1-30-2020

Assessment of a novel algorithm to determine change-of-direction angles while running using inertial sensors

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10.1519/JSC.0000000000003064
This is an Author's Accepted Manuscript version of:
Balloch, A. S., Meghji, M., Newton, R. U., Hart, N. H., Weber, J. A., Ahmad, I. , & Habibi, D. (2020). Assessment of a Novel Algorithm to Determine Change-of-Direction Angles While Running Using Inertial Sensors. *Journal of Strength and Conditioning Research*. 34(1) 134 - 144.
Published version of record available here
This Journal Article is posted at Research Online.
https://ro.ecu.edu.au/ecuworkspost2013/5901

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Journal of Strength and Conditioning Research

Assessment of a Novel Algorithm to Determine Change of Direction Angles Whilst Running Using Inertial Sensors

--Manuscript Draft--

Manuscript Number:	JSCR-08-11151R1
Full Title:	Assessment of a Novel Algorithm to Determine Change of Direction Angles Whilst Running Using Inertial Sensors
Short Title:	Quantifying Change of Direction Angles Using Inertial Sensors
Article Type:	Original Research
Keywords:	validity; accuracy; reliability; microtechnology; signal processing; accelerometry
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Manuscript Region of Origin:	AUSTRALIA
Abstract:	The ability to detect and quantify change of direction (COD) movement may offer a unique approach to load monitoring practice. Validity and reliability of a novel algorithm to calculate COD angles for pre-determined COD movements ranging from 45° to 180° in left and right directions was assessed. Five recreationally active males (age: 29.0 ± 0.5 years; height: 181.0 ± 5.6 cm; body mass: 79.4 ± 5.3 kg) ran five consecutive pre-determined COD trials each, at four different angles (45°, 90°, 135° and 180°), in each direction. Participants were fitted with a commercially available microtechnology unit where inertial sensor data was extracted and processed using a novel algorithm designed to calculate precise COD angles for direct comparison with a high-speed video (remotely piloted, position-locked aircraft) criterion measure. Validity was assessed using Bland-Altman 95% limits of agreement and mean bias. Reliability was assessed using typical error (expressed as a coefficient of variation). Concurrent validity was present for most angles. Left: (45°= 43.8 ± 2.0°; 90°= 88.1 ± 2.0°; 135°= 136.3 ± 2.1°; 180°= 181.8 ± 2.5°) and Right: (45°= 46.3 ± 1.6°; 90°= 91.9 ± 2.2°; 135°= 133.4 ± 2.0°; 180°= 179.2 ± 5.9°). All angles displayed excellent reliability (CV < 5%) whilst greater mean bias (3.6 ± 5.1°), weaker limits of agreement and reduced precision were evident for 180° trials when compared with all other angles ($p < 0.001$). High-level accuracy and reliability when detecting COD angles further advocates the use of inertial sensors to quantify sports-specific movement patterns.

Response to Reviewers:

Responses to Reviewers' Comments

JSCR-08-11151 entitled "Assessment of a Novel Algorithm to Determine Change of Direction Angles Whilst Running Using Inertial Sensors"

The authors would like thank the reviewers and editorial team for giving us the opportunity to revise this manuscript. We would like to thank the reviewers' for their favourable view of our manuscript and their thoughtful comments and suggestions to further improve the quality of our paper. We have provided a point-by-point explanation of each of the changes we have made as suggested by each of the reviewers.

Reviewer #2

We would like to thank the kind words of Reviewer 2 in relation to the high-impact nature of our manuscript and its applicability to the JSCR audience. We very much appreciate your feedback and have taken on board your comments/suggestions as follows:

Comment 1: The movement velocity is one of the factors to affect validity and reliability of microtechnology. On page 7 / line 155: "Participants were instructed to run at a moderate pace and change direction…" and on page 11 / line 258-265 described velocity determination in this study. Highly suggest that the running velocity at different angles need to provide. It will show how velocity participant ran in the study and what the running velocity the novel algorithm was high-level of accuracy and reliability in detecting, recording and calculating a precise COD angle.

Response: Running velocity (as detected using instantaneous GNSS readings from the microtechnology unit throughout each COD incident) was reported in Table 1 (Pre COD Avg Vel, Post COD Avg Vel and Total COD Avg Vel) for each COD angle (45°, 90°, 135° and 180°) in both directions (left and right). The definitions for each of these velocity calculations are described under the sub-heading 'Velocity Determination' (Page 11, Lines 257-265). In addition, we acknowledge the limitation regarding the requirement of future research using our novel algorithm to assess COD angle at greater running velocities (Page 18, Lines 428-433).

Comment 2: Authors need to address conflict of interest.

Response: A conflict of interest statement has been added under the 'Acknowledgements' heading.

Comment 3: The number of participants was only five recreationally active males. Although the effect sizes were calculated shown as Table 1, this issue could address in the limitation.

Response: A statement regarding the limitation of using only 5 participants has been added.

Reviewer #3

We would like to thank Reviewer 3 for taking the time to review our manuscript in detail and providing practical suggestions to improve the applicability of our paper to the JSCR audience. We appreciate the kind words in regards to the methodology of our manuscript and have amended the use of lay terminology and removed excessive text where necessary throughout the paper. A large chunk of information regarding GPS technology has been shifted from the introduction to the discussion (and amended as necessary). The methods section has been amended to ensure the entire body of writing is presented in past tense. Any excessively emotive language has been removed. The use of both scalar and vector terminology has been clarified where appropriate; and we now feel the paper is more suited to the JSCR audience.

Comment 1: Line 31 - velocity is a vector quantity involving both magnitude and direction

Response: The term ‘and direction’ has been removed with velocity remaining.

Comment 2: Line 36 - is frequency the best term here? Frequency in running activities typically refers to stride or step frequency which does not seem to be the point in this sentence

Response: The term ‘frequency’ has been replaced by ‘occurrence’.

Comment 3: Line 47-49 - please ensure consistent (and appropriate) use of scalar and vector terminology (here and throughout the manuscript)

Response: Thank you for the suggestion. Terminology in this paragraph has been altered to scalar quantities. This issue has been addressed throughout the paper where applicable. Numerous studies I have referenced use the term velocity and thus I have attempted to maintain the integrity of these studies by using the same terminology.

Comment 4: Line 61 - this part of the sentence reads awkwardly.

Response: This sentence has been removed from the introduction, but has been added in a clearer format to the discussion section.

Comment 5: Line 69 - why is this unexpected? All technology has some ceiling effect, such as sampling frequency for force or EMG; additionally, there are other factors that influence the accuracy of GPS, such as spatial resolution

Response: The term ‘somewhat unexpectedly’ has been removed.

Comment 6: Line 84 - what type of validity?

Response: ‘Construct’ and ‘concurrent’ validity have been added.

Comment 7: Line 110 - major is not needed

Response: The term ‘major’ has been removed.

Comment 8: Line 116 - incident is not an appropriate word choice here

Response: The term ‘incidents’ has been changed to ‘movements’. This has been amended throughout the paper.

Comment 9: Line 184 - why not use proper anatomical terminology? The entire section that follows will be difficult to read for S&C researchers and practitioners. The use of simple anatomical terminology such as anterior-posterior, left-right, superior-inferior; and associated planes will improve readability. Also, be sure that you are consistent in using present or past tense throughout the methods

Response: Proper anatomical terminology has been added in brackets immediately following the roll (mediolateral), pitch (anterior-posterior) and yaw (superior-inferior) axes of the inertial sensors. Various changes have been made to ensure the entire methods section presents in past tense.

Whilst we recognise that the ‘Algorithm Creation’ section may be difficult for S&C researchers and practitioners to fully understand, we feel it is necessary to be transparent with the precise methodological steps used in the signal processing stages of the raw inertial sensor data and calculation of COD angle within our novel algorithm.

Comment 10: Line 250 - "precisely" is not required here; along these lines, was the accuracy of this measurement tool validated?

Response: The term ‘precisely’ has been removed.

Kinovea motion analysis software (including the angle measuring tool) has been used for many purpose and in multiple peer-reviewed publications such as:
- •To quantify joint angles whilst running (Damsted C, Nielsen RO, Larsen LH. RELIABILITY OF VIDEO-BASED QUANTIFICATION OF THE KNEE- AND HIP ANGLE AT FOOT STRIKE DURING RUNNING. International Journal of Sports Physical Therapy. 2015;10(2):147-154.)
- •Flight time of a vertical jump (Balsalobre-Fernández, C., Tejero-González, C. M., del Campo-Vecino, J., & Bavaresco, N. (2014). The concurrent validity and reliability of a low-cost, high-speed camera-based method for measuring the flight time of vertical jumps. The Journal of Strength & Conditioning Research, 28(2), 528-533.)
- •Measure angular positions of lower limbs during therapeutic motion (Guzmán-Valdivia, C. H., Blanco-Ortega, A., Oliver-Salazar, M. A., & Carrera-Escobedo, J. L. (2013). Therapeutic motion analysis of lower limbs using Kinovea. Int. J. Soft Comput. Eng, 3(2), 359-365.)

