The use of inertial measurement units for analyzing change of direction movement in sports: A scoping review

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Abstract
Change of direction movement is common in sports and the ability to perform this complex movement efficiently is related to athlete’s performance. Wearable devices have been used to evaluate aspects of change of direction movement, but so far there are no clear recommendations on specific metrics to be used. The aims of this scoping review were to evaluate the reliability and validity of inertial measurement unit sensors to provide information on change of direction movement and to summarize the available evidence on inertial measurement units in analyzing change of direction movement in sports.

A systematic search was employed in MEDLINE (Ovid), CINAHL (EBSCO host), SPORTDiscus (EBSCO host), EMBASE and Cochrane Database of Systematic Reviews and Web of Science to identify eligible studies. A complementary grey literature search was employed to locate non-peer reviewed studies. The risk of bias of the studies evaluating validity and/or reliability was evaluated using the AXIS tool.

The initial search identified 15,165 studies. After duplicate removal and full-text screening 49 studies met the inclusion criteria, with 11 studies evaluating validity and/or reliability. There are promising results on the validity and reliability, but the number of studies is still small and the quality of the studies is limited. Most of the studies were conducted with pre-planned movements and participants were usually adult males. Varying sensor locations limits the ability to generalize these findings. Inertial measurement units (IMU) can be used to detect change of direction (COD) movements and COD heading angles with acceptable validity, but IMU measured or derived kinetic or kinematic variables present inconsistency and over-estimation.

Studies can be improved with larger sample sizes and agreement on the metrics used and sensor placement. Future research should include more on-field studies.

Keywords
Acceleration, agility, change of direction, motion capture, wearable technology

Introduction
Change of direction (COD) movements are common in sports. The ability to perform efficient and controlled COD movement requires technical abilities, adequate lower extremity muscle strength and speed and is relevant for both performance and injury prevention.\textsuperscript{1–3}

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International Journal of Sports Science & Coaching
© The Author(s) 2021
DOI: 10.1177/17479541211003064 journals.sagepub.com/home/sco
Agility has been identified as an important performance variable for differentiating elite and sub-elite players, and one definition of agility is the ability to change the direction of movement quickly and precisely. Better understanding of the kinematic or kinetic indicators for COD performance rather than evaluating only time or speed would provide more comprehensive understanding of COD movement and how it can be improved. From an injury point of view, COD movement has been identified as a common injury situation for anterior cruciate ligament (ACL), ankle and groin injuries, due to the multiplanar nature of this high-load movement. Previous studies have shown that correcting specific biomechanical patterns with appropriate training methods can reduce the number of ACL injuries. However, the previously utilized methods for recognizing incorrect movement patterns (i.e., measuring knee valgus in drop-jump tests or multiplanar side-jumps) have shown poor association with future injuries, which is most likely due to poor relation of standardized test movements to spontaneous movement patterns in sports. Inertial measurement units (IMUs) could be a solution for measuring biomechanical patterns during in-sport movements and providing relevant information about movement quality for performance enhancement and injury prevention purposes. Therefore, being able to measure COD movement in a feasible, valid and reliable way using IMUs might provide more on-field reflective information for coaches, players, sports medicine professionals and researchers.

Motion capture systems are recognized as the gold standard for movement analysis and are used to measure joint moments, ground reaction forces, contact times, velocities, joint angles and speed of COD movement. However, motion capture systems are not easily transported to field settings. Global positioning systems (GPS) are a potential feasible on-field monitoring system, but there are limitations with GPS in recognizing high-speed direction changes. Due to this limitation GPS does little more than identify the number or frequency of whole body COD events. In contrast, IMUs have the potential to provide information about the quality of whole-body and individual segment movements during COD. IMUs are used to analyze several types of movement, such as walking, running and postural control, but the research is still mostly conducted in laboratory settings. IMUs are also an relatively inexpensive way to monitor athletes’ movement patterns during everyday practices and games. In previous studies, wearable devices have demonstrated good accuracy for detecting and quantifying sport-specific movements and variables, including jump counts and jump heights in volleyball and for quantifying typical biomechanical patterns in running.

Research on the ability of IMUs to detect and analyze COD movement exists, but so far this information has not been evaluated or summarized to provide recommendable practices. There are previous reviews presenting the challenges on the use of IMUs for measuring ground reaction forces and the use of regression techniques for continuous biomechanical monitoring. In addition, the review by Marques et al. underlines the need for viable solutions for on-pitch/court measurements to ‘bridge the gap’ between laboratory based measures and real-life situations.

The initial step for useful field-based automated analysis would be the valid and reliable detection of COD events. From these identified COD events it can be possible to quantify important mechanical variables related to COD movement. Valid and reliable information on the quantity, variability and quality of COD movements within the sports setting would be beneficial to players, sport practitioners and researchers. IMUs can be an accessible tool for decision making and training for player development, providing perhaps a more precise alternative method to commonly used GPS. In addition, IMUs may provide valuable information in guiding injury prevention and executing research on athlete performance and injury prevention. Thus, the purpose of this scoping review was to map the existing research on IMU use in detecting and quantifying COD movements. The primary aim was to evaluate the reliability and validity of IMU sensors to detect COD movement and quantify aspects related to COD movement, such as COD heading angles, and accelerations during COD movement. The secondary aim was to summarize the current evidence on the use of IMUs for COD analysis, including settings, populations and sensor requirements.

Methods

Literature search and study selection

The literature search and study selection followed the PRISMA extension for Scoping Reviews (PRISMA-ScR) checklist. The protocol of this scoping review was registered in the Open Science Framework (OSF) platform (https://osf.io/4kjr/). A systematic literature search was conducted in MEDLINE (Ovid), CINAHL (EBSCO host), SPORTDiscus (EBSCO host), EMBASE, Cochrane Database of Systematic Reviews and Web of Science. A grey literature search of Google Scholar, www.clinicaltrials.gov, the ISRCTN registry, and ProQuest Dissertations and Theses was conducted. The captured records contained at least one search term in each of two categories: change of direction and measurement (e.g. IMU, motion capture, ground reaction force). The search strategy for MEDLINE (Ovid) is detailed in Appendix 1 and was adapted
and modified for the requirements of the other databases. The final searches were conducted on 17 September 2020. Bibliographies of included studies were examined and original studies that were not identified in electronic searches were included in this scoping review, if they met the eligibility criteria. Search results were imported into an electronic program (Covidence, Melbourne, Australia), which was used to store articles, remove duplicates and facilitate the screening process.

Study selection was conducted in two stages. In the first stage, the titles and abstracts of potentially eligible studies were screened using the selection criteria. All studies were categorized as included, excluded or uncertain. In the second stage, the full text of studies that were categorized as included or uncertain were evaluated using the selection criteria. The reason for excluding full text studies was documented according to the hierarchy of the eligibility criteria described in Appendix 2. Study selection was carried out by two independent reviewers (AMA, AMR). Discrepancies were resolved by a third author (LCB).

Eligibility criteria

To be eligible for this review, studies had to (1) be written in English (2) include human participants (3) analyze COD movement with IMUs and (4) evaluate a COD maneuver common to sports or physical activity for the purpose of exercise. Articles were excluded if COD movement did not include taking a step (e.g. turning while skiing). Abstracts were included in this scoping review.

Data extraction

Studies evaluating validity and reliability were categorized based on the aim (type of validity, reliability). From studies that evaluated validity of IMUs to evaluate COD movement validity type (construct or concurrent), gold standard/comparator, outcomes, validity and findings were extracted. From studies that evaluated the reliability of IMUs to evaluate COD movement, outcomes, reliability and findings were extracted. To summarize the current evidence on the use of IMUs for COD movement analysis, the following information was extracted from all of the included studies: author, year of publication, study population and sport as reported in the study, participant age range, sex and number of participants, setting (e.g. laboratory, indoor court or outdoor field) and surface (e.g. grass, wood flooring), device manufacturer and model, sensors and sampling frequency, device attachment location, condition (drill, game/practice) and type of COD (preplanned or unplanned; COD heading angle; cut, sidestep or turn, based on the terminology used in the study). Quality assessment was performed on the studies that evaluated validity and/or reliability of IMUs on analyzing COD movement, as that was the main focus of the present review. The AXIS tool for evaluating the risk of bias of cross-sectional studies was used for quality assessment.46

Results

Study selection

In the initial search 15,165 references were identified and after removing the duplicates, 11,378 studies were screened by title and abstract. During title and abstract screening 11,193 studies were excluded. A total of 185 full-text studies were screened and 136 of them were excluded, resulting in 49 studies in the final analysis (Figure 1).

Validity and reliability of IMUs. 11 studies35,47–56 evaluated the validity of IMU measurement when analyzing COD movements (Table 1). Eight of these studies focused on concurrent validity of IMUs compared to a standard clinical measure or a biomechanical gold standard47,48,50 and three focused on the construct validity of IMUs.54–56 The study conducted by Netto et al.51 was only published as an abstract. Four of the validity studies also evaluated reliability of the IMU measurement (Table 2).

