantify movement strategies post ACLR are required to inform patients' readiness to RTS, bridging the gap between lab and field-based methods.

Recently, wearable technology has been proposed for the purpose of movement assessment following ACLR (Bailey et al., 2016; Dan et al., 2019; Havens et al., 2018; Kim et al., 2020; Peebles et al., 2019a; Pratt and Sigward, 2018a, 2018b; Setuain et al., 2015a; Sigward et al., 2016; Thomson et al., 2018; Vervaat et al., 2020). These devices can be attached to specified anatomical locations such as the thigh (Pratt & Sigward, 2018a, 2018b) and shank (Dan et al., 2019), or worn in the shoes (Peebles et al., 2019a) (Thomson et al., 2018), to measure kinematic (Bailey et al., 2016) and kinetic parameters (Peebles et al., 2019a) (Thomson et al., 2018) (Peebles et al., 2018). Despite promising results, this research is still in its infancy. A synthesis of the literature is needed to describe how wearable technology has been used to measure movement parameters during functional tasks.

The aims of this scoping review were to; 1) report how wearable inertial sensors have been used to measure between-limb (involved vs. un-involved) and group (injured vs. healthy controls) deficits during functional tasks following ACLR; and 2) describe and critically examine the methods used, participant characteristics, outcome variables, equipment specification, and movement tasks performed.

2. Methods

Our research question was: "how has wearable technology been used to identify between-limb deficits during functional tasks following primary ACLR?". Due to the exploratory and descriptive nature of our research question, a scoping review was selected where the aim was to collate and comprehensively summarize the available literature on topics of a substantial and varied nature (Arksey & O'Malley, 2005). The general purpose for conducting scoping reviews is to identify and map the available evidence (Munn et al., 2018; Tricco et al., 2011, 2018). The framework was based on recommendations by the Joanna Briggs Institute, including an initial identification of the research question and relevant studies, data extraction and presentation and interpretation of results. The process of the study selection was reported using the Preferred Reporting Items for Systematic reviews and Meta-Analyses extension for Scoping Reviews (PRISMA-ScR) checklist (Tricco et al., 2018). Study quality and risk of bias assessments were not performed in accordance with previous recommendations as they do not influence scoping review outcomes (Arksey & O'Malley, 2005).

2.1. Selection criteria

2.1.1. Types of studies

Original, peer-reviewed research articles published in scientific journals using the English language from January 1995 to March 2021. Systematic reviews, conference abstracts, opinion pieces, magazines and newspaper articles were excluded. We only considered studies that included humans and functional movement assessments, defined as tasks comprising balance, gait (walking or running), change of direction, jumping and landing. All postsurgical time frames were deemed eligible for inclusion. Studies that: 1) adopted clinical assessments such as the pivot shift test; 2) examined patients with an ACL tear (without surgical reconstruction) or other types of knee injury (e.g. meniscus, medial collateral ligament); or 3) did not report ACLR as the primary surgical procedure were excluded.

2.1.2. Types of participants

Male or female, adolescent (13e17 years) and adults (≥18 years) of any activity level (including both athletes and non-athletes); with a history of primary ACLR using an autograft (i.e., hamstring or bone-patellar tendon-bone) were included in the review. Studies involving participants who had sustained previous ACL injuries/or undergone ACLR of the contralateral limb were excluded.

2.1.3. Types of interventions

Studies investigating the use of wearable technologies to identify lower limb deficits following ACLR. Wearable technologies were defined as a category of hands-free, electronic devices that can be worn as accessories and/or embedded in clothing and/or placed on an individuals' body. The devices are powered by microprocessors and include inertial sensors, inertial measurement units, accelerometers or insoles.

2.1.4. Types of outcomes

Any measure or index which described movement characteristics and biomechanical variables (e.g., joint angle, angular displacement, acceleration, ground reaction force) between-limb (injured vs. non-injured) and/or between-group (ACLR vs. non-injured controls).

2.2. Study selection

A pilot search was conducted using the PubMed electronic database, including the terms: "anterior cruciate ligament" AND "reconstruction" AND "inertial measurement unit" in March 2021. This pilot allowed the identification of keywords for inclusion by scanning the titles and abstracts. The search strategy was then refined and performed in April 2021 and included PubMed, EBSCO, SportDiscuss, Cochrane Library and Web of Science electronic databases. The following keywords were used:

Knee OR ACL OR "anterior cruciate ligament".

AND.

Injur* OR rupture OR repair OR Reconstr* OR Graft.

AND.

IMU OR inertia* OR "inertial measurement unit" OR acceleromet* OR magnetomet* OR goniomet* OR "in-shoe" OR insole OR gyroscope* OR magnet* AND Asymmetry OR symmetry OR "limb asymmetry" OR "limb symmetry" OR kinetic OR Kinematic OR joint angle OR "angular displacement" OR "angular velocity" OR range of motion OR acceleration OR loading OR "loading rate" OR force OR power OR implus*.

The title, abstract and index terms were screened to identify studies meeting our stated eligibility criteria. The reference lists of relevant systematic reviews found during this process were also manually searched. Discrepancies present after full-text screening were resolved via consensus or discussion with a second and third reviewer to determine its suitability for final inclusion.

2.2.1. Data extraction

The following details were extracted for the included studies: 1) authors and year of publication; 2) population (age, gender) and sample size; 3) the time participants were assessed after ACLR; 4) aims; 5) test protocol; 6) type of wearable sensor; 7) sensor placement; and 8) reported outcome measures.

3. Results

3.1. Identification of the studies

The electronic search generated 13,109 studies. Twenty-three were selected for full-text appraisal after the title and abstract screening process (Fig. 1). Twelve were removed after the full-text screening (Armitano et al., 2017; Dowling et al., 2011, 2012; Fong et al., 2011; Hohmann et al., 2015; Kim et al., 2018; Reenalda et al., 2018; Setuain et al., 2015b, 2019a, 2019b; Skvortsov et al., 2020; Tsuruoka et al., 2005). Eleven studies remained and were included in this scoping review (Bailey et al., 2016; Dan et al., 2019; Havens et al., 2018; Kim et al., 2020; Peebles et al., 2019a; Pratt and Sigward, 2018a, 2018b; Setuain et al., 2015a; Sigward et al., 2016; Thomson et al., 2018; Vervaat et al., 2020). Descriptive characteristics of each are shown in Tables 1-3.

