

UNIVERSITY OF CALGARY

Change of Direction Movement Evaluation in Soccer-Specific Environment with Inertial  
Measurement Units: Guiding Practice and Test Tasks in Youth Soccer

by

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A THESIS

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## Abstract

Soccer players perform a multitude of change of direction (COD) movements while playing. This multiplanar movement has been related to both performance and injury-risk in previous studies. However, traditional testing of COD ability has been done with preplanned protocols that lack the aspect of perception and reaction and commonly use only running time as the main variable. Therefore, the main objectives of this thesis were to explore novel methods of COD testing with the use of inertial measurement units (IMUs) in both preplanned soccer-specific tests and during game-play.

The results of Chapter Three suggest that neither peak resultant acceleration (PRA) nor peak angular velocity (PAV) is a reliable metric in final foot contact (FFC) analysis of 180° pivot turns. The intra-class correlations (ICC) for pivot turns on both sides were unacceptable. However, when separating females and males it was found that the reliability in female participants was significantly better. In Chapter Four, the in-season variability of PRA was found to be different between previously injured players and injury free players, specifically during the FFC of 180° pivot turns.

Chapter Five expanded upon the game-specific demands on COD movements based on playing positions. Significant differences in volume and types of CODs by playing position were found, which raises the question if youth soccer player testing for multiplanar movement abilities, should consider specific playing position related demands better in the future.

Chapter Six complemented the studies by providing results of measurements obtained with IMUs in relation to situational patterns during game-play. The findings indicated that running speed, COD angle, pressure from opposing player, and contact with another player prior or during

the cut would increase the acceleration during the COD, thus increasing the demands of the neuromuscular system.

In conclusion, following one or two specific metrics at single timepoints to analyze COD ability is not recommended. Future research should search for methods involving perception-reaction while performing COD and these could be complemented with wearable technology measures. The combinations of multiple variables could be used to follow-up fluctuations of player performance through a longer follow-up period.

## Preface

Each of the following five chapters are based on scientific manuscripts:

### **Chapter 2: Literature review.**

Alanen, AM., Raisanen, AM., Benson, LC. and Pasanen, K. The Use of Inertial Measurement Units for Analyzing Change of Direction Movement in Sports: A Scoping Review. *International Journal of Sport Sciences & Coaching*, 16(6), 1332-53. 2021. <https://doi.org/10.1177/17479541211003064>

### **Chapter 3: Reliability of IMU derived measurements.**

Alanen, AM., Barrons, Z., Benson, LC., Jordan, MJ., Ferber, R and Pasanen, K. Between-day Reliability of Inertial Measurement Unit Parameters During Soccer Specific Change of Direction Test. *International Journal of Sport Science and Coaching*, 2023. Manuscript ID: SPO-23-0199

### **Chapter 4: Within-season variability of IMU derived measurements.**

Alanen, AM., Bruce, O., Benson, LC., Chin, M., van den Berg, C., Jordan, MJ., Ferber, R. and Pasanen, K. Capturing Changes in Change of Direction Movement Pattern accelerations in Injured and non-injured Youth Soccer Players with Inertial Measurement Units. *Biomechanics*, 3, 155-156. 2023. <https://doi.org/10.3390/biomechanics3010014>

### **Chapter 5: Playing position analysis of Change of Direction Movements in a game.**

Alanen, AM., Gibson, E., Critchley, M., Benson, LC., Jordan, MJ., Ferber, R. and Pasanen, K. Differences in Situational Patterns of over 90° Change of Direction Movements in Youth Male and Female Soccer Players. *Journal of Human Kinetics*, 2023. Manuscript ID: JHK-00092-2023-01

## **Chapter 6: Game-analysis of Change of Directions with IMUs.**

Alanen, AM., Benson, LC., Jordan, MJ., Ferber, R and Pasanen, K. Situational differences in Change of Direction movement accelerations in youth female soccer players: Game-analysis based on Inertial measurement units. *Biomechanics*, 3(2), 250-257, 2023.  
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## **Dedication**

*To my wife, Minna; thank you for the love of adventure that allowed us to start this journey and constant support through these four years.*

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# Table of Contents

<b>Abstract.....</b>	<b>i</b>
<b>Preface.....</b>	<b>iii</b>
<b>Acknowledgements .....</b>	<b>v</b>
<b>Dedication .....</b>	<b>vi</b>
<b>List of Tables .....</b>	<b>x</b>
<b>List of Figures.....</b>	<b>x</b>
<b>List of Abbreviations, Nomenclatures and Definitions .....</b>	<b>xii</b>
<b>Epigraph .....</b>	<b>xvi</b>
<b>Chapter One: Introduction .....</b>	<b>1</b>
<b>1.1 Research questions .....</b>	<b>7</b>
<b>1.2 Thesis outline .....</b>	<b>8</b>
<b>Chapter Two: The Use of Inertial Measurement Units for Analyzing Change of Direction Movement in Sports: A Scoping Review.....</b>	<b>10</b>
<b>2.1 Abstract .....</b>	<b>11</b>
<b>2.2 Introduction .....</b>	<b>12</b>
<b>2.3 Methods .....</b>	<b>15</b>
2.3.1 Literature search and study selection.....	15
2.3.2 Eligibility criteria.....	16
2.3.3 Data extraction.....	16
<b>2.4 Methods .....</b>	<b>17</b>
2.4.1 Study selection.....	17
2.4.2 Study characteristics.....	26
<b>2.5 Discussion .....</b>	<b>42</b>
2.5.1 Concurrent validity .....	42
2.5.2 Construct validity .....	44
2.5.3 Reliability .....	44
2.5.4 Change of direction analysis settings .....	45
2.5.5 Participant characteristics.....	46
2.5.6 Device, sensor type and set-up .....	47
2.5.7 IMU metrics.....	48
<b>2.6 Conclusions and future research directions.....</b>	<b>49</b>
<b>2.7 Bridge to the next chapters.....</b>	<b>54</b>
<b>Chapter Three: Between-day Reliability of Inertial Measurement Unit Parameters During Soccer Specific Change of Direction Test .....</b>	<b>55</b>
<b>3.1 Abstract .....</b>	<b>56</b>
<b>3.2 Introduction .....</b>	<b>57</b>
<b>3.3 Materials and Methods .....</b>	<b>60</b>
3.3.1 Participants .....	60

3.3.2 Testing protocol.....	61
3.3.3 Data collection.....	62
3.3.4 Statistical analysis .....	63
<b>3.4 Results.....</b>	<b>64</b>
<b>3.5 Discussion .....</b>	<b>67</b>
<b>3.6 Conclusion.....</b>	<b>69</b>
<b>3.7 Bridge to Chapter Four .....</b>	<b>70</b>
<b>Chapter Four: Capturing In-season Change of Direction Movement Pattern Change in Youth Soccer Players with Inertial Measurement Units.....</b>	<b>71</b>
<b>4.1 Abstract .....</b>	<b>72</b>
<b>4.2 Introduction .....</b>	<b>73</b>
<b>4.3 Materials and Methods .....</b>	<b>76</b>
4.3.1 Participants .....	76
4.3.2 Testing protocol.....	77
4.3.3 Accelerometer data.....	79
4.3.4 Injury data.....	79
4.3.5 Data processing .....	80
4.3.6 Statistical analysis .....	81
<b>4.4 Results.....</b>	<b>82</b>
<b>4.5 Discussion .....</b>	<b>85</b>
<b>4.6 Conclusions .....</b>	<b>88</b>
<b>4.7 Bridge to Chapter Five.....</b>	<b>90</b>
<b>Chapter Five: Differences in Situational Patterns During Change of Direction Movements Greater than 90° in Youth Male and Female Soccer Players. ....</b>	<b>91</b>
<b>5.1 Abstract .....</b>	<b>92</b>
<b>5.2 Introduction .....</b>	<b>93</b>
<b>5.3 Materials and Methods .....</b>	<b>95</b>
5.3.1 Study design and Participants.....	95
5.3.2 Procedures .....	95
5.3.3 COD Identification .....	96
5.3.4 Statistical analysis .....	99
<b>5.4 Results.....</b>	<b>100</b>
5.4.1 Principal component analysis.....	101
<b>5.5 Discussion .....</b>	<b>104</b>
5.5.1 Limitations.....	106
<b>5.6 Conclusions .....</b>	<b>107</b>
<b>5.7 Bridge to Chapter Six.....</b>	<b>109</b>
<b>Chapter Six: The Effects of Situational Patterns on Accelerations During Change of Direction Movements: Game-Analysis of Youth Female Soccer.....</b>	<b>110</b>
<b>6.1 Abstract .....</b>	<b>111</b>
<b>6.2 Introduction .....</b>	<b>112</b>

<b>6.3 Methods</b> .....	<b>115</b>
6.3.1 Participants and design .....	115
6.3.2 Data collection .....	115
6.3.3 Statistical analysis .....	117
<b>6.4 Results</b> .....	<b>117</b>
<b>6.5 Discussion</b> .....	<b>119</b>
<b>6.7 Conclusions</b> .....	<b>121</b>
<b>Chapter Seven: Overall Discussion</b> .....	<b>123</b>
<b>7.1 Summary</b> .....	<b>123</b>
<b>7.2 Limitations and future directions</b> .....	<b>128</b>
7.2.1 Sample size .....	128
7.2.2 Generalizability .....	130
7.2.3 IMU variables and sensor placement.....	130
7.2.4 Signal processing of IMU data .....	132
<b>7.3 Conclusion</b> .....	<b>133</b>
<b>References</b> .....	<b>134</b>

## List of Tables

<b>Table 2.1</b> Characteristics of the studies evaluating the validity of IMU when measuring COD movements.	20
<b>Table 2.2</b> Characteristics of the studies evaluating the reliability of IMU when measuring COD movements.	23
<b>Table 2.3</b> Characteristics of studies using IMU to evaluate COD movement.	31
<b>Table 3.1</b> Baseline characteristics.	54
<b>Table 3.2.</b> Reliability statistics for PRA, PAV, Time to turn and total time (left/right).	58
<b>Table 3.3.</b> Differences between males and females on between-day ICC values. Z-score significance level set at $> 1.96$ .	59
<b>Table 4.1.</b> Baseline characteristics.	70
<b>Table 4.2.</b> Response feature analysis (mean changes) for peak resultant acceleration in all CODs.	75
<b>Table 4.3.</b> Comparison of injured and non-injured leg peak resultant acceleration ( $m/s^2$ ) differences in the previously injured group.	76
<b>Table 5.1.</b> Player characteristics.	92
<b>Table 5.2.</b> ANOVA for principal components 1-3.	95
<b>Table 5.3.</b> Tukey's multiple comparison of means for playing positions.	95
<b>Table 6.1.</b> Important features affecting $PA_v$ .	108
<b>Table 6.2.</b> Quantities of different CODs with corresponding $PA_v$ (mean).	114

## List of Figures

<b>Figure 2.1</b> Flowchart of study selection process, and reasons for exclusion of studies regarding the use of IMUs to analyze COD movement.	16
<b>Figure 3.1.</b> Map of the test, displaying left turning $180^\circ$ pivot turn.	56
<b>Figure 3.2.</b> Change of direction test: Player making a left turning $180^\circ$ pivot turn.	56
<b>Figure 3.3.</b> Bland-Altman plots for A) Peak Angular Velocity B) Peak Resultant Acceleration C) Total time and D) Time to turn, with limits of agreement (LoA).	59
<b>Figure 4.1.</b> Change of direction test: Player making a left turning $180^\circ$ pivot turn (PFC – left leg, FFC right leg).	72
<b>Figure 4.2.</b> Map of the test, displaying cuts on the right side.	73

<b>Figure 4.3.</b> Boxplots of differences in peak resultant acceleration (PRA) change between previously injured and non-injured groups for the final foot contact (FFC) in 180°- and 90°-degree left change of direction (COD) maneuvers.	76
<b>Figure 4.4.</b> Boxplots showing individual change of the peak resultant acceleration (PRA) (m/s <sup>2</sup> ) for the final foot contact (FFC) in 180° pivot turns and 90° cuts between Test 1 and Test 2.	77
<b>Figure 5.1.</b> Flowchart of COD and situational pattern identification.	90
<b>Figure 5.2.</b> Biplot of PCs 1 and 2 with playing positions and contributions of different variables.	94
<b>Figure 5.3.</b> Biplot of PCs 2 and 3 with playing positions and contributions of different variables.	95
<b>Figure 6.1.</b> Videorecording set-up.	109

### List of Appendixes

<b>Appendix 2.1</b> Search strategy for Medline.	47
<b>Appendix 2.2</b> Inclusion criteria.	47
<b>Appendix 2.3</b> Quality assessment of included studies.	48
<b>Appendix 4.1</b> R-packages.	82

## List of Abbreviations, Nomenclatures and Definitions

<u>Abbreviation</u>	<u>Nomenclature and Definition</u>
<b>ACL</b>	<b>Anterior Cruciate Ligament</b> ; a ligament connecting femur to the tibia. One of the key ligaments that stabilize the knee joint. Commonly injured in sports that include deceleration-acceleration and changes in direction.
<b>AvFnet</b>	Accelerometry Derived Net Force ; The net force acting on a body at any given instant, derived from acceleration measured with inertial measurement units.
<b>CB</b>	Center back
<b>CI</b>	Confidence Interval ; The mean of an estimate plus and minus the variation in that estimate.
<b>CM</b>	Center midfielder
<b>CMSA</b>	Calgary Minor Soccer Association
<b>COD</b>	Change of Direction ; preplanned and reactive whole-body changes of velocity requiring high magnitudes of vertical, mediolateral, and anteroposterior impulses to move quickly and efficiently.
<b>CODS</b>	Change of Direction Speed ; a change of direction while running, wherein no reaction to a stimulus is required.
<b>COM</b>	Center of Mass ; The best representation of human body is usually its center of mass, which is located slightly below belly button, which is nearly the geometric center of a person.
<b>CV</b>	Coefficient of Variation ; The ratio of the standard deviation to the mean.
<b>F</b>	Force ; Influence that causes the motion of an object with mass to change its velocity i.e., to accelerate.