The validity of a variety of IMU-derived metrics was analyzed relative to motion capture systems, force plates and high-speed video. Three of the studies compared IMU captured mean and peak acceleration magnitudes against motion capture systems during team sport-specific movements.51–53 Both center of mass and segmental accelerations were evaluated and sport-specific movements included a modified circuit with running and cutting tasks. The results of these studies were inconclusive, showing poor (over-estimation of accelerations)51,52 or acceptable validity.53 Three of the studies compared IMU derived peak acceleration, average loading rate (the average gradient of the resultant acceleration data from touchdown to peak acceleration within the first 140 ms of stance phase) and impulse (calculated as the integral of the resultant acceleration over time).50 cranio-caudal and resultant acceleration converted to force48 and IMU derived estimates of step-average component and resultant force47 to force plate measures of magnitude and direction of ground reaction force (GRF) and center of mass acceleration.47,48,50 The conclusions from these three studies were that IMU derived estimates may provide valid information of the vertical component and magnitude of step-average ground reaction force.
vector during 45° COD\(^\circ\) and acceptable relative measures of peak foot-strike impact forces during 45° and 90° COD,\(^9\) but IMU derived segmental accelerations overestimated the acceleration of center of mass.\(^5\) Two of the studies compared IMU captured heading angle and magnitude of inertial movement analysis events against high-speed video.\(^35,49\) Inertial movement analysis (IMA) is a manufacturer software function to extract acceleration and deceleration events and COD magnitude as sum of acceleration in two planes over time. These findings concluded that IMUs showed acceptable level of concurrent validity when used in detecting COD angles with accelerometer, gyroscope and magnetometer,\(^35\) and that different types of actions (i.e. high acceleration, deceleration and COD movement) where correctly identified by using accelerometer derived data.\(^49\)

Three studies focused on the construct validity of IMUs.\(^34-56\) Each study utilized different metrics: PlayerLoad\(^\text{TM}\) (PL), which is a cumulative measure of rate of change in acceleration;\(^54\) average instantaneous net force, which is an accelerometer derived measure of net force acting on body;\(^56\) and novel IMU-based metrics called transitional angular displacement of segment (TADS) and symmetry index (SI).\(^55\) The results of these studies suggest that when evaluating between participant and between task variations,\(^54\) joint stability after rehabilitation\(^55\) or average force produced in relation to overground speed,\(^56\) the construct validity of these IMU derived measures is acceptable.

Four studies also evaluated the reliability of IMUs to measure COD heading angles or IMU derived metrics (IMA, TADS, SI and PL).\(^35,49,54,55\) The findings concluded good or high level of reliability when measuring COD angles of 45°, 90°, 135° and 180°\(^35\) and test-retest reliability when measuring TADS SI of individuals with knee injury.\(^55\) Moderate to high reliability was found when measuring within participant test-retest differences in PL.\(^54\) Meylan et al.\(^49\) concluded that since the typical error during testing was between 13%–21% (coefficient of variation), IMA should not be used to assess accelerations or COD movement in testing settings.

**Study characteristics**

Characteristics of all studies are presented in Table 3.

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**Figure 1.** Flowchart of study selection process, and reasons for exclusion of studies regarding the use of IMUs to analyze COD movement.
| Author and year | Validity type | Gold standard/comparator | Outcomes | Validity | Findings |
|-----------------|---------------|---------------------------|----------|----------|----------|
| Balloch et al. 2020 | Concurrent validity | High-speed video | Precise COD angles | Mean bias ± SD / Cohen's d | Algorithm slightly underestimated COD angle at 45° left and 90° left and overestimates COD angle at 180° left and 90° right. 180° COD movements present higher mean bias than other angles. |
| | | | 45° left | −2.3 ± 2.7° / −0.81 |
| | | | 90° left | −3.0 ± 2.6° / −1.13 |
| | | | 135° left | −0.6 ± 2.2° / −0.26 |
| | | | 180° left | 4.9 ± 3.7° / 1.36 |
| | | | 45° right | −0.3 ± 2.3° / −0.14 |
| | | | 90° right | 1.9 ± 2.5° / 0.76 |
| | | | 135° right | −0.4 ± 3.5° / −0.10 |
| | | | 180° right | 2.4 ± 6.1° / 0.39 |
| Gurchiek et al. 2017 | Concurrent validity | Force plate | Estimates of step-average GRF (N) during 45° COD for x,y,z and resultant GRFx, GrFy, GRFz, GRFres, Orientation of GRF left, Orientation of GRF right | Root mean square error / Pearson’s correlation / Bland-Alman bias: 97.45 N / 0.75 / 77.93 N 163.49 / 0.51 / −128.70 N 54.19 N / 0.95 / −11.36 N 70.22 N / 0.93 / −35.36 N | Estimates of GRFz and GRFres had statistically significant (p < 0.05) correlation between IMU and force-plate. Estimates of instantaneous F were also analyzed but they did not agree between IMU and force-plate. |
| Meylan et al. 2017 | Concurrent validity | High-speed video | Detecting COD movement via IMA signal, m*s^-2, consisting of acceleration, deceleration and COD magnitude. 90° COD left, 90° COD right | Validity assessed by comparing IMA counts with synchronized video (no statistical analysis). | IMA signal correctly identified COD movements. |
| Nedergaard et al. 2017 | Concurrent validity | CoM acceleration derived from force plate measured GRF. | Within-task relationship between CoM and accelerometry from different accelerometers Peak resultant acceleration 45° 90° Average loading rate 45° 90° Impulse (integral of resultant acceleration time) 45° 90° | Linear regression (R2) values: Between 0.32 and 0.54 Between 0.34 and 0.61 Between 0.34 and 0.62 Between 0.32 and 0.62 Between 0.10 and 0.29 Between 0.27 and 0.59 | Weak relationship between segmental acceleration and CoM acceleration regardless of accelerometer location and task. |
| Author and year | Validity type | Gold standard/comparator | Outcomes | Validity | Findings |
|-----------------|---------------|---------------------------|----------|----------|----------|
| Netto et al. 2010<sup>51</sup> | Concurrent validity | High speed MA | Peak acceleration | % Coefficient of Variation (CV) values for vertical load and vector magnitude load: >34% | CV values are over acceptable limits. Peak acceleration data from accelerometer was higher in COD tasks when compared to MA. |
| Roell et al. 2019<sup>52</sup> | Concurrent validity | Three-dimensional MA | Mean acceleration (Complementary filter and 5Hz smoothing) Vertical acceleration Horizontal acceleration Resultant acceleration Peak acceleration (Complementary filter, 5 Hz) Vertical acceleration Horizontal acceleration Resultant acceleration | Mean bias ± standard deviation / Spearman’s correlation / root mean square error 0.12 ± 0.15 / 0.97 / 0.19–0.32 ± 0.32 / 0.91 / 0.46–0.33 ± 0.29 / 0.96 / 0.44–0.34 ± 0.84 / 0.95 / 0.91–0.89 ± 2.67 / 0.75 / 2.81–0.14 ± 1.40 / 0.95 / 1.40 | Complementary filter showed lower errors when compared with Kalman filter. Better accuracies were observed with 5 Hz resampling, when compared with 10 Hz and 100 Hz. Vertical and resultant accelerations had stronger relationships than horizontal accelerations. |
| Wundersitz et al. 2013<sup>48</sup> | Criterion validity | Force plate | Peak foot-strike impact force values (10Hz smoothing) Cranio-caudal 45° 90° 180° Resultant 45° 90° 180° | Spearman’s correlation / coefficient of variation (%)–0.33 / 0.67 19.2 0.19 / 15.8 0.18 / 20.50.67 / 14.5 0.47 / 17.2 0.23 / 23.9 | Correlations were from weak to moderate across all COD tasks for cranio-caudal force values. Smoothing affected negatively (raw data matched GRF data most closely). Correlations were from weak to strong across the COD tasks for resultant force values. Smoothing affected positively (10 Hz being most accurate). |
| Wundersitz et al. 2015<sup>53</sup> | Concurrent validity | MA system | Measuring peak accelerations (12Hz smoothing) Change of direction movement | Mean bias ± standard deviation / Cohen’s d / root mean square error 0.11 ± 0.20 / 0.18 / 0.23 | 12 Hz filtered accelerometer data had strongest relationship with MA. Peak accelerations were overestimated during COD when compared with MA. |
| Barreira et al. 2017<sup>54</sup> | Construct validity | Within- and between participant variations of AU and AU · min<sup>−1</sup> between tasks (jogging, side-cut, stride, sprint) | Within-participant: Side-cut AU Side-cut AU · min<sup>−1</sup> Between-participant: Side-cut AU Side-cut AU · min<sup>−1</sup> | Presented in a figure (no statistical analysis) Coefficient of variation (%) 15.2 17.8 | Variation between tasks for PL and PL · min<sup>−1</sup> Significant variation between participants, which is not associated with anthropometrics. |

(continued)
Population, sport and age. 35 studies involved adult participants with an age range from 18 to 42 years. Only three studies examined COD movement in individuals under 18 years and one study had a combination of youth and adults.

In 10 studies, the age of participants was not reported. The population in studies was most often males. 24 studies included only male participants. Seven studies had only female participants, and in 7 the sex was not reported.

The background of the population was varying. 24 studies did not specify the sport or background of participants. Eight studies were focused on basketball, six on soccer, three on netball and two had multiple sports (hockey, football, rugby, and/or tennis).

Study settings. 13 studies were conducted in laboratory conditions and utilized additional equipment (e.g. force-plates and motion capture systems) as a comparison to or combined with IMUs for analysis of COD movements.

Outside the laboratory, 17 studies were conducted in indoor sport or recreation facilities (e.g. playing court, dance-hall), nine on outdoor fields and two both indoors and outdoors. In eight studies, there was no mention of study settings.

Type of COD was anticipated in 33 studies and in two studies the participants performed both anticipated and un-anticipated COD movements. Eight of the studies focused on free movement within games or practices where players can perform either unplanned or planned COD movements depending on the situation.

None of the studies focused only on unplanned COD movements.

Devices and sensor attachment. 19 different types of devices were used to analyze COD movements. The most common manufacturer was Catapult Innovations, Melbourne, Australia with devices used in 17 studies.

APDM Opal IMU was used in four studies. XSENS MVN was used in two studies. Sampling rates varied from 50 Hz to 1500 Hz with the most common frequency, 100 Hz, used in 22 of 49 studies.

The location of devices was also varying. In 12 studies the devices were located on multiple body parts simultaneously (e.g. foot, shin, thigh, pelvis, and/or back) and in 18 studies the

| Author and year | Validity type | Outcomes | Gold standard/comparator | Validity findings |
|-----------------|---------------|----------|---------------------------|------------------|
| Kim et al. 2020 | Construct validity | Lower limb asymmetry between injured and non-injured limb | No statistical significance between baseline and RTS in side-step test time | |
location was between the scapulae. In four studies the device was on the lower back, in eight studies on the knee (inside a custom sleeve), tibia or thigh and in one study on the neck.