3.2. Participants

Age ranged between 18 and 34 years (mean 26 ± 4.4 years). Nine studies included both males and females (Bailey et al., 2016; Dan et al., 2019; Havens et al., 2018; Kim et al., 2020;

Peebles et al., 2019a; Pratt and Sigward, 2018a, 2018b) (Sigward et al., 2016) (Vervaat et al., 2020), 2 recruited men only (Setuain et al., 2015a) (Thomson et al., 2018). Participants varied

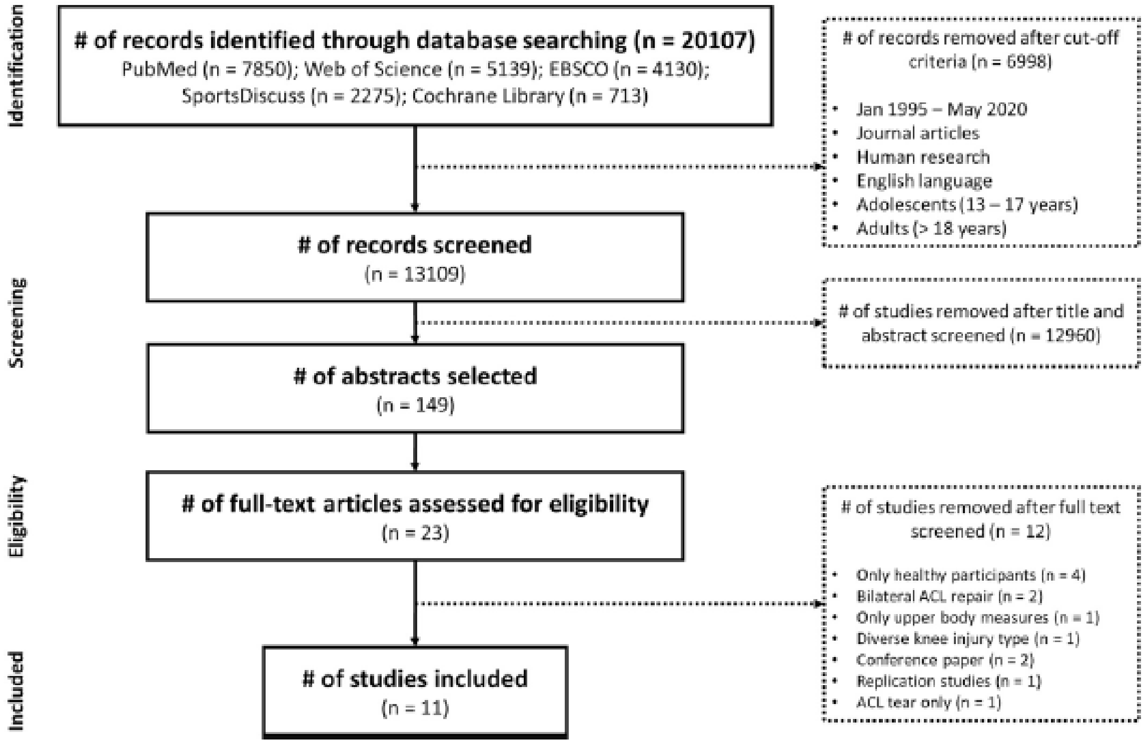

Figure 1 Flow chart of the study selection process.

between non-athletes (Bailey et al., 2016) (Peebles et al., 2019a) (Sigward et al., 2016) (Vervaat et al., 2020), recreational (Havens et al., 2018) (Pratt & Sigward, 2018a, 2018b) (Pratt & Sigward, 2018a, 2018b), and university athletes (Kim et al., 2020), elite handball (Setuain et al., 2015a) and football (Thomson et al., 2018) players. One study included both elite rugby players and non-athletes (Dan et al., 2019). Six studies used healthy participants as a control group (Bailey et al., 2016) (Dan et al., 2019) (Peebles et al., 2019a) (Setuain et al., 2015a) (Thomson et al., 2018) (Vervaat et al., 2020). The remaining 4 utilized the non-involved limb of the ACLR patients as a control (Havens et al., 2018) (Pratt & Sigward, 2018a, 2018b) (Pratt & Sigward, 2018a, 2018b) (Sigward et al., 2016).

3.3. Time post-surgery

There was a large variation in the time post-surgery to assessment (range = 1-15 months; mean 6.8 ± 3.5 months) (Bailey et al., 2016; Dan et al., 2019; Havens et al., 2018; Kim et al.,

Table 1 Study characteristics including sample size, level of participants, gender, age, height, body mass and time of assessment post ACL-R surgery of included participants.