Comment 11: Line 258 - how was velocity determined? Does this velocity include both magnitude and direction components?

Response: Instantaneous velocity (amended in the manuscript) is calculated using the velocity based on GPS Doppler shift from the GPS engine. This is the main measure of velocity in the software and is the recommended velocity metric from the microtechnology unit manufacturer (Catapult Sports). Alone, it does not provide a direction component. However, other metrics which use this velocity measure can provide some information regarding direction (e.g. acceleration / deceleration). We report the direction of each COD movement using our novel algorithm and compare it against the high-speed video criterion. The average velocity measures are provided to give the reader an understanding of the running speed that the participants completed the COD movements at.

Comment 12: Line 295 - was a minimal value set, i.e. where any larger value is considered to be a real difference?

Response: There was no minimal value set as the statistical software only required the mean and standard deviation of the differences and a maximum allowed difference between the methods to compute a recommended sample size in accordance with pre-determined Type I and Type II error probabilities. Any real differences (albeit very minor from a practical perspective) were calculated using Bland-Altman LOA and reported as mean bias (Table 1).

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26-09-2018

Prof. Nicholas A. Ratamess, PhD, CSCS, FNSCA
Editor-in-Chief.
Journal of Strength and Conditioning Research

Dear Professor Ratamess,

Thank you for considering our Original Research: “Assessment of a Novel Algorithm to Determine Change of Direction Angles Whilst Running Using Inertial Sensors” which required Major Revision (R1) as per the recent review received.

We have addressed all formatting and typographical errors raised by the reviewers in their expert assessment of our manuscript, and feel their comprehensive review and detailed comments were most helpful to improve the overall manuscript in several key areas. We wish to thank each of the reviewers for their time in the initial review.

We (the authors) state that the contents of the accompanying original research paper (revision) has not been, and will not be submitted for publication in another journal. Each of us has been involved in the preparation and development of this original research paper, and are in agreement with the contents of the manuscript which we wish to present in your journal, JSCR (Journal of Strength and Conditioning Research). We have no conflicts of interest to declare, including financial interests, activities, relationships and affiliations relating to this manuscript.

Yours sincerely,

Aaron Balloch

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ORIGINAL RESEARCH

ASSESSMENT OF A NOVEL ALGORITHM TO DETERMINE CHANGE OF DIRECTION ANGLES WHILST RUNNING USING INERTIAL SENSORS

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Brief Running Head: *Quantifying COD angles using inertial sensors*

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ASSESSMENT OF A NOVEL ALGORITHM TO DETERMINE CHANGE OF DIRECTION ANGLES WHILST RUNNING USING INERTIAL SENSORS

ABSTRACT

The ability to detect and quantify change of direction (COD) movement may offer a unique approach to load monitoring practice. Validity and reliability of a novel algorithm to calculate COD angles for pre-determined COD movements ranging from 45° to 180° in left and right directions was assessed. Five recreationally active males (age: 29.0 ± 0.5 years; height: 181.0 ± 5.6 cm; body mass: 79.4 ± 5.3 kg) ran five consecutive pre-determined COD trials each, at four different angles (45°, 90°, 135° and 180°), in each direction. Participants were fitted with a commercially available microtechnology unit where inertial sensor data was extracted and processed using a novel algorithm designed to calculate precise COD angles for direct comparison with a high-speed video (remotely piloted, position-locked aircraft) criterion measure. Validity was assessed using Bland-Altman 95% limits of agreement and mean bias. Reliability was assessed using typical error (expressed as a coefficient of variation). Concurrent validity was present for most angles. Left: (45°= 43.8 ± 2.0°; 90°= 88.1 ± 2.0°; 135°= 136.3 ± 2.1°; 180°= 181.8 ± 2.5°) and Right: (45°= 46.3 ± 1.6°; 90°= 91.9 ± 2.2°; 135°= 133.4 ± 2.0°; 180°= 179.2 ± 5.9°). All angles displayed excellent reliability (CV < 5%) whilst greater mean bias (3.6 ± 5.1°), weaker limits of agreement and reduced precision were evident for 180° trials when compared with all other angles ($p < 0.001$). High-level accuracy and reliability when detecting COD angles further advocates the use of inertial sensors to quantify sports-specific movement patterns.

KEY WORDS: validity, accuracy, reliability, microtechnology, signal processing, accelerometry

INTRODUCTION

Change of direction (COD) movements (pre-planned and reactive) are characterized by whole-body changes of velocity requiring high magnitudes of vertical, medio-lateral and anterior-posterior impulses to move quickly and efficiently (6, 34). Each COD event involves a braking and propulsive phase which highlights the importance of eccentric-concentric muscle actions for both force production and muscular endurance as the number of directional changes increases (6). As the occurrence of these movements increase, high levels of muscle damage and neuromuscular fatigue become prevalent (6, 33). The accumulation of both acute and chronic fatigue may alter movement strategy and compromise mechanical efficiency of movement during subsequent efforts or exercise bouts (32). Without adequate recovery, a reduction in movement efficiency may alter mechanical loading on lower-body joints, and inherently increase the risk of injury (13, 30). If such changes in mechanical loading can be identified, quantified, examined and subsequently integrated into load management practice through wearable technology; effective strategies may be developed to enhance performance and reduce injury risk through individually tailored, sport-specific conditioning interventions.

Global Positioning System (GPS) technology is principally used in team-sports to monitor athletes during on-field training and competition by transmitting instantaneous triangular positioning information which is used to formulate a multitude of distance, time and speed derived metrics (11, 36). This technology is widely used within elite sport as a performance analysis tool (9, 11), and whilst it has the capability to accurately calculate accumulated distance when movement is largely linear (8, 27), it is inherently prone to error during short duration, high-speed movements (10, 26) and even more so when these movements incorporate non-linear characteristics (e.g. COD movement) (14, 25).

Additionally, this technology appears to be approaching its limits with regards to more advanced movement tracking whereby an optimal sampling frequency (10 Hz) has been proposed (26), suggesting alternate technologies may be required to accurately identify and quantify more complex, sports-specific movement patterns.

Inertial sensors (accelerometers, gyroscopes, magnetometers) in wearable technology have previously been used to detect physical activity and sleep patterns in both clinical and general populations (9, 28); and to more precisely differentiate between a range of activities from sitting and standing to walking, running and jumping by assessing vector quantities of acceleration in three dimensions (anterior-posterior, medio-lateral and vertical) with high levels of validity (both construct and concurrent) and reliability (3, 9). Commercially available GPS devices implemented in elite sport currently house these inertial sensors co-located within the same unit casing as the GPS engine, which have the capability to accurately identify, record and quantify more sport-specific movements (4), yet tend to be underutilized in the professional environment and within proprietary software. These inertial sensors sample at a much higher frequency than GPS engines (most commonly 100Hz) and can therefore detect subtle changes in movement within the three-dimensional environment that GPS technology is presently incapable of (9). Additionally, inertial sensors work independently of satellite reliant GPS technology and can therefore be implemented indoors (9); superseding a fundamental limitation of GPS engines when used in isolation.

In a team-sport environment, inertial sensor technology has been effectively used to quantify a range of different movements from jumps to collisions, impacts and tackles (5, 16-18, 38). Furthermore, signals from inertial sensors coupled with various pattern recognition techniques have successfully been used to create algorithms that automatically detect and categorize collisions and tackles in heavy contact sports such as Australian rules football and rugby league (16, 17); and a range of different activities including rotational magnitude of aerial acrobatics in snowboarding (20), kick count in swimming (15), and more recently, an entire fast-bowling event in cricket (31).

Whilst these inertial sensors have previously been assessed for their ability to detect and analyze a number of different multi-planar ‘sports specific’ movements (15, 16, 20, 31, 38), these studies are infrequent, and to our knowledge, these sensor signals are yet to be used to accurately distinguish COD movement from other variables from within a commercially available microtechnology unit.