IMU sensors and metrics. Wide variety of different types of devices led to different combinations of used sensors. 19 studies used measurements from accelerometer only. 36,48,50,51,54,56,59,60,65,67,70–72,79,82,83,89,90 13 studies used the measurements from accelerometer, gyroscope and magnetometer. 35,39,47,49,61–63,66,69,76,78,80,84 Nine studies used the measurements from accelerometer and gyroscope. 53,55,57,58,74,75,77,81,85

There were several metrics derived from the IMU signals used in the analyses of the included studies. Seven studies used manufacturer-based software to generate the PL metric, which is a parameter proposed by Catapult Sports that aims to explain how much work the player has done during a game or a practice. 54,56,72,73,76,80,81 IMU-based measurement of joint angles were reported in five studies 37,38,68,86,91 and two studies examined forces at the knee joint by producing estimates of knee joint forces with IMU-obtained data which was then processed with an artificial neural network. 57,58 Accelerations were analyzed in 16 studies, 36,48–52,59,64,66,67,76,79,82,83,89,92 accelerations in combination with angular velocities and specific COD angles were analyzed in 11 studies, 55,61–63,69,74,75,77,78,85,88 ground impacts or soft tissue accelerations in four studies 60,65,70,71 and four studies analyzed ground reaction forces by scaling the acceleration vector by the subject’s mass or comparing segmental accelerations from IMUs with center of mass accelerations, which were derived from ground reaction force measures. 36,47,48,90

Table 2. Characteristics of the studies evaluating the reliability of IMU when measuring COD movements.

| Author | Outcomes | Reliability | Findings |
|--------|----------|-------------|----------|
| Balloch et al. 2020 | COD angles: | Typical Error with 90% confidence limits / Coefficient of variation | Overall reliability was on good level (TE = 1.6°–5.2°). Greater bias for 180° COD trials when compared with 45° and 135° (after Games-Howell post hoc comparison). |
| Barreira et al. 2017 | PlayerLoad (AU) and PlayerLoad per minute (AU·min⁻¹) for side-cut: | Paired t-test (p < 0.05) / Intraclass correlation | Moderate to high correlations between trials and acceptable limits of agreement (from 17% to 41%) in Bland-Altman LOA distribution scores (presented in figure). |
| Kim et al. 2020 | TADS metrics and FmSST | Intraclass correlation (95%CI): | Good to excellent test-retest reliability. |
| Meylan et al. 2017 | IMA (m²·s⁻²) for COD movement: | Pooled coefficient of variation (90%CI) / pooled intraclass correlation: | Variability of IMA magnitudes is high and intraclass correlation is low. |

AU: arbitrary units; AU·min⁻¹: arbitrary units per minute; FmSST: four meter side-step test times; IMA: inertial measurement analysis; TADS: transitional angular displacement of segment;
Table 3. Characteristics of studies using IMU to evaluate COD movement.

| Author                  | Year | Study population and sport                          | Age (Years) | Sex (Number of participants) | Setting (Surface) | Device and Sensors (Sampling frequency) | Attachment (Site) | Condition and Type of COD                      |
|-------------------------|------|-----------------------------------------------------|-------------|------------------------------|-------------------|----------------------------------------|-------------------|-----------------------------------------------|
| Ahmadi et al.38         | 2015 | Healthy and injured subjects (low-back pain)        | NR          | NR (9 healthy, 1 injured)    | Outdoor (grass)   | NR                                     | Shanks, thighs, pelvis, sacrum | NR                                                                      |
| Arpinar-Avsar et al.79  | 2020 | 3rd division soccer players                         | 20–23       | Males                        | NR                | Trigno, Delys; Accelerometer, (148 Hz) | Tibias anterior muscles | 3 agility tests, running as quickly as possible, anticipated 90° and 180° CODs |
| Atkinson et al.65       | 2016 | 1 year minimum involvement in invasion sports, free from injury | 18–24       | Males                        | NR                | SPI Pro; Accelerometer (100 Hz)         | Between scapulae | Maximal running – anticipated 90° and 180° CODs |
| Balloch et al.35        | 2020 | Recreationally active adults, free from injury      | 28–30       | Males                        | Outdoor soccer field | Catapult, Optimeye, S5; Accelerometer, Gyroscope, Magnetometer (100 Hz) | TI-T5 level | Running – anticipated 45°, 90°, 135° and 180° CODs |
| Barreira et al.54       | 2017 | Recreational athletes, used to football and free from injuries | 21–30       | Males                        | Indoor laboratory | ADXL 326; Accelerometer (100 Hz)       | Trunk | Jogging and sprinting - 180° CODs and zigzags as in soccer-specific match simulation protocol |
| Brachet et al.60        | 2003 | Pro and semipro athletes: 5 football players, 4 hockey players, 4 rugby players | 19–42       | Males and Females             | Indoor (grass) and outdoor (artificial grass) field | Entran EGCS-DISM-50; Accelerometer (0–600 Hz) | Pelvis and left distal anterior tibia | Running – anticipated 45° COD to the right |
| Brooks et al.76         | 2020 | Elite netball players                               | 20–31       | Females                      | Indoor court      | Catapult, T6; accelerometer, gyroscope, magnetometer, 100 Hz | Between scapulae | Netball matches                                    |
| Eke et al.69            | 2017 | Recreational athletes, physically active, injury and pain free (lower limb) | 18–23       | Males and Females             | Obstacle course   | APDM Opal; Accelerometer, Gyroscope, Magnetometer (128 Hz) | Feet, shanks, thighs, sacrum, torso, forearm, biceps, head | Maximal running – anticipated 45°, 90°, 135° and 180° CODs |
| Finocchietti et al.68   | 2019 | Visually impaired players and healthy controls - all amateur soccer players | 25–40       | Males                        | Indoor futsal court | XSENS MVN Link Accelerometer, gyroscope, magnetometer (240 Hz) | Lycra suit (17 sensors) | 10m shuttle running test – anticipated 180° CODs |
| Fox et al.37            | 2014 | Semi-professional basketball players                | 21–27       | Males                        | Indoor basketball court | Catapult, Optimeye, S5; Accelerometer, gyroscope (100 Hz) | Between scapulae | Basketball game: COD, ~135° to ~45° for left and 45° to 135° for right COD |
| Fox et al.67            | 2020 | NR                                                   | 19–23       | Males                        | NR                | NR Accelerometer, gyroscope             | Trunk, sacrum, thigh, shank and foot (dominant limb) | Anticipated and unanticipated 35° to 55° CODs |
| Fox et al.72            | 2020 | Semi-professional basketball players                | 19–26       | Males                        | Indoor basketball court | Catapult Innovations, OptimEye S5; Accelerometer, (100 Hz) | Between scapulae | Basketball training sessions and games |
| Fox et al.73            | 2020 | Semi-professional basketball players                | 21–27       | Males                        | Indoor basketball court | Catapult Innovations, OptimEye S5; NR | Between scapulae | Basketball games |
| Granero-Gil et al.74    | 2020 | Elite-level soccer players                          | 21–32       | NR                           | Outdoor, soccer field (grass and turf) | WIMU PRO; Accelerometer, gyroscope, (100 Hz) | NR | Soccer matches                                    |

(continued)
| Author            | Year | Study population and sport | Age (Years) | Sex (Number of participants) | Setting (Surface) | Device and Sensors (Sampling frequency) | Attachment (Site) | Condition and Type of COD |
|-------------------|------|----------------------------|-------------|-----------------------------|------------------|----------------------------------------|-------------------|--------------------------|
| Gurchiek et al.   | 2017 | NR                         | 21–25       | Males12; Females3            | Indoor laboratory | Yost Data Logger 3-Space Sensor; Accelerometer, Gyroscope, Magnetometer (450 Hz) | Sacrum level      | Running – anticipated 45° CODs |
| Hulin et al.      | 2018 | Junior rugby league players | 16–18       | NR16                        | NR               | Catapult, Optimeye, S5; Accelerometer, Gyroscope (100 Hz) | NR                | Running – anticipated 180° CODs |
| Johnson et al.    | 2019 | Teamsport athletes         | NR          | Males4; Females1            | Indoor laboratory | Noraxon DTS-3D 518; Accelerometer      | Pelvis, both thighs and shanks | Running > 2.16 m/s, anticipated 45°–90° CODs to left |
| Kim et al.        | 2020 | University athletes Group 1–10 males, 10 females, high-level activities and recreational sports, Group 2: 1 female tennis, 2 female basketball, and 12 football who sustained a knee ligament injury | NR          | Young adults Males7; Females15 | Indoor gymnasium (wood flooring) | Canesense; Accelerometer, Gyroscope (50 Hz) | Pelvis and both shanks | Running and transitions - anticipated 180° CODs |
| Lander et al.     | 2020 | Australian children        | 7–12        | NR                          | Indoor           | XSENS MVN Awinda; Accelerometer, (60Hz) | Motion capture suit, left and right hand and foot | Childrens motor skill assessment test battery |
| Lucas et al.      | 2018 | Currently active and experience competing in sports that involve frequent landing and cutting (e.g. soccer, basketball) | 21–26       | Males15; Females15           | NR               | Shimmer3; Accelerometer (500 Hz)      | Anterior-medial tibia (non-dominant leg) | Running – unanticipated and anticipated 90° CODs |
| Luteberget et al. | 2017 | National team handball players | 21–28       | Females20                   | Indoor court     | Catapult, Optimeye, S5; Accelerometer, gyroscope, magnetometer (100 Hz) | Between scapulae | Handball games (free movement) |
| Marcotte et al.   | 2018 | Healthy participants       | NR          | NR17                       | Outdoor field (grass-turf) | ActiGraph GT9X; Accelerometer, Gyroscope, Magnetometer (90 Hz) | Hips (anterior axillary line, wrists and ankles) | Walking and running – anticipated 45°, 90°, 135° and 180° CODs |
| Matsuyama et al.  | 2019 | Dancers                    | NR          | Males7                      | Indoor dance hall | ATR-Promotions, TSND151; Accelerometer, Gyroscope (125 Hz) | Arms, hips and ankles | Ballroom dance moves – 90°, 315° and 360° CODs |
| McGinnis et al.   | 2017 | Subjects from university population | NR          | NR25                       | Outdoor field    | APDM Opal; Accelerometer, Gyroscope, Magnetometer (128 Hz) | Sacrum level | Maximal running with loaded (20.5 kg vest) and unloaded (3.4 kg mock rifle – anticipated 90° and 135° CODs) |