Author	**Sample**	**Level of Participants**	**Gender**	**Age (yrs)**	**Height (m/cm)**	**Weight (kg)**	**Time of assessment post ACL-R surgery**
Setuain et al. (Setuain et al., 2015a)	Total = 22 ACL-R GR (n = 6) Healthy CGr (n = 16)	Elite handball players	M	25.5 (1.0)	188 (2.3) 188 (1.8)	92 (3.4) 89.8 (2.4)	6.3 (3.4) years
Bailey et al. (Bailey et al., 2016)	Total = 51 ACL-R Gr (n = 25) Healthy CG (n = 25)	Non-athletes	M (n = 16), F (n = 9)	24 (4.2)	1.77 (0.1) 1.75 (0.09)	83 (17.8) 73.5 (13.0)	5.6 (2.6) months
Sigward et al. (Sigward et al., 2016)	Total = 19 ACL-R Gr	Non-athletes	M (n = 5), F (n = 14)	26.8 (12.4)	NR	NR	96.7 (16.8) days
Havens et al. (Havens et al., 2018)	Total = 14 ACL-R Gr	Recreational athletes	M (n = 7), F (n = 7)	29 (12.0)	1.72 (0.1)	72.3 (13.4)	20.3 (7.1) weeks
Pratt et al. (Pratt & Sigward, 2018a, 2018b)	Total = 21 ACL-R Gr	Recreational athletes	M (n = 9), F (n = 12)	28.8 (11.2)	170.9 (9.9)	68.7 (13.1)	5.1 (1.5) months
Pratt et al. (Pratt & Sigward, 2018a, 2018b)	Total = 21 ACL-R Gr	Recreational athletes	M (n = 9), F (n = 12)	28.8 (11.2)	NR	NR	5.1 (1.5) months
Thomson et al. (Thomson et al., 2018)	Total = 32 ACL-Gr (n = 16) Healthy CGr (n = 16)	Soccer players	M	26 (4.0) 28 (4.0)	178 (6.0) 179 (6.0)	74 (6.0) 77 (9.0)	5-10 months
Dan et al. (Dan et al., 2019)	Total = 102 ACL-R Gr (n = 65) Healthy CGr 1 (n = 27) Healthy CGr 2 (n = 10)	Non-athletes Non-athletes Rugby players	M (n = 6), F (n = 19) M (n = 17), F (n = 10)	33.8 (10.0) 25.9 (9.7) 22.8 (3.6)	NR	NR	8-15 months
Peebles et al. (Peebles et al., 2019a)	Total = 55 ACL-R Gr (n = 25) Healthy CGr (n = 30)	Non-athletes	M (n = 6), F (n = 19) M (n = 12), F (n = 18)	18.7 (3.0) 22.2 (3.8)	173 (7.4) 72.3 (14.3)	171 (8.5) 66 (10.3)	1.5 (2.23) weeks after RTS. The period of RTS was not informed
Kim et al. (Kim et al., 2020)	Total = 35 ACL-R Gr (n = 15) Healthy CGr (n = 20)	University athletes	M (n = 12), F (n = 3) M (n = 10) F (n = 10)	18.7 (3.0) 22.2 (3.8)	185 (11.2) 173 (8.1)	94.9 (22.6) 71.4 (11.6)	26.1 (9.1) weeks
Vervaat et al. (Vervaat et al., 2020)	Total = 48 ACL-R Gr (n = 30) Healthy CGr (n = 18)	Non-athletes	M (n = 16), F (n = 14) M (n = 7), F (n = 11)	24.5 (8.1) 34.3 (12.2)	1.74 (0.08) 1.74 (0.1)	76.4 (14.0) 70.8 (11.5)	6 weeks 3 months

Note: Data presented as mean (SD). ACL-R = anterior cruciate ligament reconstruction; ACL-R Gr = anterior cruciate reconstruction group; CGr = control group; n = number; M = male; F = female; yrs = years; NR = not reported; m/cm = meters and centimeters; kg = kilograms.

2020) (Pratt & Sigward, 2018a, 2018b) (Pratt & Sigward, 2018a, 2018b) (Sigward et al., 2016; Thomson et al., 2018; Vervaat et al., 2020). Peebles et al. (Peebles et al., 2019a) conducted their assessment 1.5 (±2.2) weeks after patients had been cleared for RTS. The duration of the rehabilitation process was not provided by the author. The shortest and most prolonged time post-surgery for assessment was 6 weeks (Vervaat et al., 2020) and 6.3 years (Setuain et al., 2015a) respectively.

Table 2 Sensor specification including, brand, sampling rate, number of devices used and anatomical location they were placed, and derived variables for analysis.

Author	**Sensor specification**	**Sampling rate (Hz)**	**# of sensor (s)**	**Location (s)**	**Analyzed variable (s)**
Setuain et al. (Setuain et al., 2015a)	Inertial orientation tracker (MTx, 3DOF Human Orientation Tracker, Xsens Technologies B.V., Enschede, Netherlands)	100	1	Attached at the CoM (L3)	Linear acceleration Angular displacement of the CoM
Bailey et al. (Bailey et al., 2016)	3-axis, wireless accelerometer (3-Space Wireless Sensor, YEI Technology, Portsmouth, OH, USA)	200	1	Attached at the CoM (L3)	Linear acceleration of the CoM
Sigward et al. (Sigward et al., 2016)	Tri-axial accelerometers, gyroscopes and magnetometers (Opal brand, APDM Inc., Portland, OR, USA)	128	2	Bilaterally placed at the Shank	Peak shank angular velocity
Havens et al. (Havens et al., 2018)	Tri-axial accelerometers, gyroscopes and magnetometers (Opal brand, APDM Inc., Portland, OR, USA)	128	4	Bilaterally placed at the thigh and Shank	Peak thigh and shank acceleration
Pratt et al. (Pratt & Sigward, 2018a, 2018b)	Tri-axial accelerometers, gyroscopes and magnetometers (Opal brand, APDM Inc., Portland, OR, USA)	128	2	Bilaterally placed at the thigh	Thigh angular velocity
Pratt et al. (Pratt & Sigward, 2018a, 2018b)	Tri-axial accelerometers, gyroscopes and magnetometers (Opal brand, APDM Inc., Portland, OR, USA)	128	4	Bilaterally placed at the thigh and shank	Thigh, knee and shank angular velocity
Thomson et al. (Thomson et al., 2018)	Pedar-X in-shoe system (Novel, Munich, Germany)	100	2	Bilaterally placed inside the running shoes	Maximum plantar force (Fmax) Contact time
Dan et al. (Dan et al., 2019)	3D accelerometer (ST Microelectronics LSM303DLHC)	100	2	Bilaterally placed at the Shank	Frontal knee varus/valgus alignment
Peebles et al. (Peebles et al., 2019a)	Single-sensor insoles (loadsol®, Novel Electronics)	100	2	Bilaterally placed inside the running shoes	Peak impact force Loading rate Impulse

Kim et al. (Kim et al., 2020)	Tri-axial gyroscope and accelerometer (IMU CaneSense™)	50	3	CoM and bilaterally placed at the Shank	Linear acceleration of the CoM Shank angular velocity
Vervaat et al. (Vervaat et al., 2020)	Tri-axial accelerometers, gyroscopes and magnetometers (MTx, Xsens)	100	1	Attached at the CoM (L3)	Linear acceleration and angular displacement of the CoM

Note: # = number; Hz = hertz; CoM ¼ center of mass, L3 = third lumbar spine vertebra.