Given the neuromuscular implications associated with repeated COD movements, highly prevalent in team-sports (12), and the subsequent effect resulting fatigue may have on the movement efficiency of an athlete, there is clear rationale for non-linear movement patterns to be further assessed and included in both acute and chronic load monitoring practice. Therefore, the current study is a description of the use of inertial sensor technology (accelerometers, gyroscopes and magnetometers) to develop an algorithm that is able to automatically detect and record COD movements ranging from 45 to 180 degrees (both left and right direction) and concomitantly assesses the validity and reliability of the calculated COD angle.

METHODS

Experimental Approach to the Problem

This concurrent validity study was designed to investigate the accuracy of a novel algorithm to automatically detect and quantify COD angle against a high-speed video criterion measure.

Participants were required to run a series of single, pre-determined change of direction (COD) trials consisting of four different angular changes (45°, 90°, 135° and 180°) in each direction (left and right). Each participant was required to run five COD trials at each angle in each direction (*i.e.* 40 trials per participant) wearing a commercially available, and commonly used microtechnology unit (Optimeye, S5, Catapult Innovations, Melbourne, Australia) on an outdoor football field. A remotely piloted aircraft (drone; Mavic Pro; DJI, Shenzhen, China) was position-locked above the marked COD center-point to record all trials for comparison between measurement devices and for visual confirmation of correct running lines (Figure 1).

ENTER FIGURE 1 ABOUT HERE

Subjects

Five recreationally active males (mean ± SD; age, 29.0 ± 0.5 years; height, 181.0 ± 5.6 cm; body mass, 79.4 ± 5.3 kg) volunteered to participate in this study. All participants were free from injury and medical conditions that would contraindicate participation in physical activity. The study was ethically approved by the University’s Human Research Ethics Board and subjects were informed of the benefits and risks of the investigation prior to signing an institutionally approved informed consent document to participate in the study.

Procedures

Testing Protocol

Prior to commencement of testing, participants were given clear instructions to run directly on a visibly marked straight line on the ground and change direction at a marked center-point before continuing to follow a second marked straight line in accordance with the intended COD and angle (Figure 2). A dynamic warm-up was undertaken before each participant completed one warm-up COD trial at each angle (45°, 90°, 135° and 180°) in each direction (left and right) for familiarization purposes. Participants were then required to complete 5 individual COD trials consecutively at each angle in each direction in a randomized and counterbalanced fashion (to ensure any fatigue would not have an adverse or more influential effect on a given angle or direction relative to another); therefore all participants' completed five 45° COD trials to the left before moving on to the next angle and direction. Participants were instructed to run at a moderate pace and change direction by planting the outside foot to the opposite direction in a 'side-cutting' motion but were encouraged to keep each trial 'as natural as possible' (Figure 2). Participants' were provided with adequate rest of at least 60 seconds between COD trials and ensured compliance of 5 consecutive trials in each direction, confirmed with visual inspection using drone-footage post-collection. Each participant completed 40 COD trials, producing a total of 200 trials across the testing session.

ENTER FIGURE 2 ABOUT HERE

Microtechnology

Each participant was fitted with a commercially available microtechnology unit (Optimeye, S5, Catapult Innovations, Melbourne, Australia) (Figure 3a) posteriorly trunk-mounted (at the level of the upper thoracic vertebrae (T1 to T5), between the medial borders of the scapulae) in a manufacturer supplied, fitted vest (Figure 3b). This microtechnology unit houses a 10 Hz Global Navigation Satellite System antenna along with a tri-axial accelerometer, tri-axial gyroscope and tri-axial magnetometer, all sampling at 100Hz. Each unit was calibrated in accordance with the manufacturer's guidelines prior to the commencement of the testing session. Raw data was extracted from the microtechnology unit using manufacturer designed, proprietary software (Catapult Sprint 5.1, Catapult Innovations, Melbourne, Australia) for subsequent exportation and analysis.

ENTER FIGURE 3 ABOUT HERE

Algorithm Creation

Data analysis and algorithm creation were performed using MATLAB (MathWorks, Natick, MA), whereby a multi-stage algorithm was developed incorporating tri-axial inertial sensor inputs that align with the athlete's body in such a way that the x, y and z rotations correspond to the *roll* (medio-lateral), *pitch* (anterior-posterior) and *yaw* (superior-inferior) axes of the inertial sensors (Figure 4). This algorithm provides a series of signal processing computation and decision techniques to first detect that a COD movement has occurred; second detect the direction of the COD movement; and third report the precise COD angle.

ENTER FIGURE 4 ABOUT HERE

Heading Angle Calculation

Initial stages of the algorithm required input from each of the inertial sensors (accelerometer, gyroscope, and magnetometer) to optimize accuracy when computing the 'yaw' (also known as the heading or azimuth) angle. First, the gyroscope output was time-integrated by mapping the rate of change of angular velocity (w) (i.e. angular velocity / time) from an initially known orientation.

From the relationship: $w = \frac{d\theta}{dt};\ d\theta = wdt$

The overall angle change (yaw) was found by summating this quantity over many samples and then using a rotation matrix to determine the Euler yaw angle (rotation around the z-axis).

Therefore, $\theta = \int_{t+T}^{t} w dt$ or $\theta = \sum_{t+T}^{t} w \times \Delta t$

Second, the magnetometer output is able to accurately compute heading location by using the Earth's magnetic field (when parallel to the Earth's surface). However, a moving athlete will inevitably cause the magnetometer to move away from the horizontal plane (tilt) causing errors in subsequent calculations (40). Therefore, tri-axial accelerometer data was used to calculate roll and pitch angles which were subsequently integrated with the magnetometer data to correct this tilt error by mapping the magnetometer data to the horizontal plane providing an accurate heading calculation regardless of the magnetometer's position.

Finally, a complementary filter was used to obtain the final yaw angle estimation by integrating gyroscope and magnetometer yaw angle calculations for the strongest and most accurate sensor computation.

Change of Direction Angle Calculation

The 'yaw' angle calculation obtained (as described above) then entered a secondary stage of the algorithm (a modified Canny edge detection algorithm (7)) which principally follows a five-step process from the input of the yaw angle, to the detection of a COD movement, determination of a direction, and calculation of a precise angle.

Initially, a customized 2D Gaussian filter was used to remove any 'noise' from the yaw signal. The next step involved determining the intensity gradient of the yaw angles in both horizontal and vertical planes to provide both magnitude and direction. This was followed by a non-maximal suppression stage whereby a full scan of yaw angles was completed to identify the local maxima or peak (maximum change in gradient) whilst the rest of the samples were suppressed and set to zero. From here, hysteresis thresholding was used to identify 'real' edges based on pre-determined threshold values which differ with variations in angle. These edge values were then extracted and entered in to a multi-level piecewise thresholding algorithm (based on a piecewise linear relationship between the edge value and calculated angle change (yaw angle)) to calculate a precise COD angle.

High-Speed Video Analysis

A remotely piloted aircraft (drone; DJI Mavic Pro, DJI, Shenzhen, China) was positioned fifteen meters (15m) above the center-point of the marked COD grid and locked in position, remaining completely stationary for the duration of the testing session (lasting ~30 minutes). An in-built high-definition camera (1/2.3" CMOS 12MP 4K) recorded each COD trial at a sampling rate of 96 frames per second. Each COD trial was visually inspected post-collection to ensure the drone was positioned correctly and remained completely still to ensure valid trials were recorded. Subsequent video analysis was performed using Kinovea software (Kinovea, 0.8.15, http://www.kinovea.org/) where each COD trial was analyzed to allow a direct and quantifiable comparison between the algorithm-derived COD angle and the high-speed video-derived COD angle.

Following visual inspection, a pre-set distance of two meters either side of the COD center-point was deemed the beginning and the end of the COD trial, ensuring participants were 'yet to commence' and had 'completed' the COD in each trial respectively (Figure 5). This pre-defined distance was precisely measured during analysis using a software calibration tool (Kinovea, 0.8.15) from a pre-measured and clearly marked point (measuring one meter) on the COD grid. A reflective marker was fixed to the exterior of the vest where the microtechnology device was housed to allow clear determination of the device's position during video-analysis to maximize precision when calculating COD angle. COD angle was determined using an angle measuring tool within the software (Kinovea, 0.8.15) which intersected the location of the posteriorly trunk-mounted microtechnology device at both reference points (two meters either side of the COD center-point); thus calculating the resultant angle (Figure 5).

ENTER FIGURE 5 ABOUT HERE

Velocity Determination

Instantaneous velocity measures were derived from the GPS engine (Optimeye S5, Catapult Innovations) and extrapolated using identical proprietary software to that mentioned previously (Catapult Sprint 5.1, Catapult Innovations, Melbourne, Australia). 'Pre change of direction average velocity' was defined as the average velocity over two seconds preceding the point of COD, 'post change of direction average velocity' was defined as the average velocity over two seconds directly following the COD point, and 'total change of direction average velocity' was defined as the average velocity from the beginning of the 'pre change of direction' to the end of the 'post change of direction' time-stamp (including the point of COD).