(continued)
| Author            | Year | Study population and sport                                                                 | Age (Years) | Sex (Number of participants) | Setting (Surface) | Device and Sensors (Sampling frequency) | Attachment (Site) | Condition and Type of COD                                      |
|-------------------|------|-------------------------------------------------------------------------------------------|-------------|------------------------------|-------------------|-----------------------------------------|-------------------|--------------------------------------------------------------|
| Meghji et al.     | 2019 | Recreational athletes                                                                     | 28–30       | Males 6                      | Outdoor field     | Catapult, Optimeye, S5; Accelerometer,  | T1-T5 level       | Running – anticipated 45°, 90°, 135° and 180° CODs           |
| Meylan et al.     | 2017 | U20 female soccer players and women's national team players                               | 17–19 (20)  | Females 13                   | Outdoor field (turf) | Catapult, Minimax S4; Accelerometer,  | Between scapulae  | 40m and 20m sprint – anticipated 90° CODs                     |
| Nagano et al.     | 2020 | Badminton players                                                                        | 14–16       | Females 10                   | Indoor court      | Sports Sensing, SS-WS1201; Accelerometer,  | Between scapulae  | Badminton games                                              |
| Nedergaard et al. | 2017 | Team sport players, no severe injury history                                               | 18–26       | Males 20                     | Indoor laboratory | DTS, KXP94 and 518; Accelerometer (100 Hz and 1000 Hz) | Trunk, dorsal aspect of pelvis and tibia | Running 2, 3, 4, and 5 m/s – anticipated 45° and 90° CODs |
| Nedergaard et al. | 2014 | Soccer players, no previous history of ankle or knee injuries                            | 18–24       | Males 10                     | Indoor laboratory | DTS 3 D; Accelerometer (500 Hz)         | Between scapulae  | Running 50%, 70% and 90% of maximal speed – deceleration before anticipated 135° CODs |
| Netto et al.      | 2010 | NR                                                                                        | NR          | Males 5; Females 5           | NR                | SPI Pro; Accelerometer (NR)             | At the base of neck | NR                                                          |
| Odonovan et al.   | 2016 | U.S. Army Soldiers                                                                        | NR          | NR                           | NR                | NR                                      | Sacrum level       | NR                                                          |
| Roell et al.      | 2019 | Professional basketball players                                                           | NR          | NR                           | Indoor basketball | Catapult, Optimeye, S5; AccelerometerPelletier (100 Hz) | Between scapulae  | Team sport specific movements – anticipated 60°, 80°, 90° and 360° CODs |
| Sinclair          | 2017 | Competitive athletes from university level sports team                                    | 21–27       | Males 9                      | Indoor laboratory | ACL 300; Accelerometer (1000 Hz)       | Distal–anterior tibia | Maximal shuttle run – anticipated 180° CODs                  |
| Spencer et al.    | 2020 | Netball high-performance umpires                                                          | NR          | Males 5; Females 17          | Indoor court      | Catapult Innovations, Minimax X S4, Firmware 6.70; Accelerometer, (100 Hz) | Between scapulae  | Netball matches                                              |
| Staunton et al.   | 2017 | Semi-professional basketball players                                                      | 21–29       | Males 28                     | Indoor basketball | Link; Pelletier Accelerometer (100 Hz) | Inferior angle of scapulae | YoYo IR1 test – 90°, 135° cuts and basketball exercise simulation test (BEST) –180° CODs |
| Stetter et al.    | 2019 | Healthy sport students with no reported injuries                                          | 23–29       | Males 13                     | Indoor - motion analysis laboratory | NR; Pelletier Accelerometer, Gyroscope (1500 Hz) | 2 in a knee sleeve (upper and lower end) | Walking and running – anticipated 90° CODs                   |
| Stetter et al.    | 2020 | Healthy sport students with no reported injuries                                          | 23–29       | Males 13                     | Indoor - motion analysis laboratory | NR; Accelerometer, Gyroscope (1500 Hz) | 2 in a knee sleeve (upper and lower end) | Walking and running – anticipated 90° CODs                   |
| Stirling et al.   | 2019 | Recreational athletes                                                                     | 18–22       | Males 9; Females 9           | NR                | APDM Opal; Accelerometer, Gyroscope, Magnetometer (128 Hz) | Sacrum and both feet | Maximal running – anticipated 45° and 90° CODs               |

(continued)
| Author          | Year | Study population and sport                          | Age (Years) | Sex (Number of participants) | Setting (Surface) | Device and Sensors (Sampling frequency) | Attachment (Site) | Condition and Type of COD                                                                 |
|----------------|------|-----------------------------------------------------|-------------|------------------------------|-------------------|----------------------------------------|-------------------|------------------------------------------------------------------------------------------|
| Svilar et al.  | 2018 | Professional basketball players                     | 22–29       | NR                          | Indoor basketball court | Catapult, Optimeye, S5; Accelerometer, Gyroscope, Magnetometer (100 Hz) | NR                | Basketball related training sessions - free movement: Total inertial movements registered in a rightward lateral vector |
| Svilar et al.  | 2018 | Professional basketball players                     | 24–28       | Males                       | Indoor basketball court | Catapult, Optimeye, S5; Accelerometer, Gyroscope, Magnetometer (100 Hz) | NR                | Basketball training sessions – free movement: total inertial movements registered in a rightward/leeward lateral vector |
| Svilar et al.  | 2019 | Top-level basketball players                        | 22–30       | Males                       | Indoor basketball court | Catapult, Optimeye, S5; Accelerometer, Gyroscope, Magnetometer (100 Hz) | NR                | Basketball training session and games – free movement: Inertial movements registered in a rightward/leeward lateral vector |
| Tedesco et al. | 2020 | Non-elite rugby players                             | 21–31       | Males                       | Outdoor, rugby playing pitches | Custom made IMU; accelerometer, gyroscope | Both legs – anterior tibia and lateral thigh | Maximum running, 45° CODs |
| Trama et al.   | 2020 | 10 team sport athletes or runners, injury free 6 months preceding experiment | 25–41       | Males; Females | NR | Mega Electronics; Accelerometer (1000 Hz) | Gastrocnemius, vastus lateralis and heel cup of shoe | Running – anticipated 45°, 90° and 180° CODs |
| Wundersitz et al. | 2013 | Competitive team sport players, lower limb injury free 6 months preceding experiment | 19–23       | Males; Females | Indoor laboratory | SPI Pro; Accelerometer (100 Hz) | Between scapulae – Th2 level | Running – anticipated 45°, 90° and 180° CODs |
| Wundersitz et al. | 2015 | Recreationally active healthy individuals competing in one or more amateur team sport competitions per week | 21–27       | Males                       | Indoor laboratory | Catapult, Minimax S4; Accelerometer (100 Hz) | In a manufacturer provided sports vest – Th 5 level | Simulated team sport circuit – anticipated 135° CODs |
| Wundersitz et al. | 2015 | Recreationally active healthy individuals competing in one or more amateur team sport competitions per week | 21–27       | Males                       | Indoor laboratory | Catapult, Minimax S4; Accelerometer, Gyroscope (100Hz) | In a manufacturer provided sports vest – Th 5 level | Simulated team sport circuit – anticipated 135° CODs |
| Zaferiou et al. | 2017 | Recreational athletes                               | 18–22       | Males; Females | Outdoor | APDPM, Opal V1; accelerometer, gyroscope, magnetometer, (138 Hz) | Taped to the top of shoes on both feet | Running as quickly as possible – anticipated 60° and 120° CODs |
| Zago et al.    | 2019 | Soccer players                                       | 20–26       | Females                     | Indoor laboratory | GaitUp Physilog 5; Accelerometer, gyroscope (512 Hz) | Sacrum | Running 2.5 m/s – 5 m shuttle run test |

*Abstract.
COD: change of direction; IR1: Intermittent Recovery test 1; NR: not reported.
Four of the concurrent validity studies evaluated accelerations measured from trunk. All of these studies compared IMU measures with a different method, but the conclusions were similar: accelerometer data from trunk-mounted devices seems to be overestimated, so these results should be used with caution. Roell et al. and Wundersitz et al. also highlighted that higher acceleration leads to larger increases in error and that the use of the correct filtering method is important. Smoothing resultant acceleration signals of COD trials between 5 and 12 Hz gave most accurate results and eliminated differences between accelerometer and resultant GRF values. Reliable and valid results were reported for classifying COD activities (detection of acceleration, deceleration or 90° COD during sprinting), calculating COD heading angles (45°, 90°, 135° and 180°), and quantifying mechanical variables that describe the COD movement (estimate of ground-reaction forces during linear acceleration and 45° COD task). In calculation of COD heading angles with a specific algorithm 180° CODs were slightly over- or underestimated, but these were within reasonable limits.

Discussion

The aim of this scoping review was to provide information on the validity and reliability of IMU measures of COD movements and summarize the current evidence as a basis for future research. A scoping review was chosen as the field of research on wearable technology and COD is still limited and concentrates on laboratory setting evaluations with the use of motion-analysis systems or force plates or timing gates. Wearable technology has become an important part of movement analysis in sports and improvements in technology will open new possibilities for more precise methods. Previous studies have proposed that wearable technology is promising in evaluating movements and injury risk in team sports, but the reliability and validity of these methods has not been examined thoroughly.

Concurrent validity

Findings from concurrent validity studies show that IMUs are able to detect COD movements and estimating the angle of COD on an acceptable level. Peak accelerations (center of mass and segmental) seem to be overestimated when compared with motion analysis and GRF, especially when looking at segmental accelerations from different body parts. Resultant (smoothed 10 Hz) and raw cranio-caudal values (device placed between scapulae) of accelerations were similar with resultant and vertical GRF in COD tasks, except in 180°. Reported Spearman’s correlations varied from no correlation at all to strong correlations as well as measurement errors.