3.4. Sensor placement

A variety of anatomical locations were used. One study placed sensors on the centre of mass (CoM) and shank (Kim et al., 2020) while 2 selected the thigh and the shank (Havens et al., 2018) (Pratt & Sigward, 2018a, 2018b). The other studies placed sensors on the CoM (Bailey et al., 2016) (Setuain et al., 2015a) (Vervaat et al., 2020), thigh (Pratt & Sigward, 2018a, 2018b) and shank (Dan et al., 2019) (Sigward et al., 2016) only. Two studies positioned sensors inside running shoes (Peebles et al., 2019a) (Thomson et al., 2018).

3.5. Technical specification

The sampling rate of the IMU sensors varied across the studies. The most common was 100 Hz (Dan et al., 2019) (Setuain et al., 2015a) (Vervaat et al., 2020) and 128 Hz (Havens et al., 2018) (Pratt & Sigward, 2018a, 2018b) (Pratt & Sigward, 2018a, 2018b) (Sigward et al., 2016). The lowest and highest sampling rate used were 50 Hz (Kim et al., 2020) and 200 Hz (Bailey et al., 2016) respectively. The sampling rate of the insole sensors was 100 Hz (Peebles et al., 2019a) (Thomson et al., 2018).

3.6. Assessments

Jumping tasks were the most commonly used tests, () consisting mainly of bilateral and unilateral drop and countermovement jumps (Dan et al., 2019) (Setuain et al., 2015a), single leg landing (Pratt & Sigward, 2018a, 2018b) (Pratt & Sigward, 2018a, 2018b), single hop, triple hop and crossover hop tests (Dan et al., 2019) (Peebles et al., 2019a). Other testing protocols included stepping-up-and-over a box (Bailey et al., 2016), walking gait (Sigward et al., 2016), running at different speed zones (Thomson et al., 2018), 4-m side step test (Kim et al., 2020) and stair descent (Vervaat et al., 2020).

Table 3 Setting, tests performed, protocol adopted, and main testing results.

Author	**Setting (s)**	**Test (s)**	**Protocol**	**Main testing results**
Setuain et al. (Setuain et al., 2015a)	Training court	VBDJ (50 cm), VUDJ (20 cm), and VUCMJ	2 reps for each test 10 s rec between jumps	No difference in CoM acceleration and displacement between groups.
Bailey et al. (Bailey et al., 2016)	NR	SUAO test (305 mm high box) at a self-selected speed	5 trials for each leg in a random order	CoM acceleration was more asymmetrical for ACL-R patients compared to healthy counterparts.
Sigward et al. (Sigward et al., 2016)	Laboratory	10 m walking at a self-selected pace	3 successful trials for each limb	Peak knee extensor moment and shank angular velocity were significantly lower in the involved limb.
Havens et al. (Havens et al., 2018)	Laboratory	15 m running at a self-selected speed	3 successful trials	Between-limb differences in thigh axial acceleration predicted asymmetries in knee power absorption and ground reaction force.
Pratt et al. (Pratt & Sigward, 2018a, 2018b)	Laboratory	SLL task	1 successful trial of 3 reps for each leg	Thigh angular velocity ratios detected between-limb asymmetry in knee loading.
Pratt et al. (Pratt & Sigward, 2018a, 2018b)	Laboratory	SLL task	1 successful trial of 3 reps for each leg	Thigh angular velocity explained 66% and 34% of variance in knee power and knee moments asymmetry between limbs.
Thomson et al. (Thomson et al., 2018)	Laboratory	Running at 12, 14, and 16 km/h on a tread-mill in a random order	3 trials for each speed with 6 consecutive stance phase steps recorded	Greater between-limb asymmetry for Fmax at all running speeds <9 months' post-surgery. No difference in Fmax asymmetry between >9 months' post-surgery and healthy controls.
Dan et al. (Dan et al., 2019)	Laboratory	Double/single leg squat, SHD, THD, Double/single leg box drops (50 cm)	5 trials for each test	Non-athletes ACL-R patients displayed higher knee varus/valgus malalignment compared to their athletes' counterpart. The values increased during unilateral tasks.
Peebles et al. (Peebles et al., 2019a)	NR	SHD, THD, and CHD	2 reps each limb 5 min rec between test	ACL-R patients recorded lower hop distance and loading rate limb symmetry values compared to healthy controls. Larger forces were generated when hopping on the uninvolved limb relative to their involved limb.
Kim et al. (Kim et al., 2020)	Indoor gymnasium	FmSST	2 successful trials 1 min rec between reps	TADS SI between-limbs was lower at the time to RTS compared to baseline.
Vervaat et al. (Vervaat et al., 2020)	Hospital	Self-paced stair descent test	2 trials of 11 steps 5 min rec between trials	High to excellent reliability for mean step time and LSI in ACL-R patients. No differences in reliability values between ACL-R patients and healthy controls.

Note: NR = not reported; ACL-R = anterior cruciate reconstruction; RTS = return to sport; reps = repetition; min = minutes; sec = seconds; rec = recovery; m = meters; cm = centimeters; km/h = kilometers per hour; VDBJ = vertical bilateral drop jump; VUDJ = vertical unilateral drop jump; VUCMJ = vertical unilateral countermovement jump; SUAO = step-up-and-over; SLL = single leg loading; SHD = single hop for distance; THD = triple hop for distance; CHD = crossover hop for distance; FmSST = 4-m side step test; CoM = center of mass; Fmax = maximal plantar force; TADS = transitional angular displacement; SI = symmetry index; LSI = limb symmetry index.