<b>FB</b>	Fullback
<b>FFC</b>	Final Foot Contact ; Final foot ground contact is defined as the step initiating the change of direction movement.
<b>GK</b>	Goalkeeper
<b>GPS</b>	Global Positioning System ; Navigation system based on signals from satellites. In sports GPS is used to track the location of athletes and gather data such as running speed, distance and position of players.
<b>GRF</b>	Ground Reaction Force ; Force exerted by the ground on a body in contact with it.
<b>ICC</b>	Intra-class correlation ; A reliability index in test-retest, intrarater, and interrater reliability analyses.
<b>IMA</b>	Inertial Measurement Analysis ; Set of metrics that measure athlete micro-movement (low, medium or high-intensity) and direction regardless of measurement unit orientation.
<b>IMU</b>	Inertial Measurement Unit ; A device that typically consists of accelerometers (measure acceleration), gyroscopes (measure angular velocity) and magnetometer (measure magnetic field).
<b>KMO</b>	Kayser-Meyer-Olkin test ; A measure of how suited specific data is for factor analysis or principal component analysis.
<b>LASSO</b>	Least absolute shrinkage and selection operator ; Regression analysis method that performs both variable selection and regularization in order to enhance prediction accuracy and interpretation of the resulting statistical model.
<b>LoA</b>	Limits of Agreement ; Estimation of the interval within which a proportion of the differences between measurements lie.

<b>MA</b>	Motion Analysis ; Motion analysis systems calculate parameters such as distance, velocity, acceleration, and deformation angles as functions of time.
<b>PA<sub>v</sub></b>	Vertical peak acceleration (m/s <sup>2</sup> ) ; Peak acceleration of the vertical plane of the inertial measurement unit.
<b>PAV</b>	Peak angular velocity ; Peak of how fast a rigid body rotates with respect to its center of rotation.
<b>PCA</b>	Principal component analysis ; Technique for analyzing datasets containing high number of dimensions/features per observation, increasing the interpretability of data while preserving the maximum amount of information.
<b>PFC</b>	Penultimate Foot Contact ; The penultimate foot ground contact is defined as the last step before the step that initiates a change of direction movement.
<b>PHV</b>	Peak height velocity ; The period of time in which a child/youth experiences the fastest growth in their stature.
<b>PL</b>	PlayerLoad™ ; The sum of accelerations across all axes of the tri-axial accelerometer during movement.
<b>PRA</b>	Peak resultant acceleration ; Peak acceleration of all three dimensions (axial, antero-posterior, and medio-lateral) combined at the same point of time.
<b>RA</b>	Research assistant ; Professional supporting research projects.
<b>RAG</b>	Reactive agility ; Efficiency in changing a position in reaction to a stimulus.
<b>RTP</b>	Return to Play ; Returning injured athlete back to competition – athlete is able to compete in competitive level.
<b>RTS</b>	Return to Sport

; Continuum paralleled with recovery and rehabilitation – athlete is fully participating in their sport, but not at their desired performance level.

**S**

Striker

**SI**

Symmetry Index

; Interlimb symmetry during a 4-m sidestep test.

**TADS**

Transitional Angular Displacement of Segment

; A measure of dynamic joint stability, where knee range of motion over time during COD is calculated while performing 4-m sidestep test.

**TE**

Typical Error

; The pure measure of variation within each subject.

**TotalT**

Total time

; The amount of time it takes to return to starting point in this specific test.

**TT**

Time to turn.

; The amount of time it takes to reach turn in this specific test.

**W**

Winger

## Epigraph

*“Football is the most important of the least important things in life.”*

- Arrigo Sacchi

## **Chapter One: Introduction**

Soccer is by far the most popular sport in the world with 250 million players in over 200 countries. According to Canada Soccer, there are nearly one million registered players in the country and soccer is considered the fastest growing sport in the country that will be one of the hosts of the 2026 World Cup. The identification and development of talented young players is a common goal for youth soccer clubs and academies around the world and a major interest of sport science research. Sport scientists working together with coaches have a major role in identifying and addressing the key elements of continuous player development process. Youth players consider sport science to have a positive effect on their overall development as soccer players (Cooper, 2021). However, there has been a call for more soccer-specific testing including a multi-dimensional approach for performance evaluations (Forsman et al., 2016; Williams & Reilly, 2000), in order to support and understand the factors behind continuous player development better.

Soccer is an invasion-sport (athletes aim to invade opponents territory to score points/goals) requiring not only speed, balance, agility and power but also ability to percept and react to movement of the ball and other players (Bloomfield, Polman, & Donoghue, 2007; T. Reilly et al., 2000). The demands of game speed have been steadily increasing in professional soccer (Barnes et al., 2014; Bush et al., 2015), and for example the results of study by Barnes et al. (Barnes et al., 2014) concluded that the number of sprints, sprint distance and number of high-intensity actions increased 35-50% from 2006 to 2013 in the English Premier League. Fast changes of running direction accompanied by short acceleration-decelerations while anticipating and making decisions account for about 90% of these actions (Andrzejewski et al., 2013). The ability to change running direction quickly has been reported to be one of the most important physical factors in discriminating between top-level soccer players and in addition predicting success in field sports

in general (Gil et al., 2007; Pereira et al., 2018; Santoro et al., 2021). In sport science literature the ability to change running direction has been referred to as agility (Sheppard & Young, 2006). This applies also to change of direction (COD) testing, which commonly include only physical components of agility (COD speed), disregarding the cognitive component (visual-scanning and anticipation) (Nimphius et al., 2018; Sheppard & Young, 2006; W. B. Young et al., 2015). Previous studies have shown that change of direction speed (CODS) and agility represent individual skills and testing or monitoring methods that are able to combine physical and cognitive measures are needed (Paul et al., 2016; Sheppard & Young, 2006; W. B. Young et al., 2015).

Although there are several positive effects of playing sports, injuries may have negative effect on player development. In youth soccer, acute injuries account for approximately 46% of all injuries, injury risk is higher for games than practices and injury incidence increases with age (Emery et al., 2005; Junge, 2004; Le Gall et al., 2006; Pfirrmann et al., 2016). Majority of injuries affect lower extremities and the most commonly affected injury site is the ankle. Knee injuries are also common and potentially most severe injury, anterior cruciate ligament trauma, is more common in female players (2-8 times greater incidence rate when compared with males) (De Ste Croix et al., 2015; Le Gall et al., 2008). COD movement has been associated with ankle, knee, and groin injuries in youth soccer. Video-analyses have shown that non-contact ACL injuries typically occur during rapid CODs in both males and females (Della Villa et al., 2020; Kristianslund et al., 2014; Light et al., 2021; Lucarno et al., 2021; Serner et al., 2015). A majority of injuries in soccer occur in non-contact situations (Emery et al., 2005; Hawkins & Fuller, 1999) and according to injury risk factor studies, deficits in neuromuscular control (e.g., limb-asymmetry and increased knee-valgus), and muscle strength can increase injury risk (Mandorino et al., 2023). For these reasons, development of specific testing methods to monitor players' COD movement patterns

regularly is warranted. In addition, consensus statement on return to sport (RTS) by Ardern et al. (Ardern et al., 2016) expressed concern on RTS decisions being taken in isolation at the end of rehabilitation, rather than using criteria based on tests including reactive elements and decision-making that players use in game-like situations (e.g., CODs).

A constraint-led approach defines constraints as boundaries for motor learning and a stable state of movement. A player searching for an effective movement pattern to a specific goal-directed activity like COD movement, is affected by three categories of constraints: performer, environment and task (Davids, 2008; Pol et al., 2019; Renshaw et al., 2010). These constraints interact together in a non-linear way and may change performance and increase the susceptibility for injuries and are not necessarily accounted for in simple testing patterns. In addition, there are important differences between playing positions that are related to performance (player actions) and purpose (e.g., restrict opposition, score goals) in soccer which include highly complex and dynamic components, that should be taken into account in talent identification and player development (Berber et al., 2020).

A majority of COD tests use time to complete a specified running drill to evaluate players' performance and there are differences between testing protocols in regards to which subcomponents of COD ability are actually measured (Kozinc & Šarabon, 2021; Nimphius et al., 2018). Most commonly used test protocols include T-test, arrowhead test, 5-0-5 and Illinois agility test (Altmann et al., 2019; Nimphius et al., 2018). The reliability of these testing protocols has been good, although when used for younger age groups the results should be interpreted with caution because the variability in the results can be larger (Dugdale et al., 2020; Sporis et al., 2010). In addition, recent research has encouraged practitioners to introduce more tailored training practices in order to support youth players in developing effective COD abilities (Loturco et al.,

2019) and to include a cognitive stimulus (action of another player) to COD testing for larger improvements in performance (Paul et al., 2016). The major concern on traditional COD tests has been that when using time to completion as outcome variable, actual COD ability might not be discriminated from speed as linear speed has a major effect on how fast a player finishes the drill (Nimphius et al., 2016).

Effective COD requires the transfer of momentum to new direction, head leading the movement, small rotational inertia (arms and legs close to axis of rotation), full-extension of the take-off leg (hip, knee, ankle) and ground contact towards the new direction (Hewit et al., 2012). Research has also shown that biomechanical demands of COD are angle and velocity dependant and the technique parameters associated with total time to complete a COD task are not thoroughly examined (Dos'Santos et al., 2018; Jones et al., 2016). From biomechanical point of view, in relation to performance and injury risk, there are two important phases of COD – penultimate (and antepenultimate) foot contact (PFC) and final foot contact (FFC). The definition of PFC is “the last step before the step that initiates COD or inside leg during the turn” whereas FFC is defined as “the step initiating the COD or outside leg during the turn” (Green et al., 2011; Havens & Sigward, 2015b; Spiteri et al., 2013). From performance point of view, greater braking forces in shorter contact times during PFC and greater joint angles during braking are related to faster 5-0-5 performance and greater peak horizontal ground reaction forces (GRF) during PFC reduce knee joint loading during FFC (Dos'Santos, Thomas, Comfort, et al., 2019a; Dos'Santos et al., 2021a; Jones et al., 2016; Thomas et al., 2020). Stronger female soccer players are able to reduce velocity during PFC better and have greater approach velocities while executing CODs. Additionally, eccentric strength in general seems to be a predictor of faster COD performance (Jones et al., 2017; Spiteri et al., 2014). Faster 180° pivot turns have been connected with greater horizontal forces

and ground reaction times during FFC and running speed and eccentric knee flexor strength are important for fast CODs (Dos'Santos, Thomas, Jones, et al., 2019; Jones et al., 2009). When comparing different COD angles, the knee kinematic demands have been shown to be different and limb dominance evaluation during COD shows inconsistent results for risky movement patterns (Dos'Santos, Thomas, Jones, et al., 2019; Schreurs et al., 2017).

Inertial measurement units (IMU) are devices that consist of accelerometers, gyroscopes, and magnetometer. With IMUs it is possible to measure angular rate, acceleration, and magnetic field (in order to determine orientation). In sports, IMUs have been used to detect sport-specific movements (e.g., jumping, landing, sprinting), sport-specific demands (e.g., Player Load (PL)) and to collect continuous acceleration and/or angular velocity data during practices and games (Chambers et al., 2015; MacDonald et al., 2017; Skazalski et al., 2018). The accuracy of IMUs to detect sport-specific movements such as sprinting, CODs or jumping, has been good and there are studies looking at the ability to detect and analyze COD movement as well (Balloch et al., 2020; Meghji et al., 2019; Nedergaard et al., 2014; Wundersitz, Gastin, et al., 2015). Multi-dimensional approach (considering individual skill also as a part of the game) for player development and including reactive elements (decision making) to movement monitoring, requires data collection methods that capture variables of the movement on specific timepoint that are relevant for the execution or on continuous basis throughout the time of play. IMUs have potential in measuring COD movement patterns during movements in games/practices and could provide more specific information about performance enhancement or injury risk. IMUs could be utilized to provide information about the quality of not only whole-body movements, but also individual segments (e.g., specific joints) during a COD movement (Chambers et al., 2015). In previous studies, this potential has been proven when analyzing walking, running and postural control (L. C. Benson et

al., 2018; Johnston et al., 2019). In addition, IMUs provide more feasible and inexpensive way to monitor athletes' COD movements throughout the season, when compared to gold-standard methods of motion capture or force plates (Chambers et al., 2015; Seshadri et al., 2019). Global Positioning Systems (GPS) are commonly used for team sport player movement tracking, but IMUs could provide an alternative and more precise method to monitor players during consecutive training sessions and games in order to provide supporting information for player development (Camomilla et al., 2018; Chambers et al., 2015). The potential of IMUs to provide information for injury prevention and player development purposes exists, but there are still gaps between laboratory based measures and real-life situations that need to be investigated further (Gurchiek, Choquette, et al., 2019; Marques et al., 2020; McGinnis et al., 2015; McGinnis, Patel, Silva, Mahadevan, DiCristofaro, et al., 2016).

More research is needed on the reliability of testing methods including the use of IMUs and recommendations for COD testing methods including not only the speed element, but also the cognitive challenge. Understanding more specifically the different phases of COD movement and specific demands of different COD angles is valuable for recognizing possible weaknesses that might hinder performance or increase injury risk. In addition, understanding the requirements in relation to CODs for individual playing positions and the effect of situational patterns during the game can provide more individualized player analysis. Therefore, the main objectives of this thesis were to investigate the reliability of IMU based measures during COD movements during soccer-specific on-field testing, compare the within-season change in injured and non-injured player groups and provide playing position and situation specific information related to COD requirements during games.

## **1.1 Research questions**

### *Study 1: Research questions*

- (i) Are peak resultant acceleration and angular velocity recorded with IMUs reliable measures for 180° pivot turn final foot contact in youth soccer players?
- (ii) Do female and male players differ from each other regarding measurement reliability?

### *Study 2: Research questions*

- (i) Do previously injured and non-injured player groups differ when analyzing change in peak resultant accelerations for two time points within-season?
- (ii) Are there angle- (180°, 135°, 90°) or step- (PFC, FFC) specific differences between injured and non-injured players?

### *Study 3: Research questions*

- (i) How are traditionally tested COD movements related to various game situations during youth soccer games?
- (ii) Are situational differences in CODs related with playing positions during soccer games in youth players?

### *Study 4: Research questions*

- (i) What is the effect of situational patterns and playing positions to IMU measured accelerations during CODs in soccer games in youth players?
- (ii) Which positional and situational variables explain the differences in IMU measured accelerations during soccer games best in youth players?