Four of the concurrent validity studies evaluated accelerations measured from trunk. All of these studies compared IMU measures with a different method, but the conclusions were similar: accelerometer data from trunk-mounted devices seems to be overestimated, so these results should be used with caution. Roell et al. and Wundersitz et al. also highlighted that higher acceleration leads to larger increases in error and that the use of the correct filtering method is important. Smoothing resultant acceleration signals of COD trials between 5 and 12 Hz gave most accurate results and eliminated differences between accelerometer and resultant GRF values. Reliable and valid results were reported for classifying COD activities (detection of acceleration, deceleration or 90° COD during sprinting), calculating COD heading angles (45°, 90°, 135° and 180°), and quantifying mechanical variables that describe the COD movement (estimate of ground-reaction forces during linear acceleration and 45° COD task). In calculation of COD heading angles with a specific algorithm 180° CODs were slightly over- or underestimated, but these were within reasonable limits.
Construct validity

Two of the convergent validity studies focused on PlayerLoad™ and one aimed to introduce and validate the CaneSense™ method for knee motions and interlimb symmetry. These studies showed acceptable results, but were closely related to the specified methods that manufacturers have developed. Since these algorithms are not available, the evaluation or reproduction of the results can be difficult. Accelerometry derived average net force can be used to quantify external demands in basketball and detecting differences in agility after knee injury. Barreira et al. also concluded that the variation in accelerations between soccer players are probably due to differences in locomotive skills. Establishing construct validity for IMU-based measures for demands in different sports or situations (e.g. injury and return to sport) is important, due to the differing demands related to sport- and injury-specific factors. Understanding and being able to analyze sport-specific and individual COD movements and perhaps setting criteria for COD quality would be a useful tool for coaches and practitioners.

Reliability

All but one study reported good measures of reliability, although all of the reliability measurements were done using different metrics and the placement of the devices varied (e.g. between scapulae, trunk, knee). Meylan et al. analyzed the reliability of manufacturer based metrics, which showed low correlation and high variability. This means that the reliability of IMUs in COD movement analysis is promising, but no clear conclusions can be drawn. The study by Kim et al. was the only one providing insight into how individuals move during a COD by using a stability index for knee. Reliability of detecting COD angles is important for detecting COD events in real life situations and it can be used in comparison with other, possibly more important COD related metrics like speed. However, future reliability studies that concentrate on IMU metrics related to the accelerations during different phases of COD and angular accelerations can provide valuable information about possibilities in detecting how consistently a player moves during a COD and how this movement varies when COD angles or running speeds change. Reliability studies would also need to be conducted in real-life situations, where movements are faster and unpredictable. There is a need for better consistency or clear guidelines for sensor placement. Having a reliable IMU-based measure for COD movement would add depth to COD testing, which is currently mainly based on speed. A reliable analysis of the mechanics of COD movements would help coaches and players identify specific factors that need to be trained. However, more research is needed to translate these findings to actionable resources for coaches and players. Additionally, the ability to reliably analyze the mechanics of COD movement would present better knowledge on players’ readiness to return to sport. A player’s COD movement profile could be followed throughout the season and between seasons, adjustments to training could be based on reliable measures.

Change of direction analysis settings

Most of the COD studies with IMUs were conducted in laboratory settings or indoor facilities. Laboratories provide precise gold-standard methods, but these studies usually lack the ability to analyze real life movements in sports, where the fluctuation of the game and other players have major effects on athletes’ movements. Since human movement is based on several different internal and external factors that can change on a daily basis, there is a need for sport- and movement-specific analysis. There is research suggesting that the risk of ACL and ankle injuries might increase when COD movements are unplanned. Future studies should investigate COD movements in practice and game settings where COD can be both planned and unplanned.

Most of the laboratory setting studies lack unplanned movements which may not represent the way the actual movement is performed. In a multitude of sports, for example soccer, the athlete needs to control the ball simultaneously when performing COD movements. In addition, the COD requirements vary for different playing positions and sports. There are examples from running studies, where in-lab movements are different from real life movements and there is more variability in game situations, which requires repeated measurements to establish typical movement patterns.

Participant characteristics

Previous research suggests that females might be at greater risk of ACL injury during COD tasks, despite the potential confounding of other physical factors, such as muscle strength. Nevertheless, very few of the included studies involved female participants. There is evidence of the importance of doing analysis on specific populations, since COD movements are influenced by age, type of sport and limb dominance. Just one of the studies in this review included only youth athletes. Previous studies have shown that COD ability changes throughout the specialization process of athletes in team sports, with COD deficits increasing with age and specialization.
Better understanding of COD movement patterns in specific populations would further help coaches and players.

In addition, the studies in this review did not account for different characteristics of individuals performing the COD movement. For example, leg strength, limb dominance or previous training might change the way COD is performed and this should be taken into account when analyzing the movement.\(^9,^{111,112}\) The evidence regarding limb dominance as a risk factor for ACL injury from previous motion-analysis studies is inconclusive and there is inconsistency within and between studies and populations for limbs displaying high-risk mechanics.\(^{113}\) IMU-based analysis might identify new information about these factors when conducted in real life settings.

**Device, sensor type and set-up**

There is no gold-standard for IMU setup since the device location was inconsistent between studies. This is due to the many possibilities for where to attach the device to the body. For example, Catapult sensors are designed to be worn in a harness with the device positioned between the scapulae. As the most common device, trunk-mounted IMUs were used in most of the studies in this review. Previous research suggests that trunk-mounted accelerometers can overestimate the whole-body acceleration and the elasticized harness might be a contributing factor.\(^{114}\) Concerns about securing the device underline the need for recommendations on device set-up, that are based on reliable and valid methods. Sensors (accelerometer, gyroscope and magnetometer) were used based on the objectives of the study. Accelerometer-related metrics were used most often, but gyroscope and magnetometer metrics were also utilized when determining orientations. Algorithms for detecting COD angles presented in the studies were usually based on values obtained from all sensors. The range of sampling rates used was from 6 to 1500 Hz and rates around 100 Hz where most commonly used. In general, lower sampling rates were used for movement detection and higher sampling rates for measuring segmental accelerations. Methods for sport-specific standardized data-collection are needed.\(^{42}\)

**IMU metrics**

Based on the validity studies, IMUs are able to detect and correctly classify COD movement from other movements and provide information about COD heading angles. Information about COD counts and COD heading angle can be useful for coaches and players when analyzing the demands of practices and games and following players’ performance throughout the season. Practices should prepare the players for game demands and therefore the information on the amount and type of CODs in practice and games could be useful for coaches from injury prevention and performance enhancement point of view.\(^{115–117}\) No recommendations could be made for COD quality and specifying suitable metrics for COD quality analysis should be a subject for future studies. Based on the existing studies, the information provided by IMUs does not seem to be practical from a coach’s point of view so far. Since current COD tests rely on time or speed related metrics, IMU-derived metrics could provide additional information about the individual differences and variability in accelerations on different axes and angular velocities during COD movement, which could be extremely useful for coaches and players. However, future research is needed to elucidate these connections in a practical way. Differing COD angles and speed will have an effect on the accelerations and deeper analysis on these metrics might provide information on COD quality. Evaluation of COD quality might also be helpful from an injury prevention point of view, because acceleration metrics from different planes can provide information on the forces acting on joints or muscles. IMUs can measure movement patterns in three different planes of the body, which can provide relevant information regarding COD movement quality.\(^{118}\) Studies in this review concentrated on COD during final foot contact. Previous research has shown that penultimate foot contact is important regarding deceleration when doing COD movement.\(^{119}\) however, penultimate foot contact was not included in the analysis of included studies and should be considered in future research.

**Conclusions and future research directions**

COD movement is a complex and specific skill and it is related to lower extremity injuries. The studies evaluating the concurrent validity of IMUs to measure variables related to COD movement indicate that IMUs could identify COD heading angles with acceptable validity as well as detecting COD events. However, when measuring the variables related to COD movement, such as forces, acceleration and mechanical loading, the results are inconsistent and suggest that IMUs more likely over-estimate these measures, when compared to gold-standard measurements.

A multitude of devices used to monitor COD movements underline the importance of high-quality studies on reliability and validity of these devices. While most of the studies in this review measured planned COD
movements, IMU-based monitoring of unplanned COD movements in real-world settings may inform injury prevention strategies and should be considered when planning future studies. Factors that affect COD performance, such as side-to-side differences, preparation time before the COD movement and an athlete’s physical capability, should be evaluated.

Declaration of Conflicting Interests
The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding
The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: PhD student Aki-Matti Alanen is supported through University of Calgary (Kinesiology Dean’s Doctoral Scholarship). Dr Anu M Räisänen is supported through a Canadian Institutes of Health Research Postdoctoral Fellowship (MFE – 164608). Dr Lauren C Benson is funded through a Canadian Institutes of Health Research Foundation Program (Alberta Children’s Hospital Foundation). Dr Anu M Räisänen is supported through a Canadian Institutes of Health Research Foundation Program (PI C Emery) and the Vi Riddell Pediatric Rehabilitation Research Program (Alberta Children’s Hospital Foundation). Dr Lauren C Benson is funded through a Canadian Institutes of Health Research Postdoctoral Fellowship (MFE – 164608).