3.7. Outcome measures

Linear acceleration, angular velocity and displacement derived from IMU sensors were the main kinematic variables reported across the included studies (Bailey et al., 2016) (Havens et al., 2018) (Kim et al., 2020) (Pratt and Sigward, 2018a, 2018b; Setuain et al., 2015a; Sigward et al., 2016) (Vervaat et al., 2020). Additional outcome measures included frontal plane knee alignment (varus/valgus) (Dan et al., 2019), plantar force, peak impact force and loading rate using pressure insole sensors (placed inside running shoes) (Peebles et al., 2019a) (Thomson et al., 2018).

3.8. Main outcomes

3.8.1. Validity and reliability

Pratt et al. (Pratt & Sigward, 2018a, 2018b) examined the concurrent validity for measures of segment and joint angular velocity between inertial sensors (placed at the thigh and shank) and an optical motion analysis system during a single-limb landing task following ACLR. The authors reported strong agreement between both measurement systems for knee, thigh and shank angular velocities (ICC >0.90). Vervaat et al. (Vervaat et al., 2020) investigated the test-retest reliability of mean step time derived from CoM acceleration and limb symmetry index (LSI) of this variable during a stair decent task. The authors found high to excellent reliability for mean step time (ICC = 0.87-0.96) and LSI (ICC = 0.80-0.87) in ACL reconstructed patients. No differences in reliability were indicated between those with ACL reconstruction and healthy controls.

3.8.2. Kinematics

Bailey et al. (Bailey et al., 2016) examined CoM acceleration during a step-up-and-over box test and reported significantly greater asymmetry between limbs during the lift and impact phases of the test for the ACLR patients compared to healthy counterparts ($p < 0.05$). In contrast, Setuain et al. (Setuain et al., 2015a) reported no significant difference in CoM acceleration and displacement between ACLR handball athletes and heathy matched controls during a range of jumping tests, including bilateral and unilateral drop jumps and a unilateral countermovement jump. The authors also did not identify differences between limbs in the ACLR group (Setuain et al., 2015a). Kim et al. (Kim et al., 2020) combined CoM acceleration with shank angular velocity to examine the transitional angular displacement of the lower limbs during a 4-m side-step test. The authors reported the symmetry index between involved and uninvolved limbs was significantly lower at the time of RTS than baseline values ($p = 0.046$). Also, a large effect size ($d = -1.04$) was observed for the change in symmetry index from baseline (20.1 ± 11.8 weeks before injury) to RTS (26.1 ± 9.1 weeks since surgery).

Sigward et al. (Sigward et al., 2016) examined shank angular velocity during walking. Although stance and swing times were similar for both limbs, the authors reported significantly lower values in the involved limb ($p < 0.001$). Using the same placement of the IMU sensor, Dan et al. (Dan et al., 2019) examined lower limb alignment (knee varus/valgus position) during a range of bilateral and unilateral tasks across three different groups, including ACLR patients and, healthy controls who were both non-athletes, and elite Rugby players with no history of knee injury. The authors reported that the elite Rugby players displayed less knee varus/valgus movement during double and single leg squats compared with the ACLR patients ($p < 0.01$), who in turn had less varus/valgus malalignment than non-athlete controls during the same testing protocol as well as in box drop double and single leg landings ($p < 0.01$). The ACLR group also displayed higher varus/valgus movement on the involved limb during single leg box drop ($p = 0.04$) and squat ($p = 0.02$). No differences between involved and uninvolved limbs were observed during bilateral tasks.

3.8.3. Kinetics

Kinetic outcomes were reported in 2 studies.[19 24] Peebles et al. (Peebles et al., 2019a) examined the loading rate derived from a force insole during a hop testing protocol. The authors reported that ACLR patients recorded lower hop distance and loading rate limb symmetry values than healthy controls ($p < 0.05$). The ACLR group also hopped further and generated larger forces on their uninvolved relative to their involved limb. Thomson et al. (Thomson et al., 2018) used an in-shoe pressure system to examine a proxy of maximum vertical force during running at 12, 14 and 16 Km/h on a treadmill in soccer players with ACLR and healthy controls. The authors reported greater maximum vertical force asymmetry at all running speeds for players who were <9 months compared to those who were >9 months post-surgery, and the heathy controls ($p < 0.05$, $d = 1.6$-2.04). There was also a trend for elevated asymmetry with increasing speeds for those who were <9 months after ACLR but not for the other two groups. No significant difference in maximum vertical force asymmetry was observed between those who were >9 months' post-surgery and healthy controls.

3.8.4. Estimation of kinetics

Estimation of kinetics was reported in four studies (Havens et al., 2018) (Pratt & Sigward, 2018a, 2018b) (Pratt & Sigward, 2018a, 2018b) (Sigward et al., 2016). Havens et al. (Havens et al., 2018) examined thigh and shank acceleration during a self-paced running protocol. Between-limb differences in thigh axial acceleration predicted asymmetries in knee power absorption and ground reaction force, explaining 30 and 38% of the variance respectively ($p = 0.045$). Shank acceleration was not predictive of any biomechanical variable. The use of thigh and shank angular velocity to detect knee power and knee moment asymmetry following ACLR was further investigated by Pratt (Pratt and Sigward, 2018a) (Pratt & Sigward, 2018a, 2018b). Thigh angular velocity ratios detected asymmetry in knee loading during a single-limb loading forward leap and return task for a distance relative to their leg length with high sensitivity (81%) and specificity (100%) (Pratt & Sigward, 2018a, 2018b). Thigh ($r = 0.812$ and $r = 0.585$; $p < 0.001$) and knee angular velocities ($r = 0.806$ and $r = 0.536$; $p < 0.001$) were also strongly and moderately correlated to knee power and knee moments (Pratt & Sigward, 2018a, 2018b). Thigh angular velocity explained 66% and 34% of variance in knee power ($R^2 = 0.660$, $p < 0.001$) and knee moment ($R^2 = 0.342$, $p < 0.001$) asymmetry (Pratt & Sigward, 2018a, 2018b). Sigward et al. (Sigward et al., 2016) examined the relationship between shank angular velocity and knee extensor moments during walking. The authors reported a strong association between peak shank angular velocity and knee extensor moment ($r = 0.75$, $p < 0.001$) and between-limb ratios of angular velocity predicted between-limb ratios of extensor moments ($r^2 = 0.57$, $p < 0.001$).