Statistical Analyses

Six COD trials were removed following visual inspection, as slight movement of the remotely piloted aircraft (environmental factors) was detected during these trials. This left a total of 194 COD trials for use in the analyses. All statistical analyses were conducted using SPSS software (v24.0, SPSS Inc., New York, USA) and Microsoft Excel^{TM} (Microsoft, Redmond, USA) with the exception of statistical power estimation (for sample size determination) described below. Data are presented as mean ± SD for both high-speed video and algorithm derived determinants of COD angle (Table 1). Level of agreement and accuracy of the proposed algorithm was assessed by calculating the Bland-Altman 95% limits of agreement (LoA) (2) and mean bias in relation to the criterion measure (high-speed video). Effect size of the mean bias was calculated using Cohen's *d* where results were interpreted as negligible (< 0.2), small (0.2-0.6), medium (0.6-1.2), large (1.2-2.0) or very large (2.0-4.0) (22). Precision or variability of bias was assessed using a root mean square error of prediction (RMSEP). Reliability was calculated using Hopkins' spreadsheet (21) and was expressed in absolute terms as typical error (TE) ± 90% confidence intervals and relative terms as a coefficient of variation (CV) percentage where; a CV < 5% was considered 'good'; a CV between 5-10% 'moderate'; and a CV > 10% 'poor' as has been previously interpreted when assessing the reliability of sports analysis technology (5, 25).

A one-way analysis of variance (ANOVA) was conducted on the mean difference scores (or bias) between each participant to identify any potential differences in algorithm accuracy between calibrated Catapult S5 Optimeye microtechnology devices and/or movement techniques. A second one-way ANOVA was conducted to determine any differences in mean bias across each angle (45°, 90°, 135°, and 180°), independent of direction. Post-hoc comparisons were assessed using a Games-Howell test as appropriate for heteroscedastic data. A paired samples t-test was used to determine any differences in mean bias between left and right direction across all angles. Sample size requirements for LoA were calculated using MedCalc Statistical Software (v18.2.1, MedCalc Software bvba, Ostend, Belgium; http://www.medcalc.org; 2018) where 10° was set as the maximum allowed difference between methods across all trials; yielding a required sample of 171 trials. An alpha level of $p < 0.05$ was set as the level of significance for all statistical tests.

RESULTS

Concurrent validity and accuracy of the proposed algorithm is presented in Table 1. The results from the Bland-Altman analysis are shown in Table 1 and Figure 6. Concurrent validity was present across a number of angles (45° right, 135° left and right, 180° right), however the proposed algorithm slightly underestimated COD angle at 45° (-2.3 ± 2.7°, Cohen's *d* = -0.81) and 90° to the left (-3.0 ± 2.6°, Cohen's *d* = -1.13), whilst slightly overestimating COD angle at 180° (4.9 ± 3.7°, Cohen's *d* = 1.36) to the left and 90° to the right (1.9 ± 2.5°, Cohen's *d* = 0.76). No significant bias was found between the proposed algorithm and criterion measure for any other angles with a mean bias range of -0.6 ± 2.2° to 2.4 ± 6.1° and negligible to small effect size differences (Cohen's *d* = -0.26 to 0.39).

ENTER TABLE 1 ABOUT HERE

ENTER FIGURE 6 ABOUT HERE

All angles were measured with good reliability (TE = 1.6° - 5.2°; CV = 1.3 to 4.2%). Levene's test of homogeneity revealed unequal variances and therefore the Brown-Forsythe ANOVA result was interpreted, revealing no significant difference in mean bias between microtechnology devices and/or movement technique ($p = 0.25$). However, the secondary Brown-Forsythe ANOVA did reveal a significant difference in mean bias between angles ($p = 0.00$) with Games-Howell post-hoc comparisons showing a significantly greater mean bias for the 180° COD trials (3.6 ± 5.1°) when compared with 45° (-1.3 ± 2.7°; $p = 0.000$), 90° (-

0.6 ± 3.6°; p = 0.000) and 135° (-0.5 ± 2.9°; p = 0.000) COD trials (Figure 7). Weaker limits of agreement and precision were also apparent for the 180° trials (in both directions) when compared with all other angles (Table 1). There were no significant differences found in mean bias between 45°, 90° and 135° COD trials. Additionally, there was no statistically significant difference in the mean bias between left (-0.3 ± 4.2°) and right (0.9 ± 4.0°) COD trials across all angles (p = 0.06).

ENTER FIGURE 7 ABOUT HERE

DISCUSSION

The purpose of this study was to assess the validity, accuracy and reliability of a newly developed algorithm to calculate COD angle for pre-determined COD movements ranging from 45° to 180° (both left and right) and assess the level of agreement against a criterion measure.

Our novel algorithm displayed a high level of accuracy with mean differences ranging between -3.0 ± 2.6° to 4.9 ± 3.7° (-5.1% - 2.8%) in relation to the criterion measure; and proved valid across numerous COD angles (45°, 90°, 135° and 180°), in both directions (left and right). Of these, the algorithm slightly underestimated COD angle for 45° and 90° trials (left), and slightly overestimated COD angle for 90° (right) and 180° trials (left). These results are a mild bias that may be statistically present in some cases, however from a practically meaningful perspective, a bias of less than 5° or 6% for all COD angles could be considered insignificant when aiming to assess the mechanical load associated with COD movement for both acute and chronic load monitoring purposes; given there is currently no alternative in detecting, recording and reporting COD angle on-field using a commercially available and commonly used microtechnology unit. However, caution is required when quantifying 180° COD movements which evidently presented a significantly greater mean difference (bias) and showed the weakest limits of agreement (95% LoA (*Left:* -2.16°, 12.00°, *Right:* -9.51°, 14.29°)) and lowest precision (RMSEP(*Left:* 6.05°, *Right:* 6.40°) when compared with the 45°, 90° and 135° trials. Yet importantly, all angles displayed good reliability (TE = 1.5° – 5.2°; CV < 5%) between trials.

Our algorithm demonstrates a level of validity and reliability that is comparable and mostly favorable to similarly previous research whereby inertial sensor outputs have been coupled with signal processing techniques to identify more complex movement patterns. For example, categorizing rotational magnitude of aerial acrobatic maneuvers in snowboarding (20), recording kick count during freestyle swimming (15) and somewhat unsuccessfully applying a tackle detection algorithm to Australian rules football matches (18). However, these studies have typically used only one of the inertial sensors in isolation (18, 23) and in some cases only analyzed a single-axis of movement (15, 20), whereas our algorithm utilizes more than one sensor, and considers all axes of movement. Similar to the current study, previous research that has utilized the integration of multiple sensor outputs (e.g. accelerometer and gyroscope) has demonstrated a high-level of success in detecting more holistic, sports-specific movement patterns like an entire fast bowling event in cricket (31) and quantifying the contact load of collisions in professional rugby league (16). These improved findings may be due to the ability to utilize the relative strengths of each inertial sensor to compensate for the weakness of another (29). The current study adds to this body of knowledge and the successful characterization of athletic movement by successfully (accurately and reliably) quantifying COD movements.

Whilst it has been suggested that a majority of human motion occurs at a rate of less than 20Hz (24), it is clear that much higher sampling rates are required to accurately capture more detailed and complex movement characteristics. Within elite sport, GPS technology is used heavily by sports science and strength and conditioning staff to make informed load-management decisions in ‘real-time’ and prospectively when periodizing and planning subsequent training sessions. However, GPS technology requires triangular signal positioning from orbiting satellites; thus requires an outdoor venue, limiting its applicability across sporting types, some outdoor venues and all indoor venues (11) and can be vulnerable to dysfunction or interference from adverse environmental conditions and other competing technologies. Furthermore, the reliability of GPS technology is considerably reduced during high-speed movements (1, 10, 14) and is even further compromised when measuring movement patterns that incorporate COD (25); highlighting other important limitations when using GPS to quantify player movement patterns and performance.