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References
1. Häggglund M and Waldén M. Risk factors for acute knee injury in female youth football. Knee Surg Sports Traumatol Arthrosc 2016; 24: 737–746.
2. Karcher C and Buchheit M. On-court demands of elite handball, with special reference to playing positions. Sports Med 2014; 44: 797–814.
3. Brughelli M, Cronin J, Levin G, et al. Understanding change of direction ability in sport: a review of resistance training studies. Sports Med 2008; 38: 1045–1063.
4. Gil SM, Gil J, Ruiz F, et al. Characteristics of young soccer players according to their playing position. J Strength Cond Res 2007; 21: 438–445.
5. Reilly T, Williams AM, Nevill A, et al. A multidisciplinary approach to talent identification in soccer. J Sports Sci 2000; 18: 695–702.
6. Jeffreys I. A task-based approach to developing context-specific agility. Strength Cond J 2011; 33(4): 52–59.
7. Dawes J, Jeffreys I, Spiteri T, et al. Broadening the view of agility: a scientific review of the literature. J Aust Strength Cond 2014; 22: 6–25.
8. Bloomfield J, Polman RCJ and O’ Donoghue P. Physical demands of different positions in FA Premier League. J Sports Sci Med 2007; 6: 63-70.
9. Nimphius S, Callaghan S, Bezodis N, et al. Change of direction and agility tests: challenging our current measures of performance. Strength Cond J 2018; 40: 1.
10. Waldén M, Atroshi I, Magnusson H, et al. Republished research: prevention of acute knee injuries in adolescent female football players: cluster randomised controlled trial. Br J Sports Med 2012; 46: 904.
11. Waldén M, Håggglund M, Magnusson H, et al. ACL injuries in men’s professional football: a 15-year prospective study on time trends and return-to-play rates reveals only 65% of players still play at the top level 3 years after ACL rupture. Br J Sports Med 2016; 50: 744–750.
12. Dos’Santos T, Thomas C, Comfort P, et al. The effect of training interventions on change of direction biomechanics associated with increased anterior cruciate ligament loading: a scoping review. Sports Med 2019; 49: 1837–1859.
13. Fuerst P, Gollhofer A and Gehring D. Preparation time influences ankle and knee joint control during dynamic change of direction movements. J Sports Sci 2017; 35: 762–768.
14. Serner A, Tol JL, Jomaah N, et al. Diagnosis of acute groin injuries: a prospective study of 110 athletes. Am J Sports Med 2015; 43: 1857–1864.
15. Donnell-Fink LA, Klara K, Collins JE, et al. Effectiveness of knee injury and anterior cruciate ligament tear prevention programs: a meta-analysis. PLoS One 2015; 10: e0144063.
16. Krosshaug T, Steffen K, Kristianslund E, et al. The vertical drop jump is a poor screening test for ACL injuries in female elite soccer and handball players. Am J Sports Med 2016; 44: 874–883.
17. Nedergaard NJ, Dalbo S, Petersen SV, et al. Biomechanical and neuromuscular comparison of single- and multi-planar jump tests and a side-cutting maneuver: implications for ACL injury risk assessment. Knee 2020; 27: 324–333.
18. Kristianslund E and Krosshaug T. Comparison of drop jumps and sport-specific sidestep cutting: implications for anterior cruciate ligament injury risk screening. Am J Sports Med 2013; 41: 684–688.
19. King E, Richter C, Franklin-Miller A, et al. Biomechanical but not timed performance asymmetries persist between limbs 9 months after ACL reconstruction during planned and unplanned change of direction. J Biomech 2018; 81: 93–103.
20. Marshall B, Franklin-Miller A, King E, et al. Biomechanical factors associated with time to complete a change of direction cutting maneuver. J Strength Cond Res 2014; 28: 2845-2851.
21. Franklin-Miller A, Richter C, King E, et al. Athletic groin pain (part 2): a prospective cohort study on the biomechanical evaluation of change of direction identifies three clusters of movement patterns. Br J Sports Med 2017; 51: 460–468.
22. McFadden C, Daniels K and Strike S. The sensitivity of joint kinematics and kinetics to marker placement during a change of direction task. J Biomech 2020; 101: 109635.
23. Marques JB, Paul DJ, Graham-Smith P, et al. Change of direction assessment following anterior cruciate
ligament reconstruction: a review of current practice and considerations to enhance practical application. *Sports Med* 2020; 50: 55–72.

24. Condello G, Kernozek TW, Tessitore A, et al. Biomechanical analysis of a change-of-direction task in college soccer players. *Int J Sports Physiol Perform* 2016; 11: 96–101.

25. Suzuki Y, Ae M, Takenaka S, et al. Comparison of support leg kinetics between side-step and cross-step cutting techniques. *Sports Biomech* 2014; 13: 144–153.

26. Cummins C, Orr R, O’Connor H, et al. Global positioning systems (GPS) and microtechnology sensors in team sports: a systematic review. *Sports Med* 2013; 43: 1025–1042.

27. Benson LC, Räisänen AM, Volkova VG, et al. Workload a-WEAR-ness: monitoring workload in team sports with wearable technology. A scoping review. *J Orthop Sports Phys Ther* 2020; 50: 549–564.

28. Chambers R, Gabbett TJ, Cole MH, et al. The use of wearable microsensors to quantify sport-specific movements. *Sports Med* 2015; 45: 1065–1081.

29. Benson LC, Clermont CA, Bosnjak E, et al. The use of wearable devices for walking and running gait analysis outside of the lab: a systematic review. *Gait Posture* 2018; 63: 124–138.

30. Johnston W, O’Reilly M, Argent R, et al. Validity and utility of inertial sensor systems for postural control assessment in sport science and medicine applications: a systematic review. *Sports Med* 2019; 49: 783–818.

31. Seshadri DR, Li RT, Voos JE, et al. Wearable sensors for monitoring the internal and external workload of the athlete. *npj Digit Med* 2019; 2: 71.

32. Skazalski C, Whiteley R, Hansen C, et al. A valid and reliable method to measure jump-specific training and competition load in elite volleyball players. *Scand J Med Sci Sports* 2018; 28: 1578–1585.

33. Borges TO, Moreira A, Bacchi R, et al. Validation of the VERT wearable jump monitor device in elite youth volleyball players. *Biol Sport* 2017; 34: 239–242.

34. MacDonald K, Bahr R, Baltich J, et al. Validation of an inertial measurement unit for the measurement of jump count and height. *Phys Ther Sport* 2017; 25: 15–19.

35. Balloch AS, Meghji M, Newton RU, et al. Assessment of a novel algorithm to determine change-of-direction angles while running using inertial sensors. *J Strength Cond Res* 2020; 34: 134–144.

36. Nedergaard NJ, Kersting U and Lake M. Using accelerometry to quantify deceleration during a high-intensity soccer turning manoeuvre. *J Sports Sci* 2014; 32: 1897–1905.

37. Fox A, Davidson S, McGinnis R, et al. Exploring the use of wireless inertial measurement units for biomechanical analysis of side-step cutting manoeuvres. *J Sci Med Sport* 2014; 18: e144–5–e145.

38. Ahmadi A, Mitchell E, Richter C, et al. Toward automatic activity classification and movement assessment during a sports training session. *IEEE Internet Things J* 2015; 2: 23–32.

39. Meghji M, Balloch A, Habibi D, et al. An algorithm for the automatic detection and quantification of athletes’ change of direction incidents using IMU sensor data. *IEEE Sensors J* 2019; 19: 4518–4527.

40. Ancillao A, Tedesco S, Barton J, et al. Indirect measurement of ground reaction forces and moments by means of wearable inertial sensors: a systematic review. *Sensors (Switzerland)* 2018; 18: 2564.

41. Gurchiek RD, Cheney N and McGinnis RS. Estimating biomechanical time-series with wearable sensors: a systematic review of machine learning techniques. *Sensors (Switzerland)* 2019; 19: 5227.

42. Camomilla V, Bergamini E, Fantozzi S, et al. Trends supporting the in-field use of wearable inertial sensors for sport performance evaluation: a systematic review. *Sensors (Switzerland)* 2018; 18: 873.

43. McGinnis RS, Patel S, Silva J, et al. Skin mounted accelerometer system for measuring knee range of motion. *Proc Annu Int Conf IEEE Eng Med Biol Soc EMBS* 2016; 2016: 5298–5302.

44. McGinnis RS, Cain SM, Tao S, et al. Accuracy of femur angles estimated by IMUs during clinical procedures used to diagnose femoroacetabular impingement. *IEEE Trans Biomed Eng* 2015; 62: 1503–1513.

45. Gurchiek RD, Choquette RH, Beynnon BD, et al. Open-source remote gait analysis: a post-surgery patient monitoring application. *Sci Rep* 2019; 9: 17966.

46. Downes MJ, Brennan ML, Williams HC, et al. Development of a critical appraisal tool to assess the quality of cross-sectional studies (AXIS). *BMJ Open* 2016; 6: e011458–7.

47. Gurchiek RD, McGinnis RS, Needle AR, et al. The use of a single inertial sensor to estimate 3-dimensional ground reaction force during accelerative running tasks. *J Biomech* 2017; 61: 263–268.

48. Wundersitz DWT, Netto KJ, Aisbett B, et al. Validity of an upper-body-mounted accelerometer to measure peak vertical and resultant force during running and change-of-direction tasks. *Sports Biomech* 2013; 12: 403–412.

49. Meylan C, Trewin J and McKean K. Quantifying explosive actions in international women’s soccer. *Int J Sports Physiol Perform* 2017; 12: 310–315.

50. Nedergaard NJ, Robinson MA, Eusterwiedmann E, et al. The relationship between whole-body external loading and body-worn accelerometer during team-sport movements. *Int J Sports Physiol Perform* 2017; 12: 18–26.

51. Netto K, Tran J, Gastin P, et al. Validity of GPS housed accelerometer data in running and cutting. *J Sci Med Sport* 2010; 13: e37.

52. Roell M, Mahler H, Lienhard J, et al. Validation of wearable sensors during team sport-specific movements in indoor environments. *Sensors (Switzerland)* 2019; 19: 3458.

53. Wundersitz DWT, Gastin PB, Robertson S, et al. Validation of a trunk-mounted accelerometer to measure peak impacts during team sport movements. *Int J Sports Med* 2015; 36: 742–746.