4. Discussion

The preliminary findings of our scoping review indicate that following ACLR, kinetic and kinematic deficits are consistently identified between the involved vs. uninvolved limbs and compared to healthy controls. However, caution should be applied as the number of validation studies using criterion measures was relatively small, and differences were not always observed. This may be due to different methods including the task used, sensor placement and specification, absence of a control group and time of assessment post-surgery.

4.1. Between-limb differences identified using wearable technology

4.1.1. Kinematics

In total, four of five studies (Bailey et al., 2016) (Dan et al., 2019) (Kim et al., 2020) (Sigward et al., 2016) identified kinematic differences. Dan et al. (Dan et al., 2019) reported alterations in lower limb alignment (knee varus/valgus position) derived from a tibial mounted accelerometer during a single leg box drop and squat. In the remaining studies, observed differences included: 1) higher lift and impact indexes derived from CoM acceleration for the involved limb during a step up and over test (Bailey et al., 2016); 2) low transitional angular displacement symmetry derived from CoM acceleration and shank angular velocity during a 4-m side-step test at the time of RTS compared to baseline values (pre-injury assessment) (Kim et al., 2020); and 3) lower shank angular velocity for the involved limb during walking (Sigward et al., 2016). No between-limb differences in the time to complete the task were shown, indicating the performance outcome was achieved in the presence of kinematic compensations. Previous research has reported similar findings using three-dimensional motion analysis (King et al., 2018). Residual between-limb differences in a range of biomechanical variables were present when changing direction, even though the time taken to complete the task did not differ when cutting of each leg (King et al., 2018). Further research is needed to examine kinematic variables derived from wearable technology during more sports representative tasks that involve rapid limb loading, such as sprinting and change of direction.

4.1.2. Kinetics

Two studies in our review examined kinetic differences between-limbs (Peebles et al., 2019a) (Thomson et al., 2018). Increased loading rate asymmetry and lower ground reaction force on the involved limb derived from a force insole (Loadsol®, Novel, Germany) were shown during a hop for distance test (Peebles et al., 2019a); and greater maximum vertical force asymmetry was evident during a running test protocol at different speed thresholds (12, 14 and 16 Km/h) using an in-shoe pressure system (PedarX, Novel, Germany). (Thomson et al., 2018).

The Loadsol® has capacitive force sensors that transmit data over Bluetooth to a smartphone or tablet. Previous research has reported the validity of the loadsol® compared to a force plate in healthy participants during a single leg hop and bilateral stop jump (Peebles et al., 2018). ICCs for peak impact force, loading rate and impulse were classified as moderate to excellent (0.765-0.987); however, there was evidence of bias with the loadsol underestimating force plate measures. Limb symmetry values were similar between the two measurement systems (Peebles et al., 2018). Associations with kinetic measures including peak and average knee extension moment, and total knee work derived from three-dimensional motion analysis have also been examined (Peebles et al., 2019b). Results indicated impulse limb symmetry measured by the loadsol predicted average and peak knee extension moment symmetry, explaining 47 and 61% of the variance respectively. In addition, ~ half of the variance (42%) in knee work symmetry was explained by the loadsol measurement of peak impact force asymmetry. It should be noted that this study used a sampling rate of 100 Hz. The 'loadsol' is also capable of measuring at 200 Hz and has shown stronger validity compared to criterion measures (Peebles et al., 2018).

The PedarX in-shoe pressure system is a thin (1.9 mm) flexible insole with an array of capacitive pressure sensors connected via cables to a data logger box that is carried on a belt by the athlete. Data is sampled at 100 Hz and can be transmitted to a laptop in real-time (Peebles et al., 2018). Validity and reliability of the PedarX system has previously been reported as excellent (Barnett et al., 2000) when compared to a force plate. Maximum plantar peak vertical ground reaction force is slightly underestimated compared to force plate systems. However, underestimation is repeated in a reliable manner (Barnett et al., 2000) (St€oggl & Martiner, 2017). During walking and running tasks, intraclass correlation coefficient (ICC) values between 0.96 and 0.98 have been reported for maximum plantar force (Van Alsenoy et al., 2019).

Four studies also examined the ability of wearables to estimate kinetics (Havens et al., 2018) (Pratt & Sigward, 2018a, 2018b) (Pratt & Sigward, 2018a, 2018b) (Sigward et al., 2016). Results showed knee power absorption, and ground reaction force asymmetry was predicted by thigh axial acceleration during a self-paced running protocol (Havens et al., 2018). Another study demonstrated knee loading asymmetry, knee power and moments were predicted by thigh and knee angular velocity respectively during a single limb loading task (Pratt & Sigward, 2018a, 2018b) (Pratt & Sigward, 2018a, 2018b). Knee extensor moments were also predicted by shank angular velocity during walking (Sigward et al., 2016). Associations with second ACL injury and knee extensor moment asymmetry have been shown in athletes returning to cutting sports (Paterno et al., 2010). Cumulatively, these preliminary findings indicate that wearable sensors display moderate-strong predictive ability for the detection of residual kinetic deficits including between-limb differences in knee power absorption and extensor moments following ACL reconstruction. These findings may have implications for re-injury risk and provide a viable alternative, 'bridging the gap' when laboratory protocols are either not available or feasible.