## 1.2 Thesis outline

This is a manuscript-based thesis including seven chapters in total. Chapter two is a scoping review, which synthesises previously published studies on COD analysis in sports. Chapters from three to six are original research articles that have been already published in scientific papers or have been submitted for peer-review. Each of these chapters is a standalone journal article and require a bridge-chapter between the chapters, which have been added to this thesis and are not a part of the original articles. There is a possibility for repetition of information and some redundancy for the introductory parts, due to the fact that each chapter is a separate journal article. However, this thesis aims to provide a cohesive report of a specific research area. Aki-Matti Alanen is the first author of each manuscript and has done majority of the work regarding the data analysis and writing. All co-authors have given their permission to include these manuscripts to this dissertation.

**Chapter two:** The Use of Inertial Measurement Units for Analyzing Change of Direction Movement in Sports: A Scoping Review.

**Chapter three:** Between-day Reliability of Inertial Measurement Unit Parameters During Soccer Specific Change of Direction Test.

**Chapter four:** Capturing In-season Change of Direction Movement Pattern Change in Youth Soccer Players with Inertial Measurement Units.

**Chapter five:** Differences in Situational Patterns During Change of Direction Movements Greater than 90° in Youth Male and Female Soccer Players.

**Chapter six:** Situational Pattern Effects on Accelerations During Change of Direction Movements: Game-Analysis of Youth Female Soccer.

**Chapter seven:** Summary of the significant findings of this thesis, including discussion, limitations, and directions for future studies in this area.

## **Chapter Two: The Use of Inertial Measurement Units for Analyzing Change of Direction**

### **Movement in Sports: A Scoping Review**

Aki-Matti Alanen, Anu Raisanen, Lauren C. Benson & Kati Pasanen

Alanen AM, Raisanen AM, Benson LC & Pasanen K. (2021) The use of inertial measurement units for analyzing change of direction movement in sports: A scoping review. *International*

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## 2.1 Abstract

Change of direction (COD) 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 COD 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 (IMU) sensors to provide information on COD movement and to summarize the available evidence on inertial measurement units in analyzing COD 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. IMUs can be used to detect 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:** Accelerometer, wearable technology, motion capture, change of direction, cutting, side-step

## 2.2 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 (Brughelli et al., 2008; Hägglund & Waldén, 2016; Karcher & Buchheit, 2014). Agility has been identified as an important performance variable for differentiating elite and sub-elite players (Gil, S.M., Gil, J., Ruiz & Irazusta, A., Irazusta, 2007; T. Reilly et al., 2000), and one definition of agility is the ability to change the direction of movement quickly and precisely (Bloomfield, Polman, & O' Donoghue, 2007; Dawes et al., 2014; Jeffreys, 2011). 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 (Nimphius et al., 2018). 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 (Dos'Santos, Thomas, Comfort, et al., 2019b; Fuerst et al., 2017; Serner et al., 2015; Waldén et al., 2012, 2016). Previous studies have shown that correcting specific biomechanical patterns with appropriate training methods can reduce the number of ACL injuries (Donnell-Fink et al., 2015). 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 (Kristianslund & Krosshaug, 2013; Krosshaug et al., 2015; Nedergaard et al., 2020). 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 (Franklyn-Miller et al., 2017; King et al., 2018; Marques et al., 2019; Marshall et al., 2014; McFadden et al., 2020). However, motion capture systems are not easily transported to field settings (Condello et al., 2016; King et al., 2018; Suzuki et al., 2014). Global positioning systems (GPS) are a potential feasible on-field monitoring system, but there are limitations with GPS in recognizing high-speed direction changes (Cummins et al., 2013). Due to this limitation GPS does little more than identify the number or frequency of whole body COD events (L. Benson et al., 2020). In contrast, IMUs have the potential to provide information about the quality of whole-body and individual segment movements during COD (Chambers et al., 2015). IMUs are used to analyze several types of movement, such as walking, running and postural control (L. C. Benson et al., 2018; Johnston et al., 2019), 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 (Chambers et al., 2015; Seshadri et al., 2019). 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 (L. C. Benson et al., 2018; Borges et al., 2017; Chambers et al., 2015; MacDonald et al., 2017; Skazalski et al., 2018). Research on the ability of IMUs to detect and analyze COD movement exists (Ahmadi et al., 2015; Balloch et al., 2020; A. Fox et al., 2014; Meghji et al., 2019; Nedergaard et al., 2014), 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 (Ancillao et al., 2018) and the use of regression techniques for continuous biomechanical monitoring (Gurchiek, Cheney, et al., 2019). In addition, the review by Marques et al. (Marques et al., 2019) 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 (Camomilla et al., 2018; Chambers et al., 2015). In addition, IMUs may provide valuable information in guiding injury prevention and executing research on athlete performance and injury prevention (Gurchiek, Choquette, et al., 2019; McGinnis et al., 2015; McGinnis, Patel, Silva, Mahadevan, Dicristofaro, et al., 2016). 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.

## 2.3 Methods

### 2.3.1 Literature search and study selection

The literature search and study selection followed the PRISMA extension for Scoping Reviews (PRISMA-ScR) checklist (Downes et al., 2016). The protocol of this scoping review was registered in the Open Science Framework (OSF) platform (<https://osf.io/4xkjr/>). 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](http://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 September 17, 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).

### 2.3.2 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.

### 2.3.3 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

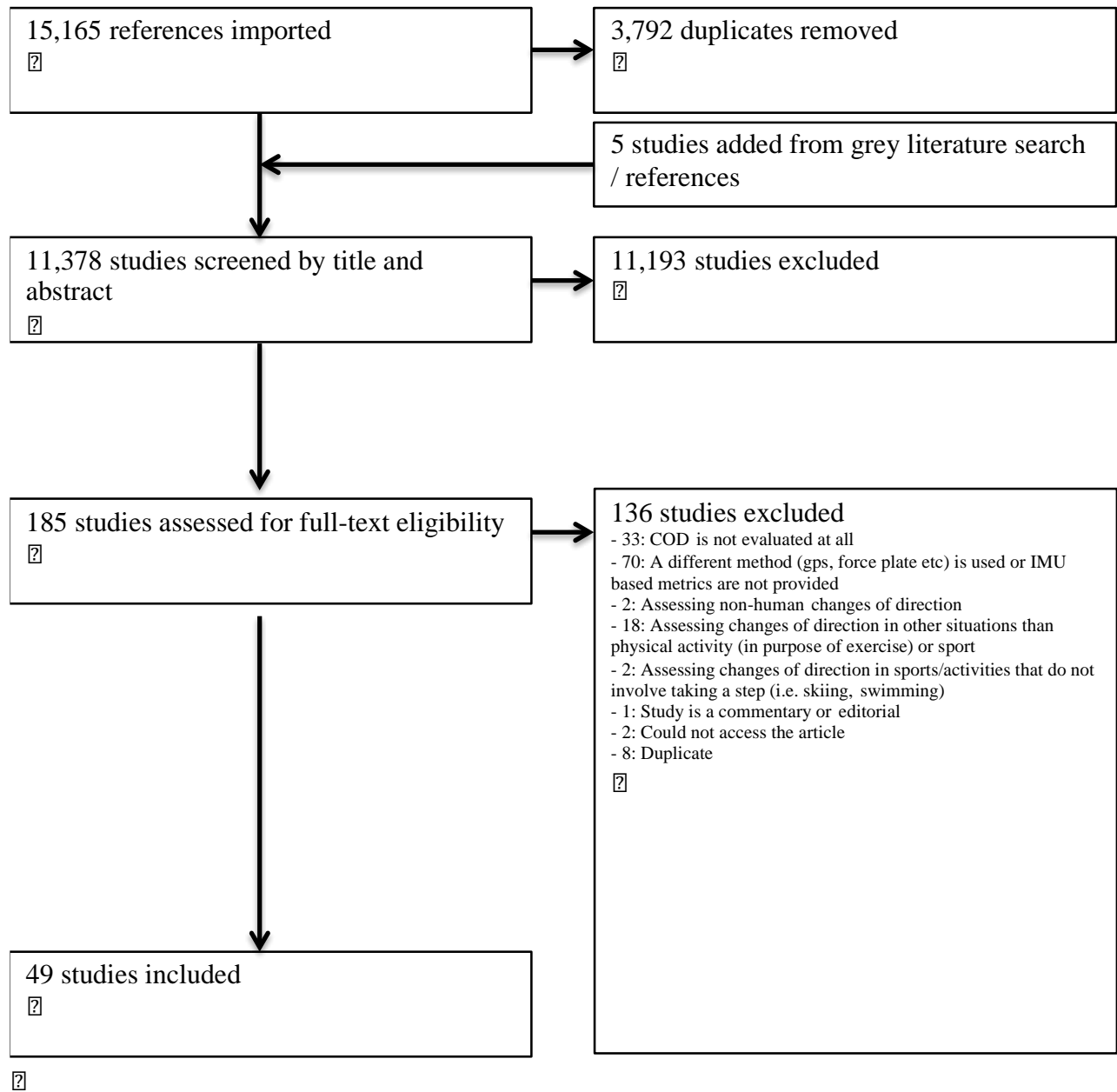
present review. The AXIS tool for evaluating the risk of bias of cross-sectional studies was used for quality assessment (Downes et al., 2016).

## **2.4 Methods**

### 2.4.1 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).

PRISMA flowchart illustrating the search and study selection process



**Figure 2.1.** Flowchart of study selection process, and reasons for exclusion of studies regarding the use of IMUs to analyze COD movement.

### *Validity and reliability of IMUs*

Eleven studies (Balloch et al., 2020; Barreira et al., 2017; Gurchiek et al., 2017; K. J. A. E. Kim et al., 2020; Meylan et al., 2017; Nedergaard et al., 2017; Netto et al., 2010; Roell et al., 2019; Staunton et al., 2017; Wundersitz et al., 2013; Wundersitz, Gastin, et al., 2015) 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 standard (Balloch et al., 2020; Gurchiek et al., 2017; Meylan et al., 2017; Nedergaard et al., 2017; Netto et al., 2010; Roell et al., 2019; Wundersitz et al., 2013; Wundersitz, Gastin, et al., 2015) and three focused on the construct validity of IMUs (Barreira et al., 2017; K. J. A. E. Kim et al., 2020; Staunton et al., 2017). The study conducted by Netto et al. (Netto et al., 2010) 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 (Netto et al., 2010; Roell et al., 2019; Wundersitz, Gastin, et al., 2015). 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) (Netto et al., 2010; Roell et al., 2019) or acceptable validity (Wundersitz, Gastin, et al., 2015). 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 milliseconds of stance phase) and impulse (calculated as the integral of the resultant acceleration over time) (Nedergaard et al., 2017), cranio-

caudal and resultant acceleration converted to force (Wundersitz et al., 2013) and IMU derived estimates of step-average component and resultant force (Gurchiek et al., 2017) to force plate measures of magnitude and direction of ground reaction force (GRF) and center of mass acceleration (Gurchiek et al., 2017; Nedergaard et al., 2017; Wundersitz et al., 2013). 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 (Gurchiek et al., 2017) and acceptable relative measures of peak foot-strike impact forces during 45° and 90° COD (Wundersitz et al., 2013), but IMU derived segmental accelerations overestimated the acceleration of center of mass (Nedergaard et al., 2017). Two of the studies compared IMU captured heading angle and magnitude of inertial movement analysis events against high-speed video (Balloch et al., 2020; Meylan et al., 2017). 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, (Balloch et al., 2020) and that different types of actions (i.e., high acceleration, deceleration and COD movement) were correctly identified by using accelerometer derived data (Meylan et al., 2017).

Three studies focused on the construct validity of IMUs (Barreira et al., 2017; K. J. A. E. Kim et al., 2020; Staunton et al., 2017). Each study utilized different metrics: PlayerLoad™ (PL), which is a cumulative measure of rate of change in acceleration (Barreira et al., 2017); average instantaneous net force, which is an accelerometer derived measure of net force acting on body (Staunton et al., 2017); and novel IMU-based metrics called transitional angular displacement of segment (TADS) and symmetry index (SI) (K. J. A. E. Kim et al., 2020). The results of these

studies suggest that when evaluating between participant and between task variations (Barreira et al., 2017), joint stability after rehabilitation (K. J. A. E. Kim et al., 2020) or average force produced in relation to overground speed (Staunton et al., 2017), 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). (Balloch et al., 2020; Barreira et al., 2017; K. J. A. E. Kim et al., 2020; Meylan et al., 2017) The findings concluded good or high level of reliability when measuring COD angles of 45°, 90°, 135° and 180° (Balloch et al., 2020) and test-retest reliability when measuring TADS SI of individuals with knee injury (K. J. A. E. Kim et al., 2020). Moderate to high reliability was found when measuring within participant test-retest differences in PL (Barreira et al., 2017). Meylan et al. (Meylan et al., 2017) 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.

**Table 2.1.** Characteristics of the studies evaluating the validity of IMU when measuring COD movements.

Author and year	Validity type	Gold standard/comparator	Outcomes	Validity	Findings
Balloch et al. 2020 (Balloch et al., 2020)	Concurrent validity	High-speed video	Precise COD angles 45° left 90° left 135° left 180° left  45° right 90° right 135° right 180° right	Mean bias ±SD / Cohen's d -2.3±2.7° / -0.81 -3.0±2.6° / -1.13 -0.6±2.2° / -0.26 4.9±3.7° / 1.36  -0.3±2.3° / -0.14 1.9±2.5° / 0.76 -0.4±3.5° / -0.10 2.4±6.1° / 0.39	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.
Gurchiek et al. 2017 (Gurchiek et al., 2017)	Concurrent validity	Force plate	Estimates of step-average GRF ( <i>N</i> ) during 45° COD for x,y,z and resultant <i>GRF<sub>x</sub></i> <i>GRF<sub>y</sub></i> <i>GRF<sub>z</sub></i> <i>GRF<sub>res</sub></i>  <i>Orientation of GRF left</i> <i>Orientation of GRF right</i>	Root mean square error / Pearson's correlation / Bland-Altman 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 Angular error 10.0±6.0° 8.5±3.8°	Estimates of <i>GRF<sub>z</sub></i> and <i>GRF<sub>res</sub></i> had statistically significant ( $p \leq 0.05$ ) correlation between IMU and force-plate. Estimates of instantaneous <i>F</i> were also analyzed but they did not agree between IMU and force-plate.
Meylan et al. 2017 (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 (Nedergaard et al., 2017)	Concurrent validity	CoM acceleration derived from force plate measured GRF.	Within-task relationship between CoM and accelerometry from different accelerometers	Linear regression ( $R^2$ ) values:	Weak relationship between segmental acceleration and CoM acceleration regardless of accelerometer location and task.