54. Barreira P, Robinson MA, Drust B, et al. Mechanical Player Load™ using trunk-mounted accelerometry in
football: is it a reliable, task- and player-specific observation? J Sports Sci 2017; 35: 1674–1681.
55. Kim KJAE, Galley R, Agrawal V, et al. Quantification of agility testing with inertial sensors after a knee injury. Med Sci Sports Exerc 2020; 52: 244–251.
56. Staunton C, Wundersitz D, Gordon B, et al. Construct validity of accelerometer-derived force to quantify basketball movement patterns. Int J Sports Med 2017; 38: 1090–1096.
57. Stetter BJ, Ringhof S, Krafft FC, et al. Estimation of knee joint forces in sport movements using wearable sensors and machine learning. Sensors (Switzerland) 2019; 19: 3690.
58. Stetter BJ, Krafft FC, Ringhof S, et al. A machine learning and wearable sensor based approach to estimate external knee flexion and adduction moments during various locomotion tasks. Front Bioeng Biotechnol 2020; 8: 9.
59. Sinclair JK. Effects of court specific and minimalist footwear on the biomechanics of a maximal 180° cutting manoeuvre. Hum Mov 2017; 18: 29–36.
60. Brachet P, Blackburn S, Nicol AC, et al. Body and limb accelerations during football activities on artificial turf. 2003. Paper presented at XIXth Congress of the International Society of Biomechanics, Dunedin, New Zealand.
61. Svilar L, Castellano J, Jukic I, et al. Positional differences in elite basketball: selecting appropriate training-load measures. Int J Sports Physiol Perform 2018; 13: 947–952.
62. Svilar L, Castellano J and Jukić I. Comparison of 5vs5 training games and match-play using microsensor technology in elite basketball. J Strength Cond Res 2019; 33: 1897–1903.
63. Svilar L and Jukić I. Load monitoring system in top-level basketball team. Kinesiology (Zagreb, Online) 2018; 50: 25–33.
64. Luteberget LS and Spencer M. High-intensity events in international women’s team handball matches. Int J Sports Physiol Perform 2017; 12: 56–61.
65. Atkinson M, Rosalie S and Netto K. Physical demand of seven closed agility drills. Sports Biomech 2016; 15: 473–480.
66. Stirling L, Eke C and Cain SM. Examination of the perceived agility and balance during a reactive agility task. PLoS One 2018; 13: e0198875.
67. Wundersitz DWT, Josman C, Gupta R, et al. Classification of team sport activities using a single wearable tracking device. J Biomech 2015; 48: 3975–3981.
68. Finocchietti S, Gori M and Souza Oliveira A. Kinematic profile of visually impaired football players during specific sports actions. Sci Rep 2019; 9: 10660.
69. Eke CU, Cain SM and Stirling LA. Strategy quantification using body worn inertial sensors in a reactive agility task. J Biomech 2017; 64: 219–225.
70. Lucas LA, England BS, Mason TW, et al. Decision making influences tibial impact accelerations during lateral cutting. J Appl Biomech 2018; 34: 414–418.
71. Trama R, Hautier C and Blache Y. Input and soft-tissue vibration characteristics during sport-specific tasks. Med Sci Sports Exerc 2020; 52: 112–119.
72. Fox JL, O’Grady CJ and Scanlan AT. The relationships between external and internal workloads during basketball training and games. Int J Sports Physiol Perform 2020; 18: 1–6.
73. Fox JL, Stanton R, Sargent C, et al. The impact of contextual factors on game demands in starting, semi-professional, male basketball players. Int J Sports Physiol Perform 2020; 15: 450–456.
74. Granero-Gil P, Gómez-Carmona CD, Bastida-Castillo A, et al. Influence of playing position and laterality in centripetal force and changes of direction in elite soccer players. PLoS One 2020; 15: e0232123.
75. Tedesco S, Crowe C, Ryan A, et al. Motion sensors-based machine learning approach for the identification of anterior cruciate ligament gait patterns in on-the-field activities in rugby players. Sensors (Switzerland) 2020; 20: 3029.
76. Brooks ER, Benson AC, Fox AS, et al. Physical movement demands of elite-level netball match-play as measured by an indoor positioning system. J Sports Sci 2020; 38: 1488–1495.
77. Zago M, Sforza C, Dolci C, et al. Use of machine learning and wearable sensors to predict energetics and kinematics of cutting maneuvers. Sensors (Switzerland) 2019; 19: 9–11.
78. Zaferiou AM, Ojeda L, Cain SM, et al. Quantifying performance on an outdoor agility drill using foot-mounted inertial measurement units. PLoS One 2017; 12: e0188184.
79. Arpinar-Avsar P and Celik H. Does minimizing co-contraction increase agility test performance? IES 2020; 28: 111–118.
80. Simpson MJ, Jenkins DG, Scanlan AT, et al. Relationships between external- and internal-workload variables in an elite female netball team and between playing positions. Int J Sports Physiol Perform 2020; 15: 841–846.
81. Hulin BT, Gabbett TJ, Johnston RD, et al. Playerload variables: sensitive to changes in direction and not related to collision workloads in rugby league match play. Int J Sports Physiol Perform 2018; 13: 1136–1142.
82. Lander N, Nahavandi D, Mohamed S, et al. Bringing objectivity to motor skill assessment in children. J Sports Sci 2020; 38: 1539–1549.
83. Nagano Y, Sasaki S, Higashihara A, et al. Movements with greater trunk accelerations and their properties during badminton games. Sports Biomech 2020; 19: 342–352.
84. Marcotte RT, Bassett DR, Weinhandl JT, et al. Application of the ActiGraph GT9X IMU for the assessment of turning during walking and running. Biomed Phys Eng Express 2018; 0465003. https://doi.org/10.1088/2057-1976/aad0d0
85. Matsuyama H, Hiroi K, Kaji K, et al. Ballroom dance step type recognition by random forest using video and...
wearable sensor. In: UbiComp/ISWC 2019 Adjunct: Adjunct proceedings of the 2019 ACM international joint conference on pervasive and ubiquitous computing and proceedings of the 2019 ACM international symposium on wearable computers, 2019, pp. 774–780. New York: ACM. September 9–13, London, United Kingdom.

86. McGinnis RS, Cain SM, Davidson SP, et al. Inertial sensor and cluster analysis for discriminating agility run technique and quantifying changes across load. Biomed Signal Process Control 2017; 32: 150–156.

87. Fox JL, O’Grady CJ and Scanlan AT. Game schedule congestion affects weekly workloads but not individual game demands in semi-professional basketball. Biol Sport 2020; 37: 59–67.

88. Odonovan MP, Kaplan JT and Hancock CL. IMU assessment of agility performance while wearing an energy-harvesting backpack. Medicine & Science in Sports & Exercise 2016; 48 (S5): 635–636.

89. Spencer K, Paget N, Kilding A, et al. Physical, physiological, and technical demands of national netball matches at different competition levels. J Sports Sci 2020; 38: 1660–1665.

90. Johnson WR, Mian A, Robinson MA, et al. Multidimensional ground reaction forces and moments from wearable sensor accelerations via deep learning. IEEE Transactions on Biomedical Engineering 2020; 1: 289–297.

91. Fox AS. Change-of-direction biomechanics: is what’s best for anterior cruciate ligament injury prevention also best for performance? Sports Med 2018; 48: 1799–1807.

92. Roell M, Roecker K, Gehring D, et al. Player monitoring in indoor team sports: concurrent validity of inertial measurement units to quantify average and peak acceleration values. Front Physiol 2018; 9: 1–13.

93. Nygaard Falch H, Guldeit Rædergård H and van den Tillaar R. Effect of different physical training forms on change of direction ability: a systematic review and meta-analysis. Sports Med - Open 2019; 5: 53.

94. Kadelubowski B, Keiner M, Hartmann H, et al. The relationship between change of direction tests in elite youth soccer players. Sports 2019; 7: 111.

95. Claudino JG, Capanema D de O, de Souza TV, et al. Current approaches to the use of artificial intelligence for injury risk assessment and performance prediction in team sports: a systematic review. Sports Med - Open 2019; 5: 28.

96. Benson LC, Ahamed Nu Kobsar D and Ferber R. New considerations for collecting biomechanical data using wearable sensors: number of level runs to define a stable running pattern with a single IMU. J Biomech 2019; 85: 187–192.

97. Born D-P, Zinner C, Dikeng P, et al. Multi-directional sprint training improves change-of-direction speed and reactive agility in young highly trained soccer players. J Sports Sci Med 2016; 15: 314–319.

98. Keller S, Koob A, Corak D, et al. How to improve change-of-direction speed in junior team sport athletes—horizontal, vertical, maximal, or explosive strength training? J Strength Cond Res 2020; 34: 473–482.

99. Young W and Farrow D. The importance of a sport-specific stimulus for training agility. Strength Cond J 2013; 35: 39–43.

100. Buchheit M and Simpson BM. Player-tracking technology: half-full or half-empty glass? Int J Sports Physiol Perform 2017; 12: S235–S241.

101. Impellizzeri FM, Marcra SM and Coutts AJ. Internal and external training load: 15 years on. Int J Sports Physiol Perform 2019; 14: 270–273.

102. Hughes G and Dally N. Gender difference in lower limb muscle activity during landing and rapid change of direction. Sci Sport 2015; 30: 163–168.

103. Benjaminse A, Gokeler A, Fleisig GS, et al. What is the true evidence for gender-related differences during plant and cut maneuvers? A systematic review. Knee Surg Sports Traumatol Arthrosc 2011; 19: 42–54.

104. Nimphius S. Exercise and sport science failing by design in understanding female athletes. Int J Sports Physiol Perform 2019; 14: 1157–1158.

105. Nimphius S, McBride JM, Rice PE, et al. Comparison of quadriceps and hamstring muscle activity during an isometric squat between strength-matched men and women. J Sport Sci Med 2019; 18: 101–108.

106. Achenbach L, Krutsch W, Koch M, et al. Contact times of change-of-direction manoeuvres are influenced by age and the type of sports: a novel protocol using the SpeedCourt® system. Knee Surg Sports Traumatol Arthrosc 2019; 27: 991–999.

107. Loturco I, Jeffreys I, Abad CCC, et al. Change-of-direction, speed and jump performance in soccer players: a comparison across different age-categories. J Sports Sci 2020; 38: 1279–1285.

108. Yanci J, Los Arcos A, Castillo D, et al. Sprinting, change of direction ability and horizontal jump performance in youth runners according to gender. J Hum Kinet 2017; 60: 199–207.

109. Fiorilli G, Iuliano E, Mitrotasios M, et al. Are change of direction and reactive agility useful for determining the optimal field position for young soccer players? J Sport Sci Med 2017; 16: 247–253.

110. Dellal A and Wong D. Repeated sprint and change-of-direction abilities in soccer players: effects of age group. J Strength Cond Res 2013; 27: 2504–2508.

111. Jones P, Herrington L and Graham-Smith P. Braking characteristics during cutting and pivoting in female soccer players. J Electromyogr Kinesiol 2016; 30: 46–54.

112. Pojskic H, Åslin E, Krolo A, et al. Importance of reactive agility and change of direction speed in differentiating performance levels in junior soccer players: reliability and validity of newly developed soccer-specific tests. Front Physiol 2018; 9: 506.