4.2. Differences to healthy controls

In the absence of normative values from healthy controls, symmetry indices and between-limb (involved vs. uninvolved) comparisons may overestimate the level of function (Wellsandt et al., 2017). Bilateral deficits have been demonstrated after ACL injury (Hiemstra et al., 2007; Palmieri-Smith et al., 2008; Urbach et al., 2001), challenging the validity of only examining limb symmetry to determine rehabilitation status. In our scoping review, five studies included a control group (Bailey et al., 2016) (Dan et al., 2019) (Peebles et al., 2019a) (Setuain et al., 2015a) (Thomson et al., 2018). Results showed that three out of five studies (Bailey et al., 2016) (Peebles et al., 2019a) (Thomson et al., 2018) identified more pronounced differences for the ACLR group at the time of return to sport relative to healthy controls.

Between-group differences were not evident in two out of five studies (Dan et al., 2019) (Setuain et al., 2015a). Dan et al. (Dan et al., 2019) showed improved lower limb alignment scores in those with ACLR derived from an accelerometer mounted on the tibia during a double leg squat and single/double leg box drop compared to normal healthy controls but not elite athletes. The authors suggested lower limb control is associated more with athletic ability and younger age than injury status. The absence of matched controls in this study limits our interpretation. Setuain et al. (Setuain et al., 2015a) also reported no between-group differences for CoM acceleration and displacement during a range of jumping tests six years after surgery. These data indicate the normalization of movement patterns several years following ACL reconstruction. Further research is needed including healthy matched controls to more clearly elucidate the sensitivity of wearable technology to identify between limb deficits during movement tasks at different time-points following ACLR.

4.3. Methodological considerations that guide our interpretation and can affect our ability to identify relevant deficits

4.3.1. Validity and reliability

Before integrating wearable technology into routine clinical practice, it is imperative that wearable devices are accurate, reliable and valid. The preliminary evidence including the studies in our scoping review indicate moderate to strong agreement between IMUs and gold standard techniques (e.g., optical motion capture system and force plates) to detect knee loading (knee moments and knee joint power) (Pratt & Sigward, 2018a, 2018b) and strong to excellent reliability (Vervaat et al., 2020). However, caution should be applied as the available literature is sparse, and the range of movement tasks and variables assessed were also limited. Currently, the validity of these devices to detect knee loading differences has only been examined in walking (Sigward et al., 2016), self-paced running (Havens et al., 2018), and a single limb forward lunge and return task for a distance relative to leg length (Pratt & Sigward, 2018a, 2018b) (Pratt & Sigward, 2018a, 2018b). Further research is needed to confidently determine the validity of wearable technology to monitor progress during rehabilitation and enhance the efficacy of RTS decisions. A broader range of tasks should also be examined, including those occurring at high velocities with more rapid limb loading, representative of sport demands.

4.3.2. Effect of time post-surgery

Two studies from our review indicate that elapsed time post-surgery affects the ability of wearable technology to identify between-limb (injured vs non-injured) and group (ACL reconstructed vs controls) differences. Setuain et al. (Setuain et al., 2015a) examined drop jumps and a unilateral countermovement jump in handball athletes with and without ACLR six years after surgery. No between-group or limb differences were reported in CoM acceleration and displacement suggesting these athletes had restored task performance and kinematic movement strategy. However, there was a large standard deviation in the time from surgery to testing (±3.4 years) and only 6 participants with a history of ACLR were recruited, limiting the interpretation of the results.

Thomson et al. (Thomson et al., 2018) examined maximum vertical force asymmetry using an in-shoe pressure system in soccer players with and without ACLR during a running task on a treadmill at 12, 14 and 16 Km/h. The authors reported significantly greater asymmetry across all running speeds for the players <9 months post-surgery than those ≥9 months and their healthy counterparts. No significant asymmetries were reported between players ≥9 months' post-surgery and healthy controls. Other studies[8 51] using gold standard assessment modes, including force plates and three-dimensional motion analysis have reported biomechanical asymmetries can remain >9 months post ACL reconstruction. Maximum vertical force may lack sensitivity to identify movement deficits, with impulse (Read et al., 2020) and rate of force development (Angelozzi et al., 2012) more able to identify residual deficits in the later periods of rehabilitation following ACLR. Further research is warranted to include longitudinal assessment of key variables in a range of movement tasks following ACLR using wearable technology and compare to gold standard methods to more clearly determine temporal recovery.

4.3.3. Sensor specification

For accurate measurement, the sampling rate should be a minimum of two times the highest frequency in the signal of interest (Jerri, 1977). It has been assumed that voluntary human movements do not exceed 10 Hz; thus, adopting a sampling frequency ≥20 Hz to record human movement might be considered reasonable (Khan et al., 2016). However, complex movements may not follow this principle. To determine the frequency of the signal and required sampling rate, the movement pattern assessed (e.g. jumping, squatting), dependent variables of interest (e.g. mean, peak and rate dependent variables) and measurement system used (e.g. accelerometer, force plates, position transducers) should be considered (McMaster et al., 2014). If the sampling rate is too low, relevant information can be lost.

In our scoping review, the lowest and highest sampling rates were 50 Hz (Kim et al., 2020) and 200 Hz (Bailey et al., 2016) respectively. The most common was 100 Hz (Dan et al., 2019) (Setuain et al., 2015a) (Vervaat et al., 2020) and 128 Hz. (Havens et al., 2018) (Pratt & Sigward, 2018a, 2018b) (Pratt & Sigward, 2018a, 2018b) (Sigward et al., 2016). Zhou et al. (Zhou et al., 2020) suggested a sampling rate of 100 Hz is sufficient to analyse walking and running. Provot et al. (Provot et al., 2017) observed that 100 Hz generally represents the spectrum of cumulative frequencies between low (i.e. 8 Km/h) and high-speed (i.e. 18 Km/h) running based activity. Khan et al. (Khan et al., 2016) reported an optimal sampling rate for walking, going up/downstairs, jumping and running ranges from 30 to 63 Hz, substantially below the original signal used (100 Hz). Cumulatively, it appears the studies included in our review used sensors sampling at an appropriate rate for the movements examined. Still, practitioners are encouraged to consider their suitability based on the intended use and further research is warranted including a broader range of tasks with higher force production demands and movement velocities.