			Peak resultant acceleration 45° 90° Average loading rate 45° 90° Impulse (integral of resultant acceleration time) 45° 90°	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	
Netto et al. 2010* (Netto et al., 2010)	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 (Roell et al., 2019)	Concurrent validity	Three-dimensional MA	Mean acceleration (Complementary filter and 5Hz smoothing)  Vertical acceleration Horizontal acceleration Resultant acceleration  Peak acceleration (Complimentary filter, 5Hz)  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 5Hz resampling, when compared with 10Hz and 100Hz. Vertical and resultant accelerations had stronger relationships than horizontal accelerations.
Wundersitz et al. 2013 (Wundersitz et al., 2013)	Criterion validity	Force plate	Peak foot-strike impact force values (10Hz smoothing)  Cranio-caudal 45° 90° 180°  Resultant 45° 90°	Spearman's correlation / coefficient of variation (%)  -0.33 / 19.2 0.19 / 15.8 0.18 / 20.5  0.67 / 14.5 0.47 / 17.2	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.

			180°	0.23 / 23.9	Smoothing affected positively (10Hz being most accurate).
Wundersitz et al. 2015 (Wundersitz, Gastin, et al., 2015)	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	12Hz filtered accelerometer data had strongest relationship with MA. Peak accelerations were overestimated during COD when compared with MA.
Barreira et al. 2017 (Barreira et al., 2017)	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.
Kim et al. 2020 (K. J. A. E. Kim et al., 2020)	Construct validity	Lower limb asymmetries between injured and non-injured limb	Baseline - return to sport (wk)  Side-step test time Symmetry index	T-test, significance level p ≤ 0.05 p = 0.32 p = 0.046	No statistical significance between baseline and RTS in side-step test time. Small statistical significance between symmetry index of the baseline to RTS.
Staunton et al. 2017 (Staunton et al., 2017)	Construct validity	Within player relationships with AvFnet and overground speed.	Compared with running speed: AvFnet AU · min <sup>-1</sup>  Agreement between predicted and measured AvFnet: Jog and COD Run and COD	Bivariate Pearson's correlation: 0.95 0.80  Mean bias / ratio mean (95% limits of agreement): 18% / 1.18 (0.92-1.44) 14% / 1.14 (0.94-1.34)	Accelerometry derived AvFnet produced nearly perfect within-player relationships with overground running speed.  Moderate agreement between predicted and measured AvFnet.

\*Abstract

GRF = Ground Reaction Force, IMA = Inertial Movement Analysis, CoM = Center of Mass, MA = Motion Analysis, AU = Arbitrary Units, AU · min<sup>-1</sup> = Arbitrary Units per minute, RTS = Return to Sport, AvFnet = Accelerometry derived Net Force

**Table 2.2.** Characteristics of the studies evaluating the reliability of IMU when measuring COD movements.

Author	Outcomes	Reliability	Findings
Balloch et al. 2020 (Balloch et al., 2020)	COD angles: 45° left 90° left 135° left 180° left  45° right 90° right 135° right 180° right	Typical Error with 90% confidence limits / Coefficient of variation 1.9 (1.5-2.6) / 4.2 1.6 (1.3-2.1) / 1.7 1.8 (1.4-2.4) / 1.3 3.0 (2.4-4.0) / 1.7  1.5 (1.2-2.0) / 3.3 2.2 (1.8-2.9) / 2.5 2.0 (1.6-2.7) / 1.5 5.2 (4.2-6.9) / 3.0	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 (Barreira et al., 2017)	PlayerLoad (AU) and PlayerLoad per minute (AU · min <sup>-1</sup> ) for side-cut: AU AU · min <sup>-1</sup>	Paired t-test (p≤0.05) / Intraclass correlation  0.260 / 0.892 0.535 / 0.921	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 (K. J. A. E. Kim et al., 2020)	TADS metrics and FmSST:  TADS right TADS left TADS SI FmSST	Intraclass correlation (95%CI):  0.87 (0.63-0.96) 0.89 (0.64-0.96) 0.81 (0.58-0.92) 0.90 (0.61-0.95)	Good to excellent test-retest reliability.
Meylan et al. 2017 (Meylan et al., 2017)	IMA (m*s <sup>-2</sup> )for COD movement:  IMA COD left IMA COD right	Pooled coefficient of variation (90%CI) / pooled intraclass correlation:  13 (11-18) / 0.52 (0.26-0.74) 16 (13-21) / 0.54 (0.28-0.74)	Variability of IMA magnitudes is high and intraclass correlation is low.

AU = Arbitrary Units, AU · min<sup>-1</sup> = Arbitrary Units per minute, TADS = Transitional Angular Displacement of Segment, FmSST = Four Meter Side-step test times, IMA = Inertial Measurement Analysis

#### 2.4.2 Study characteristics

Characteristics of all studies are presented in Table 3.

##### *Population, sport and age*

Thirty-five studies involved adult participants with an age range from 18 to 42 years (Arpinar-Avsar & Celik, 2020; M. Atkinson et al., 2016; Balloch et al., 2020; Barreira et al., 2017; Brachet et al., 2003; Brooks et al., 2020; Eke et al., 2017; Finocchietti et al., 2019; A. Fox et al., 2014; J. L. Fox, O'Grady, et al., 2020; J. L. Fox, Stanton, et al., 2020; Granero-Gil, Gómez-Carmona, Bastida-Castillo, Rojas-Valverde, De La Cruz, et al., 2020; Gurchiek et al., 2017; K. J. A. E. Kim et al., 2020; Lucas et al., 2018; Luteberget & Spencer, 2017; Meghji et al., 2019; Nedergaard et al., 2014, 2017; Simpson et al., 2020; Sinclair, 2017; Staunton et al., 2017; Stetter et al., 2019, 2020; Stirling et al., 2018; Svilar et al., 2018, 2019; Svilar & Jukić, 2018; Tedesco et al., 2020; Trama et al., 2020; Wundersitz et al., 2013; Wundersitz, Gastin, et al., 2015; Wundersitz, Josman, et al., 2015; Zaferiou et al., 2017; Zago et al., 2019). Only three studies examined COD movement in individuals under 18 years (Hulin et al., 2018; Lander et al., 2020; Nagano et al., 2020), and one study had a combination of youth and adults (Meylan et al., 2017). In ten studies, the age of participants was not reported (Ahmadi et al., 2015; J. L. Fox, O'Grady, et al., 2020; W. R. Johnson et al., 2019; Marcotte et al., 2018; Matsuyama et al., 2019; McGinnis et al., 2017; Netto et al., 2010; Odonovan et al., 2016; Roell et al., 2019; Spencer et al., 2020). The population in studies was most often males. 24 studies included only male participants (Arpinar-Avsar & Celik, 2020; M. Atkinson et al., 2016; Balloch et al., 2020; Barreira et al., 2017; Brachet et al., 2003; Finocchietti et al., 2019; A. Fox et al., 2014; J. L. Fox, O'Grady, et al., 2020; J. L. Fox, Stanton, et al., 2020; Matsuyama et al., 2019; Meghji et al., 2019; Nedergaard et al., 2014, 2017; Sinclair,

2017; Staunton et al., 2017; Stetter et al., 2019, 2020; Svilar et al., 2018, 2019; Svilar & Jukić, 2018; Tedesco et al., 2020; Wundersitz, Gastin, et al., 2015; Wundersitz, Josman, et al., 2015). Seven studies had only female participants (Brooks et al., 2020; Luteberget & Spencer, 2017; Meylan et al., 2017; Nagano et al., 2020; Roell et al., 2019; Simpson et al., 2020; Zago et al., 2019), 11 had both males and females (Eke et al., 2017; Gurchiek et al., 2017; W. R. Johnson et al., 2019; K. J. A. E. Kim et al., 2020; Lucas et al., 2018; Netto et al., 2010; Spencer et al., 2020; Stirling et al., 2018; Trama et al., 2020; Wundersitz et al., 2013; Zaferiou et al., 2017) and in seven the sex was not reported (Ahmadi et al., 2015; Granero-Gil, Gómez-Carmona, Bastida-Castillo, Rojas-Valverde, De La Cruz, et al., 2020; Hulin et al., 2018; Lander et al., 2020; Marcotte et al., 2018; McGinnis et al., 2017; Odonovan et al., 2016).

The background of the population was varying. Twenty-four studies did not specify the sport or background of participants (Ahmadi et al., 2015; M. Atkinson et al., 2016; Balloch et al., 2020; Barreira et al., 2017; Eke et al., 2017; J. L. Fox, O'Grady, et al., 2020; Gurchiek et al., 2017; W. R. Johnson et al., 2019; Lander et al., 2020; Lucas et al., 2018; Marcotte et al., 2018; McGinnis et al., 2017; Meghji et al., 2019; Nedergaard et al., 2017; Netto et al., 2010; Sinclair, 2017; Stetter et al., 2019, 2020; Stirling et al., 2018; Trama et al., 2020; Wundersitz et al., 2013; Wundersitz, Gastin, et al., 2015; Wundersitz, Josman, et al., 2015; Zaferiou et al., 2017). Eight studies were focused on basketball (A. Fox et al., 2014; J. L. Fox, O'Grady, et al., 2020; J. L. Fox, Stanton, et al., 2020; Roell et al., 2019; Staunton et al., 2017; Svilar et al., 2018, 2019; Svilar & Jukić, 2018), six on soccer (Arpinar-Avsar & Celik, 2020; Finocchietti et al., 2019; Granero-Gil, Gómez-Carmona, Bastida-Castillo, Rojas-Valverde, De La Cruz, et al., 2020; Meylan et al., 2017; Nedergaard et al., 2014; Zago et al., 2019), three on netball (Brooks et al., 2020; Simpson et al., 2020; Spencer et al., 2020) and two had multiple sports (hockey, football, rugby, and/or tennis)

(Brachet et al., 2003; K. J. A. E. Kim et al., 2020), or rugby (Hulin et al., 2018; Tedesco et al., 2020).

### *Study settings*

Thirteen 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 (Barreira et al., 2017; Gurchiek et al., 2017; W. R. Johnson et al., 2019; Lucas et al., 2018; Nedergaard et al., 2014; Roell et al., 2019; Sinclair, 2017; Stetter et al., 2019, 2020; Wundersitz et al., 2013; Wundersitz, Gastin, et al., 2015; Wundersitz, Josman, et al., 2015; Zago et al., 2019). Outside the laboratory, 17 studies were conducted in indoor sport or recreation facilities (e.g., playing court, dancehall) (Brooks et al., 2020; Finocchietti et al., 2019; A. Fox et al., 2014; J. L. Fox, O’Grady, et al., 2020; J. L. Fox, Stanton, et al., 2020; K. J. A. E. Kim et al., 2020; Lander et al., 2020; Luteberget & Spencer, 2017; Matsuyama et al., 2019; Nagano et al., 2020; Nedergaard et al., 2017; Simpson et al., 2020; Spencer et al., 2020; Staunton et al., 2017; Svilar et al., 2018, 2019; Svilar & Jukić, 2018), nine on outdoor fields (Ahmadi et al., 2015; Balloch et al., 2020; Granero-Gil, Gómez-Carmona, Bastida-Castillo, Rojas-Valverde, De La Cruz, et al., 2020; Hulin et al., 2018; McGinnis et al., 2017; Meghji et al., 2019; Meylan et al., 2017; Tedesco et al., 2020; Zaferiou et al., 2017) and two both indoors and outdoors (Brachet et al., 2003; Marcotte et al., 2018). In eight studies, there was no mention of study settings (Arpinar-Avsar & Celik, 2020; M. Atkinson et al., 2016; Eke et al., 2017; J. L. Fox, O’Grady, et al., 2020; Netto et al., 2010; Odonovan et al., 2016; Stirling et al., 2018; Trama et al., 2020). Type of COD was anticipated in 33 studies (Ahmadi et al., 2015; Arpinar-Avsar & Celik, 2020; M. Atkinson et al., 2016; Balloch et al., 2020; Barreira et al., 2017; Brachet et al., 2003; Eke et al., 2017; Finocchietti et al., 2019; Gurchiek et al., 2017; W. R. Johnson et al., 2019; K. J. A. E. Kim et al.,

2020; Lander et al., 2020; Lucas et al., 2018; Marcotte et al., 2018; McGinnis et al., 2017; Meghji et al., 2019; Nedergaard et al., 2014; Netto et al., 2010; Odonovan et al., 2016; Roell et al., 2019a; Sinclair, 2017; Staunton et al., 2017; Stetter et al., 2019, 2020; Stirling et al., 2018; Tedesco et al., 2020; Trama et al., 2020; Wundersitz et al., 2013; Wundersitz, Gastin, et al., 2015; Wundersitz, Josman, et al., 2015; Zaferiou et al., 2017; Zago et al., 2019) and in two studies (J. L. Fox, O’Grady, et al., 2020; Meylan et al., 2017) 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 (Brooks et al., 2020; A. Fox et al., 2014; J. L. Fox, O’Grady, et al., 2020; J. L. Fox, Stanton, et al., 2020; Granero-Gil, Gómez-Carmona, Bastida-Castillo, Rojas-Valverde, De La Cruz, et al., 2020; Hulin et al., 2018; Luteberget & Spencer, 2017; Matsuyama et al., 2019; Nagano et al., 2020; Simpson et al., 2020; Spencer et al., 2020; Svilar et al., 2018, 2019; Svilar & Jukić, 2018). None of the studies focused only on unplanned COD movements.