GPS technology has improved using higher sampling rates (10 Hz) where an ‘acceptable’ level of accuracy (CV $\leq$ 11.3%) and reliability (CV $\leq$ 6.0%) has been demonstrated when calculating instantaneous velocity during high-speed straight-line running (36), in contrast with less advanced GPS technologies (1-5 Hz sampling rate) which have proven to be less reliable when calculating instantaneous velocities during similar movement patterns (10, 19, 25). This logically suggests a potential linear relationship between higher sampling frequencies and greater detection sensitivity, leading to improved accuracy and reliability of GPS at higher sampling rates when measuring distance and instantaneous velocity during high-speed movements. However, Johnston et al. (26) recently demonstrated a potential ceiling effect, whereby GPS technology sampling at 10 Hz demonstrated superior accuracy and reliability than a 15 Hz sampling frequency when measuring distance run at high-speed. Interestingly, neither technology was considered to be valid when calculating peak speed, however this may have been due to a limitation within the criterion measure itself (26). Consequently, GPS technology (*i.e.* satellite-based positioning) may be approaching its limits with regard to player monitoring capabilities, paving the way for high-frequency inertial sensors to more accurately identify sports-specific movement patterns, such as in the current study.

Furthermore, previous research has revealed inconsistencies in reliability between microtechnology devices when comparing GPS derived distance and speed measures (8, 14, 19, 26, 37) , whereas research assessing 'inter-unit' reliability in relation to inertial sensor derived metrics, whilst scarce, has indicated more positive results (4, 23); likely due to their self-contained nature (*i.e.* no reliance on satellite connectivity). These findings are in agreement with the current study where no differences in accuracy were found between microtechnology devices and suggests that assuming manufacturer calibration instructions are adhered to, and units are functioning correctly; our algorithm is highly accurate across multiple Catapult S5 Optimeye microtechnology devices and a variety of COD movement techniques (as each participant wore a different microtechnology device). This, however, requires further investigation, but may have important practical applications across a squad of athletes where movement technique will likely differ between individuals.

The proposed algorithm requires inputs from each of the inertial sensors (accelerometer, gyroscope, magnetometer) prior to undergoing a series of signal processing techniques to compute a 'heading' or 'yaw' angle which subsequently enters a secondary custom-designed Canny edge detection algorithm to compute a precise COD angle. Canny edge detection is a gradient-based edge detection method often used in image processing to determine the level of variance between different image pixels with a goal to identify sudden changes in an image and identify certain objects (39). The algorithm presented in the current study uses a modified Canny edge detector to determine the level of variance, or find transitions in the yaw angle signal derived from the inertial sensor inputs before hysteresis thresholding allows the identification of ‘real edges’ which are extracted and entered into a multi-level piecewise thresholding algorithm to calculate a precise COD angle. Importantly, the pre-determined piecewise quantization thresholds can be manipulated which has the potential to improve the accuracy of the angle change calculation and thus lead to greater optimization of the algorithm in the future. This is currently under investigation.

There are some limitations within the current study that must be acknowledged. Whilst only 5 participants were used, the primary measure of this study was based around the comparison between raw inertial sensor data and a high-speed video criterion; thus the number of COD trials conducted are of most importance. The remotely piloted aircraft used in this study was able to be locked in position directly above the clearly marked COD point, however it may be susceptible to very slight deviations during windy conditions which could lead to a degree of parallax error within the high-speed video footage given the height of the drone (15m) (35). Any trials where movement of the remotely piloted aircraft was deemed to have occurred were subsequently removed. Furthermore, given that the proposed algorithm is designed around a gradient-based edge detection method, it was not possible to precisely time-match the point at which the algorithm defines the ‘beginning’ and the ‘end’ of each COD trial with the high-speed video footage. Therefore, the two meter distance either side of the COD center-point was chosen based on visual inspection as a distance ensuring participants were ‘yet to commence’ and had ‘completed’ the COD in each trial respectively. However, these limitations did not appear to have an effect on the level of accuracy displayed in the current study when comparing the proposed algorithm to the criterion measure, and in fact, this technology may offer a time-efficient, highly practical resource for field-based performance monitoring and analysis.

Additionally, whilst future research using our algorithm to quantify COD angles at greater running velocities is warranted, we present an algorithm that has the capacity to operate at a commonly adopted, high-frequency inertial sensor sampling rate (100Hz); and thus we strongly suggest that any changes in running velocity will not impact the resultant COD angle calculation provided that the duration of an individual COD movement is not less than the time-frame equivalent to this sampling rate (10ms).

Although the current study utilized recreationally active males, we suggest that the proposed algorithm is highly applicable to team-sport athletes given the identical positioning of the microtechnology device seen during training and competition in a number of elite sports (Figure 3b) and the similarity in accuracy between participants evident in the current study. Whist the proposed algorithm displayed a high-level of accuracy for pre-determined COD movements of varying angles, this study took place in a controlled environment and thus the focus of future research will assess the algorithm's performance during more dynamic, reactive and unpredictable movement patterns typical of team-sport activity.

PRACTICAL APPLICATIONS

Through this study we have demonstrated an acceptable level of concurrent validity and a high-level of accuracy and reliability in detecting, recording and calculating a precise COD angle for pre-determined COD movements ranging from 45° through to 180° (left and right directions), with low-level bias (less than ± 5°). This novel algorithm has been designed using inertial sensor inputs which have a much greater capacity (sampling hundreds of times per second in multiple axes) to measure more complex human motion than GPS technology is currently able; coupled with sophisticated signal processing techniques. Currently, the ability to extract, manipulate and interpret this inertial sensor data in to more practical and sports-specific metrics is viewed as a challenge (24), yet provides an opportunity for sports scientists to impart more advanced signal processing techniques on these extracted features and facilitate more in-depth analyses of the physical demands of numerous sports and communicate this critical information effectively to sports practitioners and coaches. The ability to automatically detect COD movements and accurately and reliably calculate COD angle is something, to our knowledge, is yet to be quantified in a sporting environment and offers sports scientists, strength and conditioning practitioners, and athletes, an additional, non-linear, sports-specific variable that may provide a new perspective to both acute and chronic load monitoring practice.

ACKNOWLEDGEMENTS

The authors wish to thank the participants' for their time as well as the Fremantle Dockers Football Club for use of their microtechnology devices. The authors' declare no conflicts of interest.

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FIGURE LEGENDS

Figure 1. Aerial view and schematic representation of the pre-marked COD grid displaying all COD angles that participants were required to run.

Figure 2. A sample of the high-speed video footage recorded by the remotely piloted aircraft showing the requirements of each participant to run directly on a clearly marked straight line before changing direction (90° to the left in this example) at a marked center-point, then continuing on another straight line in accordance with the intended direction and angle.

Figure 3.

(a) Catapult Optimeye S5 microtechnology unit (52mm x 96mm x 12mm); housing a 10Hz Global Navigation Satellite System antenna, along with a tri-axial accelerometer, gyroscope and magnetometer, all sampling at 100Hz; (b) Commercially manufactured, trunk-mounted, fitted vest displaying the placement of the microtechnology unit.

Figure 4. A visual representation of the tri-axial nature of the inertial sensors housed within a trunk-mounted wearable microtechnology unit for human locomotion (yaw, pitch, and roll).

Figure 5. A sample of a single COD (90° to the left) analyzed using high-speed video to determine the precise angle that the participant changed direction; in relation to the intended marked path.

Figure 6. Bland-Altman plots showing the systematic bias in algorithm defined change of direction angle (thick black line), 95% confidence interval of the bias (thin black line), the 95% limits of agreement (dashed black line) and the line of equality (dotted black line). In

each plot, the difference between algorithm defined and high-speed video COD angle for each trial is plotted against the mean of the measurements.

Figure 7. Mean Bias ± SD of each COD angle independent of direction. *denotes a significantly greater mean bias when compared with all other COD angles.