113. Dos Santos T, Bishop C, Thomas C, et al. The effect of limb dominance on change of direction biomechanics: a systematic review of its importance for injury risk. Phys Ther Sport 2019; 37: 179–189.
114. Edwards S, White S, Humphreys S, et al. Caution using data from triaxial accelerometers housed in player tracking units during running. *J Sports Sci* 2019; 37: 810–818.

115. Bahr R and Krosshaug T. Understanding injury mechanisms: a key component of preventing injuries in sport. *Br J Sports Med* 2005; 39: 324–329.

116. Gabbett TJ. The training-injury prevention paradox: should athletes be training smarter and harder? *Br J Sports Med* 2016; 50: 273–280.

117. Buchheit M, Simpson BM and Mendez-Villanueva A. Repeated high-speed activities during youth soccer games in relation to changes in maximal sprinting and aerobic speeds. *Int J Sports Med* 2013; 34: 40–48.

118. Sankey SP, Robinson MA and Vanrenterghem J. Whole-body dynamic stability in side cutting: implications for markers of lower limb injury risk and change of direction performance. *J Biomech* 2020; 104: 109711.

119. Dos'Santos T, Thomas C, Comfort P, et al. Role of the penultimate foot contact during change of direction: implications on performance and risk of injury. *Strength Cond J* 2019; 41: 87–104.

### Appendix 1. Search strategy for Medline.

| 1 | Wearable electronic devices/ |
| 2 | Accelerometry/ or actigraphy/ |
| 3 | Inertial measurement unit.mp. |
| 4 | Imu.mp. |
| 5 | Motion capture.mp. |
| 6 | Ground reaction*.mp. |
| 7 | 1 OR 2 OR 3 OR 4 OR 5 OR 6 |
| 8 | Change of direction.mp. |
| 9 | Turning.mp. |
| 10 | Sidestep.mp. |
| 11 | Agility.mp. |
| 12 | Cutting movement.mp. |
| 13 | Cod.mp. |
| 14 | Acceleration/ or deceleration/ |
| 15 | 8 OR 9 OR 10 OR 11 OR 12 OR 13 OR 14 |
| 16 | 7 AND 15 |

Terms 1–6 were searched individually and then combined with an OR to capture all records that contained at least one of the terms. The process was repeated separately for terms 8–14. Then the final search was for records that contained at least one of term 1–6 and at least one of terms 8–14.

*: keyword; /: Subject heading; .mp.: broad search (search for references where word appears in several specific fields, including the title, abstract, subject heading, author keywords, and more).

### Appendix 2. Exclusion criteria.

| 1 | COD is not evaluated at all. |
| 2 | A different method (e.g. global positioning system, force plate) is used or IMU based metrics are not provided. |
| 3 | Assessing non-human changes of direction. Assessing changes of direction in other situations than physical activity (in purpose of exercise) or sport. Assessing changes of direction in sports/activities that do not involve taking a step (e.g. skiing, swimming). |
| 4 | Study is a commentary or editorial. |
| 5 | Describe if excluding for a different reason. |
Appendix 3. Quality assessment for all validity/reliability studies.

| Introduction | Balloch et al. 2019 | Gurchiek et al. 2017 | Nedergaard et al. 2017 | Roell et al. 2019 | Wundersitz et al. 2013 | Wundersitz et al. 2015 | Barreira et al. 2017 | Kim et al. 2020 | Meylan et al. 2017 | Staunton et al. 2017 |
|--------------|---------------------|----------------------|------------------------|-------------------|-----------------------|-----------------------|----------------------|-----------------|------------------|----------------------|
| 1. Were the aims/objectives of the study clear? | Y | Y | Y | Y | Y | Y | Y | NA | Y | Y |
| Methods | | | | | | | | | | |
| 2. Was the study design appropriate for the stated aim(s)? | Y | Y | Y | Y | Y | Y | Y | NA | Y | Y |
| 3. Was the sample size justified? | N | N | N | N | N | N | N | N | N | N |
| 4. Was the target/reference population clearly defined? (Is it clear who the research was about?) | N | N | N | Y | Y | N | N | N | N | N |
| 5. Was the sample frame taken from an appropriate population base so that it closely represented the target/reference population under investigation? | N | N | N | Y | Y | N | N | N | N | Y |
| 6. Was the selection process likely to select subjects/participants that were representative of the target/reference population under investigation? | N | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| 7. Were the risk factor and outcome variables measured appropriate to the aims of the study? | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| 8. Were the risk factor and outcome variables measured correctly using instruments/measurements that had been trialled, piloted or published previously? | Y | Y | Y | Y | Y | Y | Y | Y | Y | Y |
| 9. Is it clear what was used to determined statistical | Y | Y | N | Y | Y | Y | Y | Y | Y | Y |

(continued)
significance and/or precision estimates? (e.g. p-values, confidence intervals)

10. Were the methods (including statistical methods) sufficiently described to enable them to be repeated?

|                      | Balloch et al. 2019 | Gurchiek et al. 2017 | Nedergaard et al. 2017 | Roell et al. 2019 | Wundersitz et al. 2013 | Wundersitz et al. 2015 | Barreira et al. 2017 | Kim et al. 2020 | Meylan et al. 2017 | Staunton et al. 2017 |
|----------------------|---------------------|----------------------|-----------------------|------------------|------------------------|-----------------------|-------------------|-----------------|-------------------|---------------------|
| Y                    | Y                   | Y                    | Y                     | Y                | Y                      | Y                     | Y                 | Y               | Y                 | Y                   |

Results

11. Were the basic data adequately described?

|                      | Balloch et al. 2019 | Gurchiek et al. 2017 | Nedergaard et al. 2017 | Roell et al. 2019 | Wundersitz et al. 2013 | Wundersitz et al. 2015 | Barreira et al. 2017 | Kim et al. 2020 | Meylan et al. 2017 | Staunton et al. 2017 |
|----------------------|---------------------|----------------------|-----------------------|------------------|------------------------|-----------------------|-------------------|-----------------|-------------------|---------------------|
| Y                    | Y                   | Y                    | Y                     | Y                | Y                      | Y                     | Y                 | Y               | Y                 | Y                   |

12. Does the response rate raise concerns about non-response bias?

|                      | Balloch et al. 2019 | Gurchiek et al. 2017 | Nedergaard et al. 2017 | Roell et al. 2019 | Wundersitz et al. 2013 | Wundersitz et al. 2015 | Barreira et al. 2017 | Kim et al. 2020 | Meylan et al. 2017 | Staunton et al. 2017 |
|----------------------|---------------------|----------------------|-----------------------|------------------|------------------------|-----------------------|-------------------|-----------------|-------------------|---------------------|
| NA                   | NA                  | NA                   | NA                    | NA               | NA                     | NA                    | NA                | NA              | NA                | NA                  |

13. If appropriate, was information about non-responders described?

|                      | Balloch et al. 2019 | Gurchiek et al. 2017 | Nedergaard et al. 2017 | Roell et al. 2019 | Wundersitz et al. 2013 | Wundersitz et al. 2015 | Barreira et al. 2017 | Kim et al. 2020 | Meylan et al. 2017 | Staunton et al. 2017 |
|----------------------|---------------------|----------------------|-----------------------|------------------|------------------------|-----------------------|-------------------|-----------------|-------------------|---------------------|
| NA                   | NA                  | NA                   | NA                    | NA               | NA                     | NA                    | NA                | NA              | NA                | NA                  |

14. Were the results internally consistent?

|                      | Balloch et al. 2019 | Gurchiek et al. 2017 | Nedergaard et al. 2017 | Roell et al. 2019 | Wundersitz et al. 2013 | Wundersitz et al. 2015 | Barreira et al. 2017 | Kim et al. 2020 | Meylan et al. 2017 | Staunton et al. 2017 |
|----------------------|---------------------|----------------------|-----------------------|------------------|------------------------|-----------------------|-------------------|-----------------|-------------------|---------------------|
| Y                    | Y                   | Y                    | Y                     | Y                | Y                      | Y                     | Y                 | Y               | Y                 | Y                   |

15. Were the results presented for all the analyses described in the methods?

Discussion

16. Were the authors' discussions and conclusions justified by the results?

|                      | Balloch et al. 2019 | Gurchiek et al. 2017 | Nedergaard et al. 2017 | Roell et al. 2019 | Wundersitz et al. 2013 | Wundersitz et al. 2015 | Barreira et al. 2017 | Kim et al. 2020 | Meylan et al. 2017 | Staunton et al. 2017 |
|----------------------|---------------------|----------------------|-----------------------|------------------|------------------------|-----------------------|-------------------|-----------------|-------------------|---------------------|
| Y                    | Y                   | Y                    | Y                     | Y                | Y                      | Y                     | Y                 | Y               | Y                 | Y                   |

17. Were the limitations of the study discussed?

Other

18. Were there any funding sources or conflicts of interest that may affect the authors' interpretation of the results?

|                      | Balloch et al. 2019 | Gurchiek et al. 2017 | Nedergaard et al. 2017 | Roell et al. 2019 | Wundersitz et al. 2013 | Wundersitz et al. 2015 | Barreira et al. 2017 | Kim et al. 2020 | Meylan et al. 2017 | Staunton et al. 2017 |
|----------------------|---------------------|----------------------|-----------------------|------------------|------------------------|-----------------------|-------------------|-----------------|-------------------|---------------------|
| N                    | N                   | N                    | N                     | N                | N                      | N                     | N                 | U               | U                 | N                   |

19. Was ethical approval or consent of participants attained?

|                      | Balloch et al. 2019 | Gurchiek et al. 2017 | Nedergaard et al. 2017 | Roell et al. 2019 | Wundersitz et al. 2013 | Wundersitz et al. 2015 | Barreira et al. 2017 | Kim et al. 2020 | Meylan et al. 2017 | Staunton et al. 2017 |
|----------------------|---------------------|----------------------|-----------------------|------------------|------------------------|-----------------------|-------------------|-----------------|-------------------|---------------------|
| Y                    | Y                   | Y                    | Y                     | Y                | Y                      | Y                     | Y                 | Y               | Y                 | Y                   |