#### *Devices and sensor attachment*

Nineteen 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 (Balloch et al., 2020; Brooks et al., 2020; A. Fox et al., 2014; J. L. Fox, O’Grady, et al., 2020; J. L. Fox, Stanton, et al., 2020; Hulin et al., 2018; Luteberget & Spencer, 2017; Meghji et al., 2019; Meylan et al., 2017; Roell et al., 2019; Simpson et al., 2020; Spencer et al., 2020; Svilar et al., 2018, 2019; Svilar & Jukić, 2018; Wundersitz, Gastin, et al., 2015; Wundersitz, Josman, et al., 2015). APDM Opal IMU was used in four studies (Eke et al., 2017; McGinnis et al., 2017; Stirling et al., 2018; Zaferiou et al., 2017). XSENS MVN was used in two studies (Finocchietti et

al., 2019; Lander et al., 2020). Sampling rates varied from 50Hz to 1500Hz with the most common frequency, 100Hz, 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) (Ahmadi et al., 2015; Brachet et al., 2003; Eke et al., 2017; Finocchietti et al., 2019; J. L. Fox, O'Grady, et al., 2020; K. J. A. E. Kim et al., 2020; Lander et al., 2020; Marcotte et al., 2018; Matsuyama et al., 2019; Nedergaard et al., 2017; Stirling et al., 2018; Trama et al., 2020) and in 18 studies the location was the between the scapulae (M. Atkinson et al., 2016; Balloch et al., 2020; Brooks et al., 2020; A. Fox et al., 2014; J. L. Fox, O'Grady, et al., 2020; J. L. Fox, Stanton, et al., 2020; Luteberget & Spencer, 2017; Meghji et al., 2019; Meylan et al., 2017; Nagano et al., 2020; Nedergaard et al., 2014; Roell et al., 2019a; Simpson et al., 2020; Spencer et al., 2020; Staunton et al., 2017; Wundersitz et al., 2013; Wundersitz, Gastin, et al., 2015; Wundersitz, Josman, et al., 2015). In four studies the device was on the lower back (Gurchiek et al., 2017; McGinnis et al., 2017; Odonovan et al., 2016; Zago et al., 2019), in eight studies on the knee (inside a custom sleeve), tibia or thigh (Arpinar-Avsar & Celik, 2020; W. R. Johnson et al., 2019; Lucas et al., 2018; Sinclair, 2017; Stetter et al., 2019, 2020; Tedesco et al., 2020; Zaferiou et al., 2017) and in one study on the neck (Netto et al., 2010).

### *IMU sensors and metrics*

Wide variety of different types of devices led to different combinations of used sensors. Nineteen studies used measurements from accelerometer only (Arpinar-Avsar & Celik, 2020; M. Atkinson et al., 2016; Barreira et al., 2017; Brachet et al., 2003; J. L. Fox, O'Grady, et al., 2020; W. R. Johnson et al., 2019; Lander et al., 2020; Lucas et al., 2018; Nagano et al., 2020; Nedergaard et al., 2014, 2017; Netto et al., 2010; Sinclair, 2017; Spencer et al., 2020; Staunton et al., 2017;

Trama et al., 2020; Wundersitz et al., 2013; Wundersitz, Josman, et al., 2015). 13 studies used the measurements from accelerometer, gyroscope and magnetometer (Balloch et al., 2020; Brooks et al., 2020; Eke et al., 2017; Gurchiek et al., 2017; Marcotte et al., 2018; Meghji et al., 2019; Meylan et al., 2017; Simpson et al., 2020; Stirling et al., 2018; Svilar et al., 2018, 2019; Svilar & Jukić, 2018; Zaferiou et al., 2017). Nine studies used the measurements from accelerometer and gyroscope (Granero-Gil, Gómez-Carmona, Bastida-Castillo, Rojas-Valverde, De La Cruz, et al., 2020; Hulin et al., 2018; K. J. A. E. Kim et al., 2020; Matsuyama et al., 2019; Stetter et al., 2019, 2020; Tedesco et al., 2020; Wundersitz, Gastin, et al., 2015; Zago et al., 2019).

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 (Barreira et al., 2017; Brooks et al., 2020; J. L. Fox, O'Grady, et al., 2020; J. L. Fox, Stanton, et al., 2020; Hulin et al., 2018; Simpson et al., 2020; Staunton et al., 2017). IMU-based measurement of joint angles were reported in five studies (Ahmadi et al., 2015; Finocchietti et al., 2019; A. Fox et al., 2014; A. S. Fox, 2018; McGinnis et al., 2017) 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 (Stetter et al., 2019, 2020). Accelerations were analyzed in 16 studies (Arpinar-Avsar & Celik, 2020; Brooks et al., 2020; Lander et al., 2020; Luteberget & Spencer, 2017; Meylan et al., 2017; Nagano et al., 2020; Nedergaard et al., 2014, 2017; Netto et al., 2010; Roell et al., 2018, 2019; Sinclair, 2017; Spencer et al., 2020; Stirling et al., 2018; Wundersitz et al., 2013; Wundersitz, Josman, et al., 2015), accelerations in combination with angular velocities and specific COD angles were analyzed in 11 studies (Eke et al., 2017; Granero-Gil, Gómez-Carmona, Bastida-Castillo, Rojas-Valverde, De La

Cruz, et al., 2020; K. J. A. E. Kim et al., 2020; Matsuyama et al., 2019; Odonovan et al., 2016; Svilar et al., 2018, 2019; Svilar & Jukić, 2018; Tedesco et al., 2020; Zaferiou et al., 2017; Zago et al., 2019), ground impacts or soft tissue accelerations in four studies (M. Atkinson et al., 2016; Brachet et al., 2003; Lucas et al., 2018; Trama et al., 2020) 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 (Gurchiek et al., 2017; W. R. Johnson et al., 2019; Nedergaard et al., 2014; Wundersitz et al., 2013).

#### *Condition and type of COD*

In seven studies, participants were instructed to approach the COD at maximal running speed (Arpinar-Avsar & Celik, 2020; M. Atkinson et al., 2016; McGinnis et al., 2017; Meylan et al., 2017; Sinclair, 2017; Tedesco et al., 2020; Zaferiou et al., 2017). In 18 studies, speed was described as running, jogging or sprinting (Balloch et al., 2020; Barreira et al., 2017; Brachet et al., 2003; Finocchietti et al., 2019; Hulin et al., 2018; W. R. Johnson et al., 2019; K. J. A. E. Kim et al., 2020; Lucas et al., 2018; Marcotte et al., 2018; Meghji et al., 2019; Nedergaard et al., 2014b, 2017; Stetter et al., 2019, 2020; Trama et al., 2020; Wundersitz et al., 2013; Zago et al., 2019). In 18 studies, there was no information regarding the running speed (not reported at all or CODs were done at varying speeds during games or practices) (Brooks et al., 2020; A. Fox et al., 2014; J. L. Fox, O'Grady, et al., 2020; J. L. Fox, Stanton, et al., 2020; Granero-Gil, Gómez-Carmona, Bastida-Castillo, Rojas-Valverde, De La Cruz, et al., 2020; Lander et al., 2020; Luteberget & Spencer, 2017; Matsuyama et al., 2019; Roell et al., 2019a; Simpson et al., 2020; Spencer et al., 2020; Staunton et al., 2017; Svilar et al., 2018, 2019; Svilar & Jukić, 2018; Wundersitz, Gastin, et al., 2015b; Wundersitz, Josman, et al., 2015). Four of the studies included 45° CODs (Brachet et al.,

2003; Finocchietti et al., 2019; Tedesco et al., 2020; Trama et al., 2020), 90° CODs (Lucas et al., 2018; Meylan et al., 2017; Stetter et al., 2019, 2020), 135° CODs (McGinnis et al., 2017; Nedergaard et al., 2014; Wundersitz, Gastin, et al., 2015; Wundersitz, Josman, et al., 2015) or 180° CODs (Barreira et al., 2017; Hulin et al., 2018; K. J. A. E. Kim et al., 2020; Sinclair, 2017). 19 studies included a combination of two or more COD angles ranging from 45° to 360° (Arpinar-Avsar & Celik, 2020; M. Atkinson et al., 2016; Balloch et al., 2020; A. Fox et al., 2014; W. R. Johnson et al., 2019; Luteberget & Spencer, 2017; Marcotte et al., 2018; Matsuyama et al., 2019; Meghji et al., 2019; Nedergaard et al., 2017; Roell et al., 2019; Simpson et al., 2020; Staunton et al., 2017; Svilar et al., 2018, 2019; Svilar & Jukić, 2018; Wundersitz et al., 2013; Zaferiou et al., 2017).

**Table 3.3.** 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. (Ahmadi et al., 2015)	2015	Healthy and injured subjects (low-back pain)	NR	NR (9 healthy, 1 injured)	Outdoor (grass) soccer pitch	NR	Shanks, thighs, pelvis, sacrum	NR
Arpinar-Avsar et al. (Arpinar-Avsar & Celik, 2020)	2020	3rd division soccer players	20-23	Males (13)	NR	Trigno, Delsys; Accelerometer, (148Hz)	Tibialis anterior muscles	3 agility tests, running as quickly as possible, anticipated 90° and 180° CODs
Atkinson et al. (M. Atkinson et al., 2016)	2016	1year minimum involvement in invasion sports, free from injury	18-24	Males (20)	NR	SPI Pro; Accelerometer (100Hz)	Between scapulae	Maximal running – anticipated 90° and 180° CODs
Balloch et al. (Balloch et al., 2020)	2020	Recreationally active adults, free from injury	28-30	Males (7)	Outdoor soccer field	Catapult, Optimeye, S5; Accelerometer, Gyroscope, Magnetometer (100Hz)	T1-T5 level	Running – anticipated 45°, 90°, 135° and 180° CODs
Barreira et al. (Barreira et al., 2017)	2017	Recreational athletes, used to football and free from injuries	21-30	Males (15)	Indoor laboratory	ADXL 326; Accelerometer (100Hz)	Trunk	Jogging and sprinting - 180° CODs and zigzags as in soccer-specific match simulation protocol
Brachet et al. (Brachet et al., 2003)	2003	Pro and semipro athletes: 5 football players, 4 hockey players, 4 rugby players	19-42	Males and Females (13)	Indoor (grass) and outdoor (artificial grass) field	Entran EGCS-D1SM-50; Accelerometer (0-600Hz)	Pelvis and left distal-anterior tibia	Running – anticipated 45° COD to the right
Brooks et al. (Brooks et al., 2020)	2020	Elite netball players	20-31	Females (12)	Indoor court	Catapult, T6; accelerometer, gyroscope, magnetometer, 100Hz	Between scapulae	Netball matches

Eke et al. (Eke et al., 2017)	2017	Recreational athletes, physically active, injury and pain free (lower limb)	18-23	Males (9) Females (9)	Obstacle course	APDM Opal; Accelerometer, Gyroscope, Magnetometer (128Hz)	Feet, shanks, thighs, sacrum, torso, forearms, biceps, head	Maximal running – anticipated 45°,90°,135° and 180° CODs
Finocchietti et al. (Finocchietti et al., 2019)	2019	Visually impaired players and healthy controls - all amateur soccer players	25-40	Males (6,8)	Indoor futsal court	XSENS MVN Link; Accelerometer, gyroscope, magnetometer (240Hz)	Lycra suit (17 sensors)	10m shuttle running test – anticipated 180° CODs
Fox et al. (A. Fox et al., 2014)	2014	Semi-professional basketball players	21-27	Males (8)	Indoor basketball court	Catapult, Optimeye, S5; Accelerometer, gyroscope (100Hz)	Between scapulae	Basketball game: COD; -135° to -45° for left and 45° to 135° for right COD
Fox et al.* (J. L. Fox, O’Grady, et al., 2020a)	2020	NR	19-23	Males (7)	NR	NR Accelerometer, gyroscope	Trunk, sacrum, thigh, shank and foot (dominant limb)	Anticipated and unanticipated 35° to 55° CODs
Fox et al.(J. L. Fox, O’Grady, et al., 2020b)	2020	Semi-professional basketball players	19-26	Males (8)	Indoor basketball court	Catapult Innovations, OptimEye S5; accelerometer, (100Hz)	Between scapulae	Basketball training sessions and games
Fox et al.(J. L. Fox, Stanton, et al., 2020)	2020	Semi-professional basketball players	21-27	Males (5)	Indoor basketball court	Catapult Innovations, OptimEye S5; NR	Between scapulae	Basketball games
Granero-Gil et al.(Granero-Gil, Gómez-Carmona, Bastida-Castillo, Rojas-Valverde, De La Cruz, et al., 2020)	2020	Elite-level soccer players	21-32	NR	Outdoor, soccer field (grass and turf)	WIMU PRO; Accelerometer, gyroscope, (100Hz)	NR	Soccer matches

Gurchiek et al. (Gurchiek et al., 2017)	2017	NR	21-25	Males (12) Females (3)	Indoor laboratory	Yost Data Logger 3-Space Sensor; Accelerometer, Gyroscope, Magnetometer (450Hz)	Sacrum level	Running – anticipated 45° CODs
Hulin et al. (Hulin et al., 2018)	2018	Junior rugby league players	16-18	NR (16)	NR	Catapult, Optimeye, S5; Accelerometer, Gyroscope (100Hz)	NR	Running – anticipated 180° CODs
Johnson et al. (W. R. Johnson et al., 2019)	2019	Teamsport athletes	NR	Males (4) Females (1)	Indoor laboratory	Noraxon DTS-3D 518; Accelerometer	Pelvis, both thighs and shanks	Running > 2.16m/s, anticipated 45°-90° CODs to left
Kim et al. (K. J. A. E. Kim et al., 2020)	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	Young adults	Males (10) Females (25)	Indoor gymnasium (wood flooring)	CaneSense; Accelerometer, Gyroscope (50Hz)	Pelvis and both shanks	Running and transitions - anticipated 180° CODs
Lander et al. (Lander et al., 2020)	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. (Lucas et al., 2018)	2018	Currently active and experience competing in sports that involve frequent landing and cutting (e.g., soccer, basketball)	21-26	Males (15) Females (15)	NR	Shimmer3; Accelerometer (500Hz)	Anterior-medial tibia (non-dominant leg)	Running - unanticipated and anticipated 90° CODs
Luteberget et al. (Luteberget & Spencer, 2017)	2017	National team handball players	21-28	Females (20)	Indoor court	Catapult, Optimeye, S5;	Between scapulae	Handball games (free movement)

						Accelerometer, gyroscope, magnetometer (100Hz)		
Marcotte et al. (Marcotte et al., 2018)	2018	Healthy participants	NR	NR (17)	Outdoor field (grass-turf)	ActiGraph GT9X; Accelerometer, Gyroscope, Magnetometer (90Hz)	Hips (anterior axillary line), wrists and ankles	Walking and running – anticipated 45°, 90°, 135° and 180° CODs
Matsuyama et al. (Matsuyama et al., 2019)	2019	Dancers	NR	Males (7)	Indoor dance hall	ATR-Promotions, TSND151; Accelerometer, Gyroscope (125Hz)	Arms, hips and ankles	Ballroom dance moves - 90°, 315° and 360° CODs
McGinnis et al. (McGinnis et al., 2017)	2017	Subjects from university population	NR	NR (32)	Outdoor field	APDM Opal; Accelerometer, Gyroscope, Magnetometer (128Hz)	Sacrum level	Maximal running with loaded (20,5kg vest) and unloaded (3,4kg mock rifle – anticipated 90° and 135° CODs
Meghji et al. (Meghji et al., 2019)	2019	Recreational athletes	28-30	Males (6)	Outdoor field	Catapult, Optimeye, S5; Accelerometer, Gyroscope, Magnetometer (100Hz)	T1-T5 level	Running – anticipated 45°, 90°, 135° and 180° CODs
Meylan et al. (Meylan et al., 2017)	2017	U20 female soccer players and women’s national-team players	17-19 (20) - other group 22-32 (13)	Females (33)	Outdoor field (turf)	Catapult, Minimax S4; Accelerometer, Gyroscope, Magnetometer (100Hz)	Between scapulae	40m and 20m sprint – anticipated 90° CODs
Nagano et al. (Nagano et al., 2020)	2020	Badminton players	14-16	Females (10)	Indoor court	Sports Sensing, SS-WS1201; Accelerometer, 100Hz	Between scapulae	Badminton games