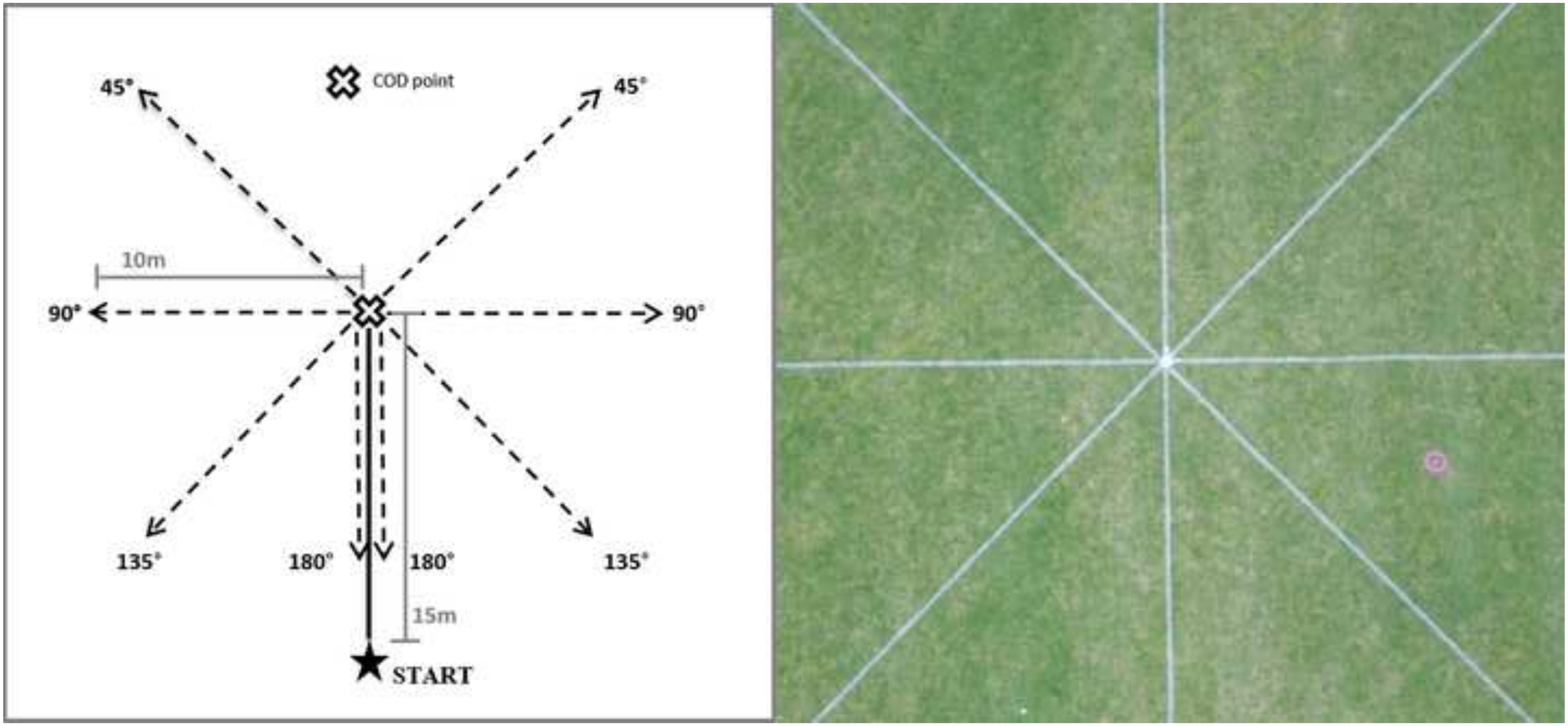
COD point
45°
45°
10m
90°
90°
135°
180°
180°
135°
15m
START

Figure 2

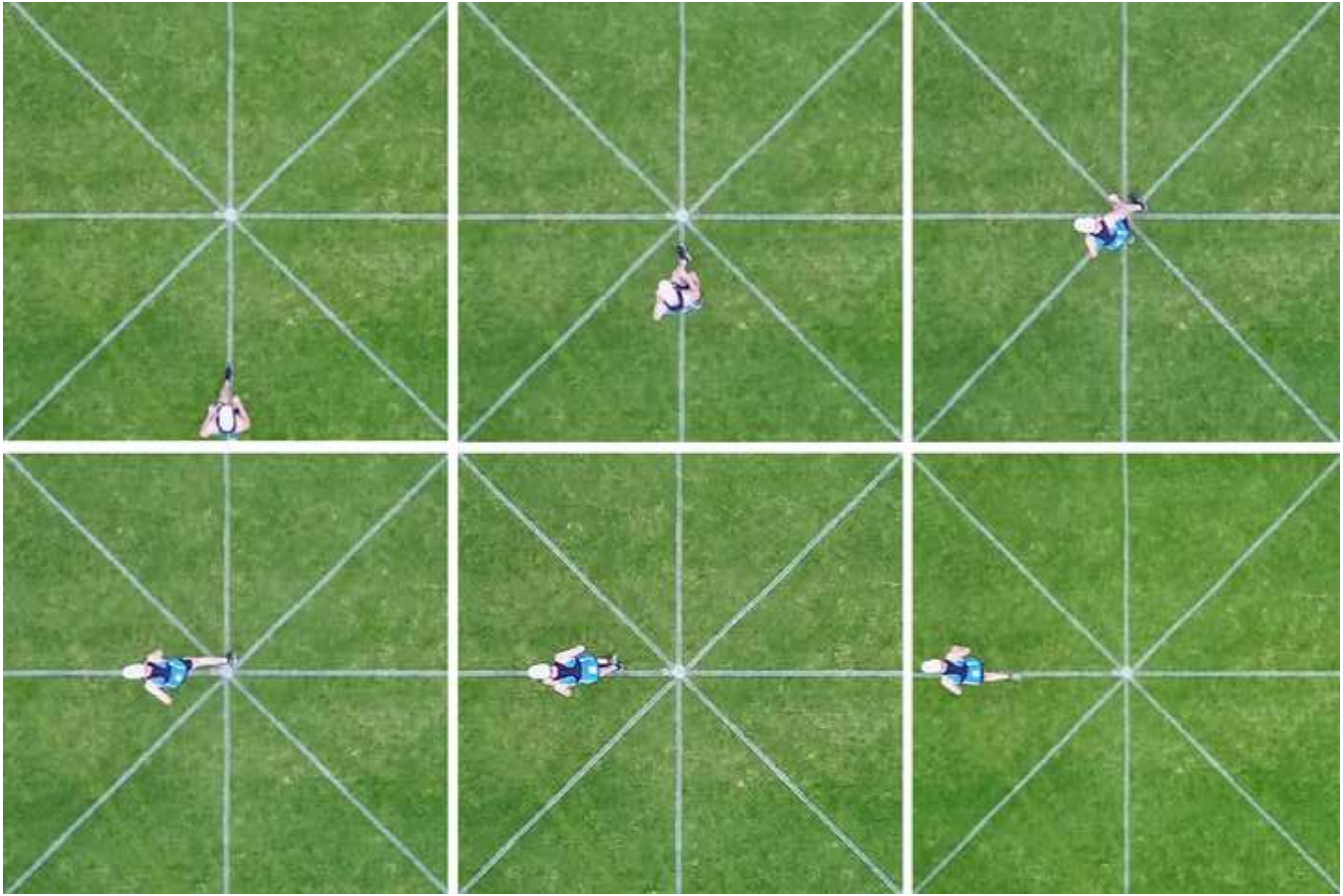

Figure 3

(A) (B)