4.3.4. IMU sensor placement

One study placed sensors on the centre of mass (CoM) and shank (Kim et al., 2020), three studies (Bailey et al., 2016) (Setuain et al., 2015a) (Vervaat et al., 2020) placed sensors on the CoM (L3) to measure between-limbs asymmetries, while two selected the thigh and shank (Havens et al., 2018) (Pratt & Sigward, 2018a, 2018b). Other studies placed sensors on the CoM (Bailey et al., 2016) (Setuain et al., 2015a) (Vervaat et al., 2020), thigh (Pratt & Sigward, 2018a, 2018b) and shank (Dan et al., 2019) (Sigward et al., 2016) only. The optimal sensor placement to measure lower limb kinetics and kinematics during functional tasks following ACLR remains unknown. According to Willy et al. (Willy, 2018), an array of IMU sensors mounted on the foot, shank, thigh and pelvis, and associated algorithms are required to calculate lower limb kinematics. Niswander et al. (Niswander et al., 2020) observed that sensors placed at the sacrum, lower anterior thigh, middle lateral shank, and heel were more sensitive and produced the lowest error compared to the reference optical motion capture system.

The combination of sensor locations should ultimately be driven by the motions and/or joints involved. Norris et al. (Norris et al., 2013) reported the placement of the sensors closest to the area of interest provides the most accurate results. A minimum of two IMU sensors mounted on the shank and thigh is required to examine the knee joint (Struzik et al., 2016). Macadam et al. (Macadam et al., 2019) measured sprint performance using inertial sensors over different anatomical locations (e.g. in-between scapulae, lumbar spine and lower limb). The authors reported that the more distal lower-limb sensors are located (i.e., closer to the foot), and the higher the sample rate (≥200 Hz), the more accurate the detection of temporal step variables (e.g., contact time, stride time). Similarly, sensor placement at the CoM (i.e., lumbar and sacrum) displays higher accuracy to measure trunk displacement and resultant peak force than sensors located in-between scapulae. Cumulatively, the further the sensor is away from the impact point (the foot), lower validity is present (Macadam et al., 2019).

4.3.5. Task used

The majority of studies in our scoping review used jump-landing tasks. () These consisted of bilateral and unilateral drop and countermovement jumps (Dan et al., 2019) (Setuain et al., 2015a), single leg landing (Pratt & Sigward, 2018a, 2018b) (Pratt & Sigward, 2018a, 2018b), single hop, triple hop and crossover hop tests (Dan et al., 2019) (Peebles et al., 2019a). Dan et al. (Dan et al., 2019) reported asymmetries during a single leg but not bilateral box drop using a 3 dimensional tibial accelerometer. However, there were differences in force distribution in the bilateral task identified using a pressure mat. The relative force demands are higher during unilateral tasks. This indicates the single leg box drop may provide a more accurate representation of limb capacity and could be a used to monitor knee function using wearable technology following ACLR. Bilateral tests allow for interlimb compensation strategies (Sigward et al., 2016) and altered force distribution. Athletes have been shown to unload the involved limb during a countermovement jump following ACLR at various time points during rehabilitation using force plate analysis (Read et al., 2020). These kinetic compensations cannot readily be identified using accelerometers and may require the use of a force platform.

Peebles et al. (Peebles et al., 2019a) also reported that hop testing (i.e., single hop, triple hop and crossover hop) was able to identify kinetic differences between limbs in ACLR patients compared to healthy controls ~ 1 week after being cleared to return to sports by their orthopedic surgeon. A recent review (Pedley et al., 2020) has shown hop testing protocols display a lower association with lower-extremity injury risk than more demanding tasks such as a drop vertical jump. Poor mechanics during drop jumps have also been associated with an increased risk of second injury following ACLR (King et al., 2020). Future research could examine the association of kinematic and kinetic variables recorded from wearable technology and subsequent ACL (re)injury risk. Other studies included in this scoping review observed between-limb loading deficits during single leg forward leap to a distance relative to their tibia followed by a reverse push off back to the start position (Pratt & Sigward, 2018a, 2018b) (Pratt & Sigward, 2018a, 2018b). These tests could be used in the earlier stages of rehabilitation. The application of wearables during sporting tasks such as change of direction remains unknown.

5. Clinical implications

The preliminary evidence of our scoping review indicates that practitioners could consider the inclusion of wearable sensors in clinical practice since this technology seems to be display moderate-strong associations with criterion measures and was consistently able to identify between-limb and group differences following ACLR. These devices may help practitioners to tailor exercise prescription and monitor progress during rehabilitation. There are also potential applications to enhance decision-making in the RTS process. However, caution should be applied as the number of validation studies was low, and only a limited number of functional tasks have been examined. For accurate measurement, some key methodological considerations are present including the type of task, anatomical location and placement of the sensors, and the sampling rate of the devices.

6. Conclusions

Cumulatively, our findings indicate that wearable sensors consistently identified residual kinetic and kinematic deficits following ACL reconstruction and may provide a viable alternative, ‘bridging the gap’ when laboratory protocols are either not available or feasible. However, further validation is needed across a wider range of tasks and time-points post-surgery using criterion measures. Differences were not observed in all studies, which may be due to differences in methods (e.g., task used, sensor placement and specification, time of assessment post-surgery) and the absence of a healthy control group. We recommend practitioners should if possible, evaluate function during rehabilitation using wearables and not just rely on outcome measures (e.g., distance hopped) to provide more objective data when making RTS decisions.

Ethical statement

Not required as it is a review article.

Declaration of competing interest

The authors confirm there are no conflicts of interest associated with any aspects or content of this manuscript.

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