Nedergaard et al. (Nedergaard et al., 2017)	2017	Team sport players, no severe injury history	18-26	Males (20)	Indoor laboratory	DTS, KXP94 and 518; Accelerometer (100Hz and 1000Hz)	Trunk, dorsal aspect of pelvis and tibia	Running 2, 3, 4, and 5 m/s – anticipated 45° and 90° CODs
Nedergaard et al. (Nedergaard et al., 2014)	2014	Soccer players, no previous history of ankle or knee injuries	18-24	Males (10)	Indoor laboratory	DTS 3D; Accelerometer (500Hz)	Between scapulae	Running 50%, 70% and 90% of maximal speed - deceleration before anticipated 135° CODs
Netto et al.* (Netto et al., 2010)	2010	NR	NR	Males (5) Females (5)	NR	SPI Pro; Accelerometer (NR)	At the base of neck	NR
Odonovan et al.* (Odonovan et al., 2016)	2016	U.S. Army Soldiers	NR	NR (12)	NR	NR	Sacrum level	NR
Roell et al. (Roell et al., 2019)	2019	Professional basketball players	NR	Females (7)	Indoor basketball court	Catapult, Optimeye, S5; Accelerometer (100Hz)	Between scapulae	Teamsport specific movements – anticipated 60°, 80°, 90° and 360° CODs
Sinclair (Sinclair, 2017)	2017	Competitive athletes from university level sports team	21-27	Males (9)	Indoor laboratory	ACL 300; Accelerometer (1000Hz)	Distal –anterior tibia	Maximal shuttle run – anticipated 180° CODs
Spencer et al. (Spencer et al., 2020)	2020	Netball high-performance umpires	NR	Males (5) Females (17)	Indoor court	Catapult Innovations, MinimaxX S4, Firmware 6.70; Accelerometer, (100Hz)	Between scapulae	Netball matches
Staunton et al. (Staunton et al., 2017)	2017	Semi-professional basketball players	21-29	Males (28)	Indoor basketball court	Link; Accelerometer (100Hz)	Inferior angle of scapulae	YoYo IR1 test - 90°, 135° cuts and basketball exercise simulation test (BEST) -180° CODs
Stetter et al. (Stetter et al., 2019)	2019	Healthy sport students with no reported injuries	23-29	Males (13)	Indoor - motion analysis laboratory	NR Accelerometer, Gyroscope (1500Hz)	2 in a knee sleeve (upper and lower end)	Walking and running – anticipated 90° CODs

Stetter et al. (Stetter et al., 2020)	2020	Healthy sport students with no reported injuries	23-29	Males (13)	Indoor - motion analysis laboratory	NR Accelerometer, Gyroscope (1500Hz)	2 in a knee sleeve (upper and lower end)	Walking and running – anticipated 90° CODs
Stirling et al. (Stirling et al., 2018)	2019	Recreational athletes	18-22	Males (9) Females (9)	NR	APDM Opal; Accelerometer, Gyroscope, Magnetometer (128Hz)	Sacrum and both feet	Maximal running – anticipated 45° and 90° CODs
Svilar et al. (Svilar et al., 2018)	2018	Professional basketball players	22-29	NR (13)	Indoor basketball court	Catapult, Optimeye, S5; Accelerometer, Gyroscope, Magnetometer (100Hz)	NR	Basketball related training sessions - free movement: Total inertial movements registered in a rightward lateral vector
Svilar et al. (Svilar & Jukić, 2018)	2018	Professional basketball players	24-28	Males (13)	Indoor basketball court	Catapult, Optimeye, S5; Accelerometer, Gyroscope, Magnetometer (100Hz)	NR	Basketball training sessions - free movement: total inertial movements registered in a rightward/ leftward lateral vector
Svilar et al. (Svilar et al., 2019)	2019	Top-level basketball players	22-30	Males (16)	Indoor basketball court	Catapult, Optimeye, S5; Accelerometer, Gyroscope, Magnetometer (100Hz)	NR	Basketball training session and games - free movement: Inertial movements registered in a rightward/leftward lateral vector
Tedesco et al. (Tedesco et al., 2020)	2020	Non-elite rugby players	21-31	Males (12)	Outdoor, rugby playing pitches	Custom made IMU; accelerometer, gyroscope	Both legs - anterior tibia and lateral thigh	Maximum running, 45° COD
Trama et al. (Trama et al., 2020)	2020	10 team sport athletes or runners, injury free 6 months preceding experiment	25-41	Males (9) Females (1)	NR	Mega Electronics; Accelerometer (1000Hz)	Gastrocnemius, vastus lateralis and heel cup of shoe	Running – anticipated 45° CODs to left ( $\pm$ 15° angle)

Wundersitz et al. (Wundersitz et al., 2013)	2013	Competitive team sport players, lower limb injury free 6 months preceding experiment	19-23	Males (12) Females (5)	Indoor laboratory	SPI Pro; Accelerometer (100Hz)	Between scapulae – Th2 level	Running – anticipated 45°, 90° and 180° CODs
Wundersitz et al. (Wundersitz, Josman, et al., 2015)	2015	Recreationally active healthy individuals competing in one or more amateur team sport competitions per week	21-27	Males (76)	Indoor laboratory	Catapult, Minimax S4; Accelerometer (100Hz)	In a manufacturer provided sports vest – Th 5 level	Simulated team sport circuit – anticipated 135° CODs
Wundersitz et al. (Wundersitz, Gastin, et al., 2015)	2015	Recreationally active healthy individuals competing in one or more amateur team sport competitions per week	21-27	Males (76)	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. (Zaferiou et al., 2017)	2017	Recreational athletes	18-22	Males (17) Females (15)	Outdoor	APDM, Opal V1; accelerometer, gyroscope, magnetometer, (128Hz)	Taped to the top of shoes on both feet	Running as quickly as possible - anticipated 60° and 120° CODs
Zago et al. (Zago et al., 2019)	2019	Soccer players	20-26	Females (13)	Indoor laboratory	GaitUp Physilog 5; Accelerometer, gyroscope (512Hz)	Sacrum	Running 2.5m/s - 5 meter shuttle run test

\* = Abstract

NR = Not Reported, COD = Change of Direction, IR1 = Intermittent Recovery test 1

### *Quality assessment*

The quality assessment results for all validity/reliability studies is presented in Appendix 3. The study by Netto et al.(Netto et al., 2010) was not assessed, since only an abstract was available. All studies scored “yes” or “not applicable” for the questions in the introduction and results categories, and one question in the discussion category. The aims and objectives of the studies were clearly stated in all studies when applicable. Regarding the methods, most of the studies had small sample sizes, defining the population and with sampling from an appropriate population base. The sample size was not justified in any of the studies. Only three studies clearly defined the target population (Roell et al., 2019a; Staunton et al., 2017; Wundersitz et al., 2013a) and had selected the sample from an appropriate population. The selection process was well defined in all studies and the measured risk factors and outcome variables were appropriate for the aims of the studies. Outcomes were measured correctly and statistical significance and precision were clear in most studies. Results were described and presented adequately and they were internally consistent. Also, the discussion and conclusions were justified by the results, although three of the studies did not include a discussion of limitations (K. J. A. E. Kim et al., 2020; Meylan et al., 2017; Staunton et al., 2017).

## 2.5 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 (Dos'Santos, Thomas, Comfort, et al., 2019b; Kadlubowski et al., 2019a; Nygaard Falch et al., 2019). 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 (Camomilla et al., 2018; Claudino et al., 2019; Cummins et al., 2013).

### 2.5.1 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 10Hz) 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 (Roell et al., 2019; Wundersitz et al., 2013; Wundersitz, Gastin, et al., 2015).

Four of the concurrent validity studies evaluated accelerations measured from trunk (Nedergaard et al., 2017; Netto et al., 2010; Roell et al., 2018; Wundersitz, Gastin, et al., 2015).

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.(Roell et al., 2019) and Wundersitz et al.(Wundersitz, Gastin, et al., 2015) 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 5Hz and 12Hz gave most accurate results and eliminated differences between accelerometer and resultant GRF values (Roell et al., 2019; Wundersitz et al., 2013; Wundersitz, Gastin, et al., 2015). Reliable and valid results were reported for classifying COD activities (detection of acceleration, deceleration or 90° COD during sprinting) (Meylan et al., 2017), calculating COD heading angles (45°, 90°, 135° and 180°) (Balloch et al., 2020), and quantifying mechanical variables that describe the COD movement (estimate of ground-reaction forces during linear acceleration and 45° COD task) (Gurchiek et al., 2017). In calculation of COD heading angles with a specific algorithm 180° CODs were slightly over- or underestimated, but these were within reasonable limits.

Generalization of these results to real life settings cannot be done, since these measurements were conducted in structured test settings with predetermined COD movements and speed. The next step would be to find out how well the methods that have shown acceptable validity work in sports practices and games, where movements are not predetermined. Detecting COD related variability in accelerations, COD movements and heading angles would provide coaches and players information about movement during practices and games, which would be useful in analyzing workloads and differences between and within players during the season. This information might also be helpful in creating an individual player's COD profile based on the amount and type of CODs they perform during games and differences in accelerations. From injury

prevention point of view, a COD profile could provide a baseline for determining and detecting changes in an individual player's COD movements throughout the season.

### 2.5.2 Construct validity

Two of the convergent validity studies focused on PlayerLoad™ (Barreira et al., 2017; Staunton et al., 2017) and one aimed to introduce and validate the CaneSense™ method for knee motions and interlimb symmetry (K. J. A. E. Kim et al., 2020). 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 (Staunton et al., 2017) and detecting differences in agility after knee injury (K. J. A. E. Kim et al., 2020). Barreira et al. (Barreira et al., 2017) 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.

### 2.5.3 Reliability

All but one study (Meylan et al., 2017) 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. (Meylan et al., 2017) 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. (K. J. A. E. Kim et al., 2020) 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.

#### 2.5.4 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 (L. C. Benson, Ahamed, et al., 2019; Seshadri et al., 2019). There is research suggesting that the risk of ACL and ankle injuries might increase when COD movements are unplanned (Fuerst et al., 2017). Future studies should investigate COD movements in practice and game settings where COD can be both planned and unplanned (Born et al., 2016.; Dos'Santos, Thomas, Comfort, et al., 2019).

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 (Keller et al., 2020; W. Young & Farrow, 2013). 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 (L. C. Benson et al., 2018; L. C. Benson, Ahamed, et al., 2019; Buchheit & Simpson, 2017; Impellizzeri et al., 2019; Johnston et al., 2019).

#### 2.5.5 Participant characteristics

Previous research suggests that females might be at greater risk of ACL injury during COD tasks (G. Hughes & Dally, 2015), despite the potential confounding of other physical factors, such as muscle strength (Benjaminse et al., 2011; Nimphius, 2019; Nimphius et al., 2019). 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 (Achenbach et al., 2019). Just one of the studies in this review included only youth athletes (Hulin et al., 2018). 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 (Dellal & Wong, 2013; Fiorilli et al., 2017; Loturco et al., 2019; Yanci et

al., 2017). 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 (Jones et al., 2016; Nimphius et al., 2018; Pojskic, Åslin, Krolo, Uljevic, et al., 2018). 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 (Dos'Santos et al., 2019). IMU-based analysis might identify new information about these factors when conducted in real life settings.

#### 2.5.6 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 (S. Edwards et al., 2019). 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 Hz to 1500 Hz and rates around 100 Hz were most commonly used. In general, lower sampling rates were used more for movement detection and higher sampling rates for measuring segmental accelerations. Methods for sport-specific standardized data-collection are needed (Camomilla et al., 2018).

#### 2.5.7 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 (Bahr & Krosshaug, 2005; Buchheit et al., 2013; Gabbett, 2016). 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 (Sankey et al., 2020). 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 (Dos'Santos et al., 2019), however, penultimate foot contact was not included in the analysis of included studies and should be considered in future research.

## **2.6 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.

**Conflict of interest**

The authors have no conflicts of interest relevant to this article.

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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

/ = 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)

\* = keyword

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.

APPENDIX 2

**Inclusion 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 of included studies

	Balloch et al 2019	Gurcniek et al 2017	Nedergaard et al	Roell et al 2019	Wundersitz et al	Wundersitz et al	Barreira et al 2017	Kim et al 2020	Meylan et al 2017	Staunton et al 2017
<b>Introduction</b>										
1. Were the aims/objectives of the study clear?	Y	Y	Y	Y	Y	Y	Y	NA	Y	Y
<b>Methods</b>										
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	Y
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 significance and/or precision estimates? (e.g., p-values, confidence intervals)	Y	Y	N	Y	Y	Y	Y	Y	Y	Y
10. Were the methods (including statistical methods) sufficiently described to enable them to be repeated?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
<b>Results</b>										

11. Were the basic data adequately described?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
12. Does the response rate raise concerns about non-response bias?	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
13. If appropriate, was information about non-responders described?	NA	NA	NA	NA	NA	NA	NA	NA	NA	NA
14. Were the results internally consistent?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
15. Were the results presented for all the analyses described in the methods?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
<b>Discussion</b>										
16. Were the authors' discussions and conclusions justified by the results?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y
17. Were the limitations of the study discussed?	Y	Y	Y	Y	Y	Y	Y	N	N	N
<b>Other</b>										
<b>18. Were there any funding sources or conflicts of interest that may affect the authors' interpretation of the results?</b>	N	N	N	N	N	N	N	U	U	N
19. Was ethical approval or consent of participants attained?	Y	Y	Y	Y	Y	Y	Y	Y	Y	Y

## **2.7 Bridge to the next chapters**

The aim of Chapter Two was to summarise the current knowledge on the use of IMUs in analyzing COD movement in sports and identify research gaps and provide recommendations for future studies.