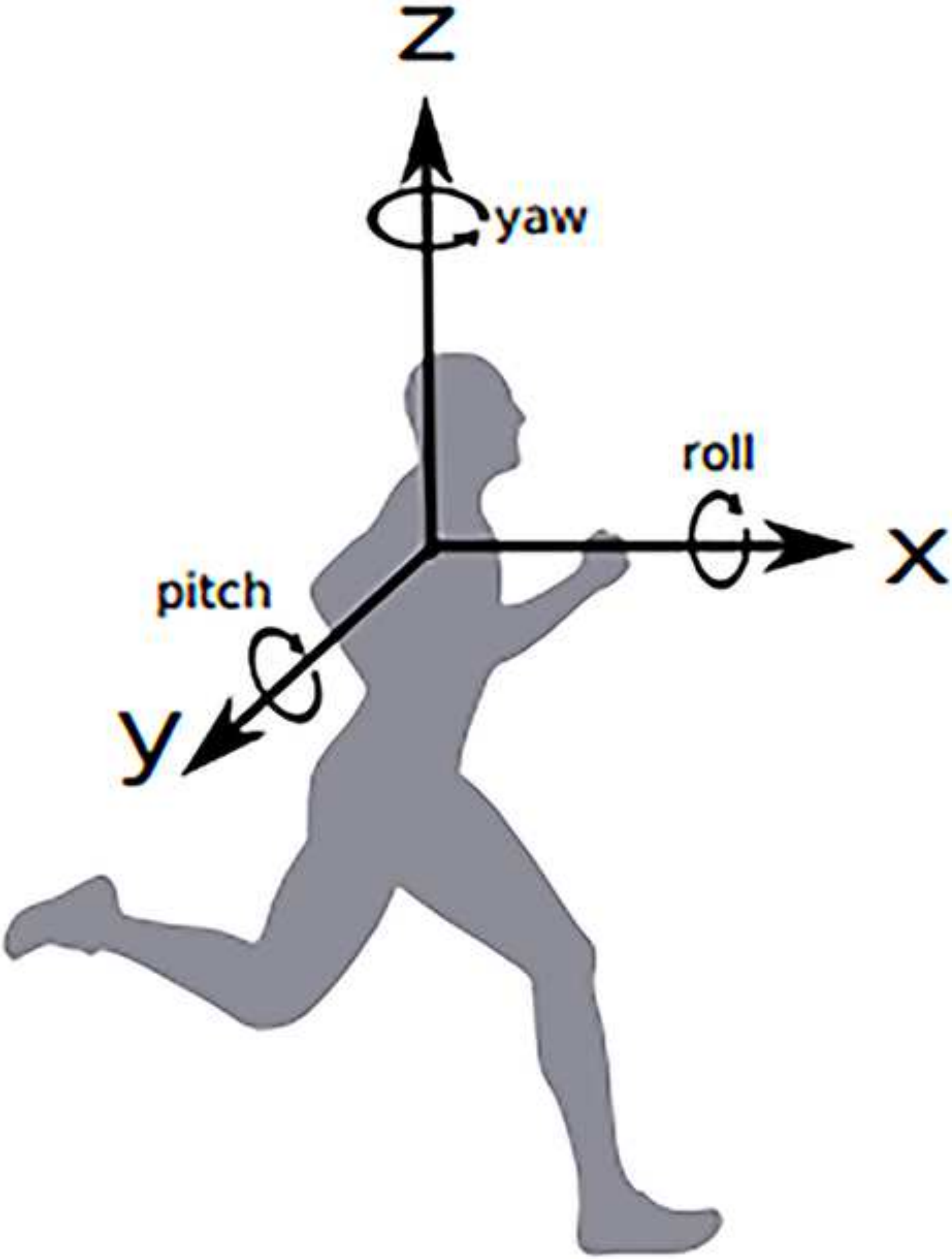
Z
yaw
roll
X
pitch
y

Figure 5

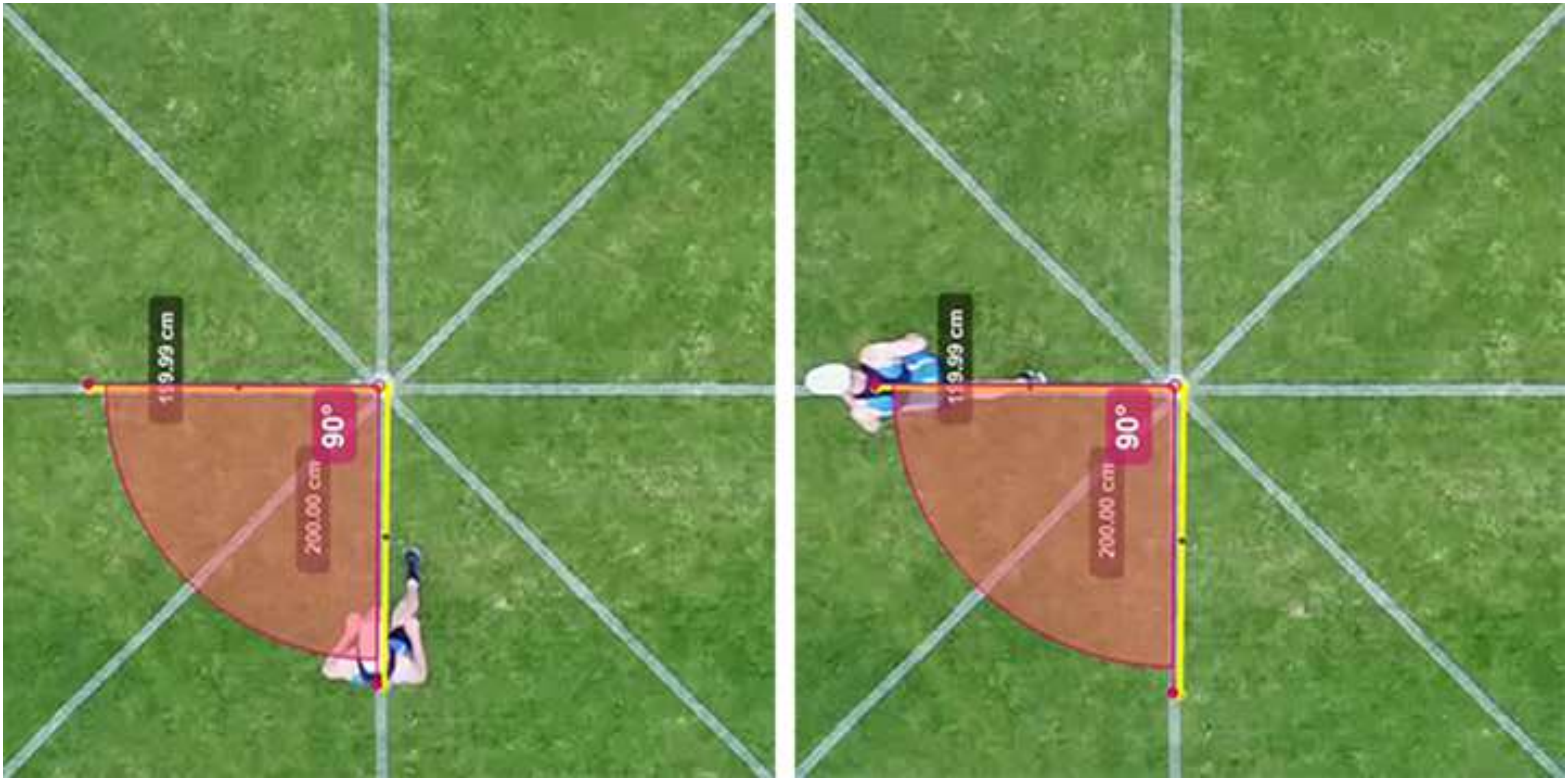

Figure 6

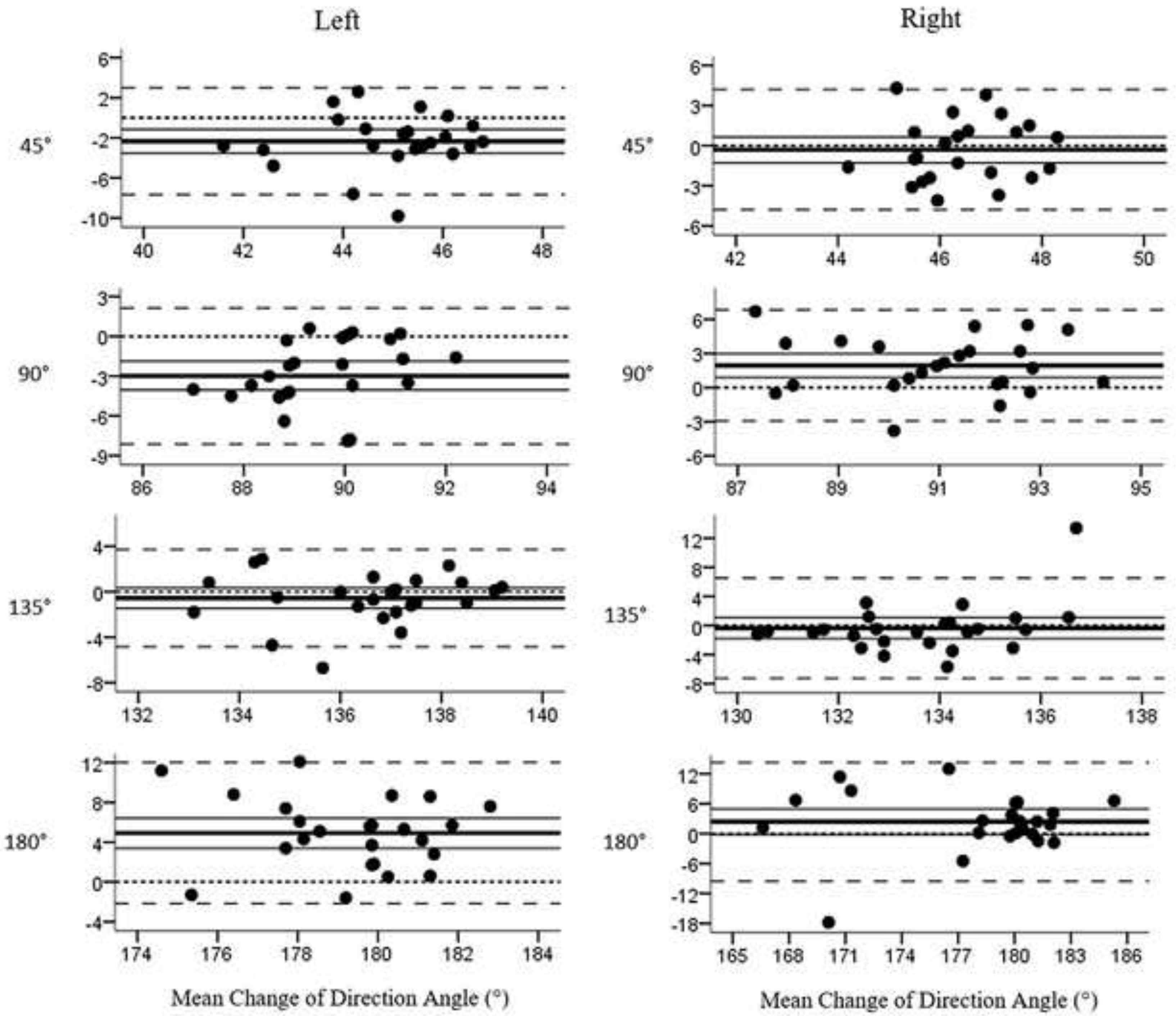
Left
Right
45°
90°
135°
180°
6
2
-2
-6
-10
40
42
44
46
48
3
0
-3
-6
42
44
46
48
50
3
0
-3
-6
-9
86
88
90
92
94
6
3
0
-3
-6
87
89
91
93
95
4
0
-4
-8
132
134
136
138
140
12
8
4
0
-4
-8
130
132
134
136
138
12
8
4
0
-4
174
176
178
180
182
184
12
6
0
-6
-12
-18
165
168
171
174
177
180
183
186
Mean Change of Direction Angle (°)
Mean Change of Direction Angle (°)