Based on the conclusions, the recommendation for future studies was to conduct studies outside laboratory conditions, in youth and female populations, and include more soccer-specific testing and monitoring methods. No recommendations could be made for device placement or metrics to be used. For these reasons, the experiments and analysis in the following chapters were planned to 1) analyze COD movements in youth populations (chapters two to six), 2) perform testing in soccer-specific environments (chapters three and four), 3) collect and analyze data with varying device placement (chapters three, four and six), 4) analyze varying acceleration and angular velocity metrics during COD movements (chapters three, four and six), 5) collect and analyze COD movements during games (chapters five and six) 6) analyze IMU data during games (chapter six) and 7) analyze COD movements in female populations specifically (chapter six).

The final discussion chapter (chapter seven) will provide overall conclusions based on these individual manuscripts and discuss the findings in light of evidence provided in current literature. The limitations and future directions are provided in order to recommend best practices for future studies on this field.

**Chapter Three: Between-day Reliability of Inertial Measurement Unit Parameters During  
Soccer Specific Change of Direction Test**

Aki-Matti Alanen, Zachary Barrons, Matthew J. Jordan, Reed Ferber & Kati Pasanen

Alanen, AM., Barrons, Z., Jordan, M.J., Ferber, R., & Pasanen, K. (Under Review). Between-day reliability of Inertial Measurement Unit Parameters During Soccer Specific Change of Direction Test. *International Journal of Sport Science and Coaching*, Manuscript ID: SPO-23-

0199

### 3.1 Abstract

This study assessed the between-day reliability of change of direction (COD) biomechanics and speed in youth soccer players with measurements obtained using inertial measurement units (IMU) and high-speed video. A soccer-specific COD test including a 180° pivot turn was performed in both directions by 15 elite female (age: 15.3±0.6 yrs; height 162.6±5.5 cm; body mass: 56.7±7.1 kg) and 22 elite male (age: 15.4±0.5 yrs; height 169±5.9 cm; body mass: 58.5±8.5 kg) youth soccer players in two consecutive days. The reliability of the variables was quantified by using intra-class correlation (ICC) analysis with limits of agreement (LoA) and Bland-Altman plots. Based on the results, neither peak resultant acceleration (PRA) or peak angular velocity (PAV) during final foot contact were sufficiently reliable for 180° pivot turn biomechanics (poor reliability, <0.5), but the reliability of players running time to turn and total time was between acceptable to good (0.9>; >0.7). However, when analysing females and males separately the PRA and PAV ICC's for females had poor to acceptable reliability, when turning left and were statistically different from males (z-score >1.96). Acceptable to good reliability with reasonable LoA imply that speed measures in different phases of COD could reliably reproduce individual differences in 180° pivot turn COD speed. Sex-related differences in repeatability of acceleration and angular velocity call for more comprehensive research in the future. A longer follow-up period is warranted to determine the individual variability of PAV and PRA throughout the season to possibly monitor COD technique variability, however they would not be recommended for the purpose of analysing individual repeatability of specific steps of COD movement.

**Keywords:** Inertial measurement unit, change of direction, youth soccer, test-retest reliability

### **3.2 Introduction**

Change of direction (COD) tests are commonly used in youth soccer to evaluate physical performance. However the tests vary based on durations, lengths and turning angles of COD (Kadlubowski et al., 2019; Nimphius et al., 2018). COD movement is characterized as running with pre-planned directional change and defined as COD speed, whereas agility includes also recognition of a stimulus, reaction, or execution of a physical response (Sheppard & Young, 2006). Soccer is a sport where agility plays important role in evading opposing players to create scoring chances or react to opposing players' movements while defending (W. B. Young et al., 2015). Research in youth soccer has shown that it is possible to discriminate between elite and sub-elite players based on agility/COD speed testing (T. Reilly et al., 2000), it is possible to use dexterity scores to predict agility (Lyle et al., 2015) and that COD speed and reactive agility (RAG) tests are reliable in youth soccer players and also discriminate between U19 and U17 players (Pojskic, Åslin, Krolo, Jukic, et al., 2018). Based on research, agility and COD speed are independent skills (W. B. Young et al., 2015) and the improvements gained in training in soccer require specific training – including reactive components to improve agility and movements without ball to improve COD speed (Sariati et al., 2020; W. B. Young et al., 2015). Therefore, the correct terminology on what is being tested is important and not always well explained in studies on COD ability. Testing and monitoring methods that combine physical and cognitive methods better are warranted, as well as variables that might explain the differences during the important phases of the movement (Paul et al., 2016; W. B. Young et al., 2015)

COD speed and performance has been shown to decline and the COD deficit increase (i.e., the time difference between a COD over a given distance compared to the same distance covered while sprinting in a straight line) in previous research for different age groups (9). This has been

shown to exist across adolescent (U15) and adult soccer players (Loturco et al., 2019). In U13-U15 players motor coordination has been shown to be influencing agility/COD speed regardless of maturation status. A longitudinal study by Forsman et al.(Forsman et al., 2016) showed that soccer-specific agility stayed relatively high through season in U12-U14 players. Therefore, reliable methods of COD movement analysis for youth age groups are warranted. However, research on COD speed should not automatically be related to agility, because agility involves a coupled sensorimotor reaction to an external stimulus, and requires different monitoring strategies to quantify factors related to on-field performance (W. Young et al., 2021).

T-test, zigzag test, 5-0-5, arrowhead test and Illinois agility run are typical COD speed tests used in team sports (Altmann et al., 2019; Nimphius et al., 2018). The outcome variable used is the time to complete the test. Reliability of these types of tests is good, however there can be more variability in the results in younger age groups (Dugdale et al., 2020; Sporis et al., 2010). Other concerns relate to the degree to which the tests quantify soccer-specific performance and the validity to discriminate COD ability from speed, since linear speed has a major effect on finishing time, possibly masking the actual COD ability (Nimphius et al., 2016). In biomechanical analysis, COD ability has been evaluated using ground reaction forces (GRF), joint angles and speed using force plates, motion capture systems and timing-gates or lasers (Condello et al., 2016; Dos'Santos et al., 2021b; King et al., 2018).

Multi-dimensional approach for player development requires data collection methods that capture variables of the movement on specific timepoint that are relevant for the execution. IMUs have potential in measuring COD movement patterns during sport-specific movements and could provide more specific information about performance enhancement or injury risk. IMUs could be utilized to provide information about the quality of not only whole-body movements, but also

individual segments during a COD movement (Chambers et al., 2015). Previous studies have aimed to quantify running kinetics in soccer players and knee-kinematics during COD tasks in soccer players. These studies have concluded that the reliability of IMU derived measurements is poor and have not recommended IMU measures for kinematic analyses (Chia et al., 2021; T. Hughes et al., 2019; Zeng et al., 2022). However, the reliability of cumulative impact loading has been reported to be acceptable as well as workload measures across playing positions in soccer players (Burland et al., 2021; Nobari et al., 2022). In addition, the intra-unit reliability for evaluation of step-metrics in team-sport based tasks and concurrent validity for ball touches and releases in soccer have been reported to be acceptable (Armitage et al., 2021; Marris et al., 2022), suggesting the usefulness of IMU based measures in soccer specific tasks.

COD movement has been studied earlier using IMUs (Balloch et al., 2020; Nedergaard et al., 2014; Wundersitz, Gastin, et al., 2015). Used variables include peak accelerations (center of mass and segmental), resultant accelerations, COD counts, COD angles and estimated GRFs (Alanen et al., 2021). The reliability of measures of the movement – forces, mechanical load or acceleration - are inconsistent and more research is needed. In runners, tibial accelerations have been shown to be affected by technique, velocity and stiffness (Sheerin et al., 2019) and lower back accelerations have been used to define a stable individual running pattern (L. C. Benson, Ahamed, et al., 2019). Angular velocities measured from the trunk have also been used when studying turning while walking (Abdollahi et al., 2022; Khobkhun et al., 2020). However, these variables have not been used earlier together with speed measurements to explain individual differences in COD, during COD speed tests.

In soccer players, reliable individual COD speed measure with IMUs, could be used in studies assessing on-field performance and possibly provide information to fill the gaps about the

individual characteristics in agility. Therefore, the primary aim of this study was to assess the between-day reliability of soccer-specific COD test (including wall-pass and fast 180° pivot turn) measured with IMUs. Secondary aim was to compare differences in reliability between females and males.

### 3.3 Materials and Methods

#### 3.3.1 Participants

Thirty-seven (15 female, 22 male) elite-level youth soccer players from a local club in Calgary, Alberta completed both baseline testing sessions and were included in the analysis of this study. Baseline characteristics of the players are presented in Table 1. Playing years, playing position and limb-dominance were collected with a baseline questionnaire and participant height, body mass and sitting height (for the use of percentage of adult height) were measured before the testing session with portable measurement units (Seca GmbH, Seca 217 and Seca 437). To be eligible to participate, the participants needed to be injury free. Participants wore t-shirt and shorts and were barefoot for the weight and height measurements. The dates of the tests were scheduled for a week when none of the teams had games and the training schedule was easy. The study ethics were approved by the Conjoint Medical Ethics Committee (REB19-0428) and all participants signed a written mature minor consent prior to participation.

**Table 3.1** Baseline characteristics.

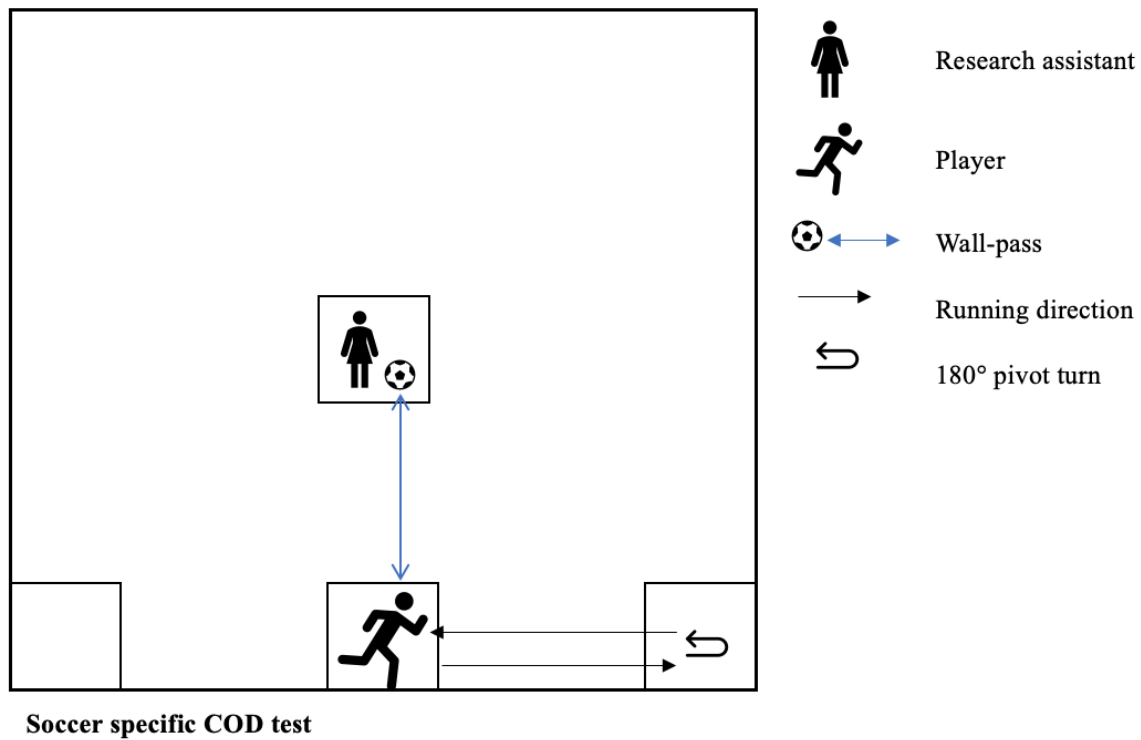
	<b>Female n = 15</b>	<b>Male n= 22</b>
Age (Mean, SD)	15.3 (0.6)	15.4 (0.6)
Height (cm) (Mean, SD)	162.6 (5.5)	169 (5.9)
Body Mass (kg) (Mean, SD)	56.7 (7.1)	58.5 (8.5)
% of adult height (Mean, SD)	98.54 (1.44)	96.23 (3)
<i>Playing position</i>		
Goalkeeper	0	1
Defender	6	5

Midfielder	4	8
Forward/winger	5	8
Years played (Mean, SD)	8.3 (2.3)	8.3 (2.6)
<i>Leg dominance</i>		
Left	2	2
Right	13	20

SD = Standard deviation, Cm = centimeters, Kg = kilograms

### 3.3.2 Testing protocol

The soccer-specific COD test that was used was initially presented by Pasanen et al. (Pasanen et al., 2015) in 2015. Participants performed the test on two consecutive days in October 2021 on a turf-field in an indoor-soccer facility. Participants arrived at the facility as teams and performed a standardized neuromuscular training warm-up before the testing session. After team warm-up, participants performed one practice run per side (left/right) to get familiarized with the running sequence. The test started with a wall pass (“give and go”) from a trained research assistant (RA), followed by a maximal effort COD trial including 180° pivot turn. The participants performed only one trial per side, to minimize the learning effects and have the participants perform as naturally as possible. Figures 1 and 2 show the sequence of the run and a player performing the test.



**Figure 3.1.** Map of the test, displaying left turning 180° pivot turn.



**Figure 3.2.** Change of direction test: Player making a left turning 180° pivot turn.

### 3.3.3 Data collection

Acceleration ( $m/s^2$ ) and angular velocity ( $rad/s$ ) were collected with wireless dual-g triaxial IMU devices (Vicon Blue Trident,  $\pm 16$  g, 1125 Hz,  $\pm 2000$  %/sec). The IMU was placed on participants lower back (L4 level) by RAs, who were trained by an experienced physiotherapist.