Figure 7

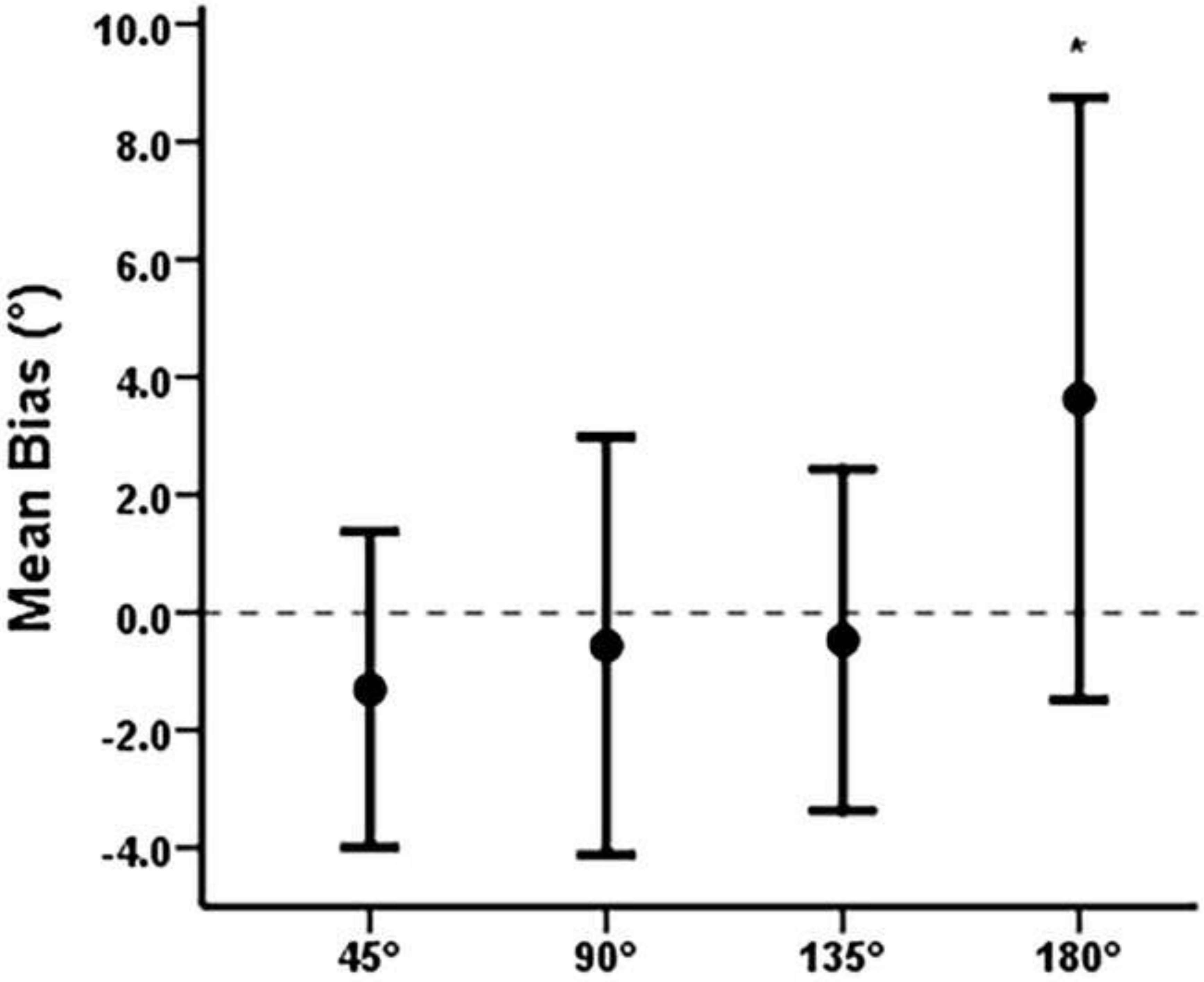

Table 1

Table 1. Accuracy, validity, precision and reliability of the proposed COD algorithm in comparison to a high-speed video criterion measure for COD angle accuracy (n = 194).

COD Angle		High-Speed Video (Mean ± SD)	Algorithm (Mean ± SD)	Mean Bias ± SD	% diff	Effect Size (Cohen’s *d*)	95% LoA (°)	RMSEP (°)	TE ± 90% CI (°)	CV (%)	Pre COD Avg Vel (ms^{-1})	Post COD Avg Vel (ms^{-1})	Total COD Avg Vel (ms^{-1})
Left	45	46.1 ± 1.9°	43.8 ± 2.0°	-2.3 ± 2.7° *	-5.1%	-0.81	-7.67, 3.01	3.55	1.9 (1.5 – 2.6)	4.2	3.81 ± 0.16	3.81 ± 0.11	3.79 ± 0.11
	90	91.1 ± 1.6°	88.1 ± 2.0°	-3.0 ± 2.6° *	-3.3%	-1.13	-8.12, 2.16	3.93	1.6 (1.3 – 2.1)	1.7	3.68 ± 0.22	3.62 ± 0.16	3.52 ± 0.16
	135	136.8 ± 1.9°	136.3 ± 2.1°	-0.6 ± 2.2°	-0.4%	-0.26	-4.83, 3.71	2.21	1.8 (1.4 – 2.4)	1.3	3.67 ± 0.21	3.55 ± 0.15	3.44 ± 0.11
	180	176.9 ± 2.9°	181.8 ± 2.5°	4.9 ± 3.7° *	2.8%	1.36	-2.16, 12.00	6.05	3.0 (2.4 – 4.0)	1.7	3.90 ± 0.18	3.78 ± 0.32	3.62 ± 0.20
Right	45	46.6 ± 1.5°	46.3 ± 1.6°	-0.3 ± 2.3°	-0.7%	-0.14	-4.80, 4.18	2.27	1.5 (1.2 -2.0)	3.3	4.00 ± 0.24	3.96 ± 0.21	3.95 ± 0.19
	90	90.0 ± 2.3°	91.9 ± 2.2°	1.9 ± 2.5° *	2.2%	0.76	-2.95, 6.85	3.12	2.2 (1.8 – 2.9)	2.5	3.52 ± 0.19	3.49 ± 0.13	3.39 ± 0.13
	135	133.8 ± 2.0°	133.4 ± 2.0°	-0.4 ± 3.5°	-0.3%	-0.10	-7.27, 6.53	3.47	2.0 (1.6 – 2.7)	1.5	3.81 ± 0.20	3.71 ± 0.15	3.56 ± 0.14
	180	176.8 ± 5.7°	179.2 ± 5.9°	2.4 ± 6.1°	1.4%	0.39	-9.51, 14.29	6.40	5.2 (4.2 – 6.9)	3.0	3.94 ± 0.24	3.68 ± 0.23	3.58 ± 0.18

*denotes a significant level of bias ($p < 0.05$) between criterion and algorithm derived COD angles; COD – change of direction; SD – standard deviation; % diff – percentage difference between algorithm and criterion derived COD angle; 95% LoA – 95% limits of agreement; RMSEP – root mean square error of prediction; TE ± 90% CI – typical error ± 90% confidence intervals; CV – coefficient of variation; Pre COD Avg Vel – Pre change of direction average velocity; Post COD Avg Vel – Post change of direction average velocity; Total COD Avg Vel – Total change of direction average velocity