Vicon iCaptureU application was used to control the devices and for synchronized videorecording of the trials. Raw IMU data was downloaded after the session and stored for the analysis. Final foot contact of 180° pivot turn was identified from IMU data with the use of a specific Matlab (MathWorks Inc., Natick, MA, USA. Version R2022b) script and verified by comparing the obtained timepoint with the timepoints from iCaptureU videos of the trials. Peak resultant acceleration (PRA) and peak angular velocity (PAV) were calculated for all trials after filtering the raw data using 6<sup>th</sup> order Butterworth filter with cut-off frequency of 40 Hz. The cut-off frequency was based on Fast-Fourier analysis of the data and previous studies on using IMUs in COD analysis (Nedergaard et al., 2014).

#### 3.3.4 Statistical analysis

Statistical analysis was performed in R-studio (R-foundation, 2022.07.1). Intra-class correlation coefficient (ICC) was used to calculate the between-day reliability for peak resultant acceleration (PRA), peak angular velocity (PAV) during the pivoting phase (Figure 2) of the 180° pivot turn for both sides (left/right) and time to the turn (TT) and total time (TotalT) from initial ball touch to initial ground contact when player returned to the starting square. Two-way random effects ICC (ICC 2,1) was used and interpreted as: excellent  $\geq 0.9$ ; 0.9 > good  $\geq 0.8$ ; 0.8 > acceptable  $\geq 0.7$ ; 0.7 > questionable  $\geq 0.6$ ; 0.6 > poor  $\geq 0.5$ ; unacceptable < 0.5 (G. Atkinson & Nevill, 1998). Z-test was used to calculate if there was a statistically significant difference between the ICC values of females and males. Critical value for the Z-test was set at 1.96.

Limits of agreement was used as the method to describe absolute reliability as recommended by Atkinson and Nevill (G. Atkinson & Nevill, 1998) and associated Bland-Altman plots were used to show the schematical measurement error and visualize possible heteroscedasticity.

### 3.4 Results

Between-day reliability for both PRA and PAV were unacceptable ( $<0.5$ ) (Table 3.2). However, when females and males were analyzed separately (Table 3.3), the ICC for PRA was from poor to acceptable for females whereas the repeatability for PAV measurements was unacceptable. For males, PRA and PAV ICC's remained unacceptable. The reliability for both sides for the running time to the turn and the total time were from acceptable to good. When analyzing groups based on sex, the reliability of time to turn and total time were from acceptable to good for females and from poor to acceptable for males. The means of the measures between the two days were not different, suggesting that a learning-effect did not influence the results.

Running times were not correlated to acceleration or angular velocity regardless of turn side or sex, suggesting that peak acceleration or angular velocity per se are not enough to quantify individual performance during COD. Based on the Bland-Altman plots (Figure 3.1), slight heteroscedasticity was suspected and based on correlation between absolute differences and individual means, PAV (both sides) and TT (left) proved to be heteroscedastic. Due to this the limits of agreement were presented additionally as ratios, as suggested by Atkinson and Nevill (G. Atkinson & Nevill, 1998). Limits of agreement show that the expected difference between test-retest for both PRA and PAV were large (approximately  $\pm 65 \text{ m/s}^2$  for PRA and  $\pm 350 \text{ rads/s}$  for PAV) (Table 3.2), which explains the unacceptable ICC values and underlines the high within-subject variability of these metrics between days.

The ICC values for both PRA and PAV for females were significantly different (Z-score  $>1.96$ ) from the ICC values of males, whereas the speed related ICCs were similar between the sexes (Table 3.3).

**Table 3.2.** Reliability statistics for PRA, PAV, Time to turn and total time (left/right).

	Mean	SD	Limits of Agreement	LoA (%)	ICC (2,1)	95% CI
PRA right (m/s <sup>2</sup> )	86.7	27.7	-64-64.5	74.1	0.24	-0.31-0.56
PRA left (m/s <sup>2</sup> )	82.1	23.8	-51.6-69.1	73.7	0.49	0.114-0.7
PAV right (rad/s)	211.8	130.5	-308.4-345.2	153.7	0.33	-0.168-0.62
PAV left (rad/s)	-260	165.8	-524.3-362.1	170.4	0.045	-0.67-0.45
Time to 180° left (s)	2.91	0.19	-0.21-0.33	17.5	0.77	0.61-0.87
Time to 180° right (s)	2.94	0.21	-0.29-0.19	15.3	0.83	0.7-0.9
Total time left (s)	1.54	0.16	-0.22-0.4	10.7	0.78	0.62-0.87
Total time right (s)	1.56	0.16	-0.44-0.29	12.5	0.74	0.55-0.85

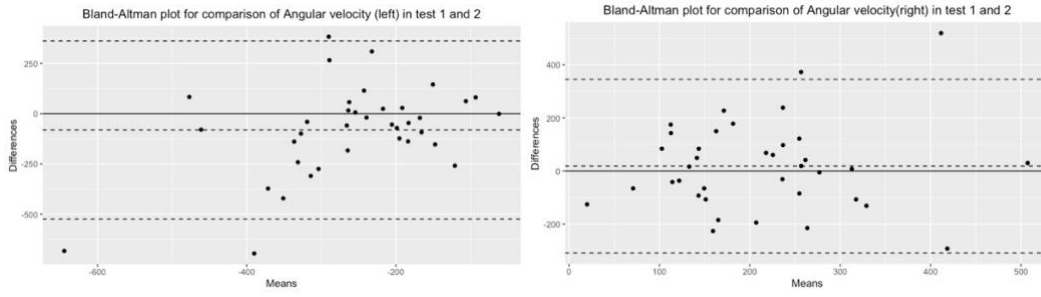
PRA = Peak Resultant Acceleration, PAV=Peak Angular Velocity, SD=Standard deviation, ICC=Intra-Class Correlation, CI=Confidence Interval

**Table 3.3.** Differences between males and females on between-day ICC values. Z-score significance level set at > 1.96.

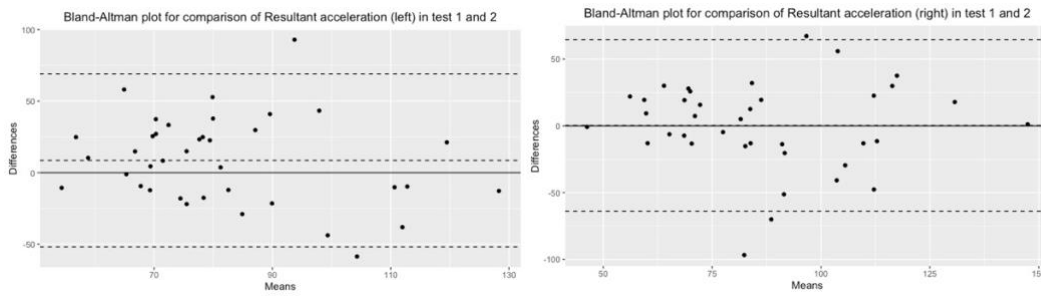
Variables	Between-day ICC		
	Females	Males	Z-score
PRA right	0.78	0.18	4.26
PRA left	0.52	0.0	3.71
PAV right	0.38	0.158	3.17
PAV left	0.47	0.0	6.71
Time to 180° right	0.85	0.73	0.67
Time to 180° left	0.77	0.73	0.31
Total time right	0.79	0.57	1.05
Total time left	0.69	0.74	0.26

ICC=Intra-Class Correlation, PRA = Peak Resultant Acceleration, PAV=Peak Angular Velocity

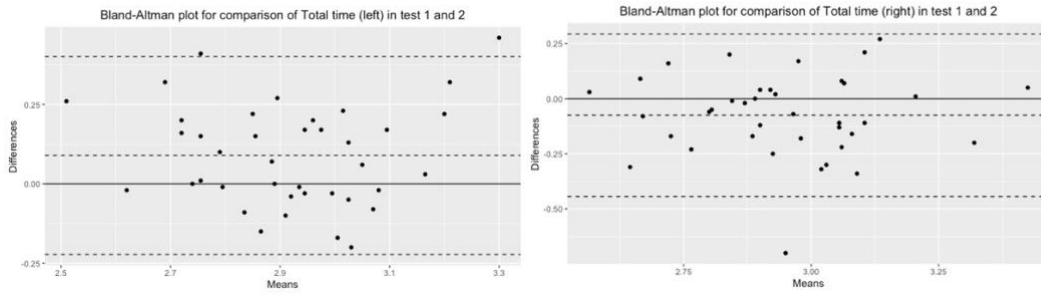
A)



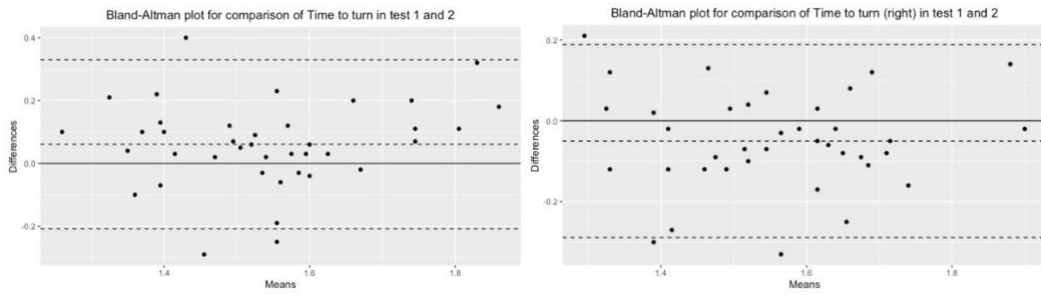
B)



C)



D)



**Figure 3.3.** Bland-Altman plots for A) Peak Angular Velocity B) Peak Resultant Acceleration C) Total time and D) Time to turn, with limits of agreement (LoA).

### 3.5 Discussion

This study determined the between-day reliability of IMU measured peak resultant acceleration (PRA), peak angular velocity (PAV), time to the turn (TT) and total time (TotalT) during a 180° pivot turn in a soccer-specific COD test. PRA and PAV showed unacceptable reliability regardless of the turning side (left/right), whereas TT and TotalT achieved acceptable to good reliability. In addition, females and males did not have comparable reliability for PRA and PAV, indicating that females tended to have better repeatability for these specific variables regardless of turning side. These results imply that PRA and PAV would not reproduce reliable results for COD tests for youth soccer-players, but timing different phases of the trial could be used for player evaluation. Monitored sex-related differences call for further studies on the phenomena and inclusion of other IMU captured variables to the analysis.

Previous studies analyzing the reliability of IMU metrics have mostly concentrated on manufacturer provided metrics, like IMU step metric or impact load (Armitage, 2021.; Burland et al., 2021), showing acceptable reliability. However, COD related reliability studies are more often laboratory based and due to inconclusive results the recommendations for metrics are lacking (Alanen et al., 2021). There are more studies published using IMUs for analysis while running, which also have been reported to be far away from real-world conditions (L. C. Benson et al., 2022). Research has shown that for running, approximately 4-5 days of data-collection with IMUs is necessary to define a stable running pattern (Ahamed et al., 2019; L. C. Benson, Ahamed, et al., 2019). The unacceptable reliability found in our results could be related to not having enough trials per individual. The biomechanical execution of 180° pivot cut is more complex than running and for the purpose of this study players only did trials on two consecutive days. Movement variability has also been seen in studies looking at jump-landings, suggesting day-to-day variability in high-

energy movements (Bishop et al., 2020, Mar 1). However, lower back measured PRAs for drop-landing and rebound jumps have shown moderate to good reliability in previous studies (Simons & Bradshaw, 2016).

Between-day reliability of running times related to 180° pivot cut were acceptable or good. Similar results have been seen when analyzing the reliability of other COD tests including 180° pivot turns (Ryan et al., 2022). This is an important result for this study as well, as it shows that although the players finished the task in same speed, the way of performing the actual pivot turn varied based on PRA and PAV values. To understand this variability and how it is possibly related to biomechanical factors during the COD movement, would be the goal for future studies. In this study, the skeletal maturity was assessed by measuring sitting height and calculating the percentage of adult height (Table 1). An individual is generally considered to have passed their peak height velocity (PHV) once they reach 97% of their adult height (Malina et al., 2019). Female players mean of percentage of adult height was over 98% (SD=1.44), but for males the mean was under 96% (SD=3), indicating that several male players were still in PHV stage. Less mature individuals have been shown to have greater differences in performance between testing and training sessions (Dugdale et al., 2020), which could explain the differences that were seen in the reliability values between males and females in our study. In addition, this would further suggest that caution should be used when evaluating maturing athletes and especially comparing athletes in different maturational stages with each other.

This was the first study to report between-day reliability for peak resultant acceleration, peak angular velocity, time to reach the turn and total time during a soccer-specific 180° pivot cut. Based on these results, PRA or PAV can't be recommended to be used as individual factors of COD repeatability. However, these metrics might prove useful in combination with other

variables, especially when trying to explain differences between males and females and changes throughout the maturational status.

### **3.6 Conclusion**

The between-session reliability of acceleration and angular velocity related variables was unacceptable, whereas speed related variables showed acceptable to good reliability. In addition, female soccer players showed better reliability in acceleration and angular velocity related variables than males. Based on these results, COD speed in different stages of a soccer-specific test is a reliable method to discriminate between athletes. Acceleration and angular velocity related variables need to be combined with other variables to possibly provide more information in the future, related to differences between athletes, regarding sex and maturational status.

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### **Disclosure statement**

The authors have no potential conflict of interest to report.

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### **3.7 Bridge to Chapter Four**

The aim of Chapter Three was to evaluate the test-retest reliability of peak resultant acceleration, peak angular velocity and running times during a soccer-specific COD test. These variables have been used before in sport- or movement specific testing with varying results (Abdollahi et al., 2022; Balloch et al., 2020; Sheerin et al., 2019). Based on the results, IMU derived metrics are not a reliable method to evaluate individual movement between days, even though running speed showed acceptable to good reliability.

In Chapter Three, males and females were analyzed separately which indicated better reliability of IMU measures for the females. Sex or growth-related factors can have a major effect on movement patterns, increasing between-day variability. Another intrinsic factor related to movement pattern changes and major risk factor for injuries, is previous injury status. Previous injuries affect motor control and may lead to changed biomechanics during multidimensional movements, like COD. In addition, previous studies on other tests challenging motor control have reported increased variability between tests when followed up for a longer period. Therefore test-retest reliability might not be the most informative way of describing complex movement patterns, but following these variables within-season and understanding how and why they may change due to intrinsic or extrinsic risk factors.

**Chapter Four: Capturing In-season Change of Direction Movement Pattern Change in Youth Soccer Players with Inertial Measurement Units**

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<https://doi.org/10.3390/biomechanics3010014>

## 4.1 Abstract

This study aimed to examine the utility of inertial measurement unit (IMU) technology to identify angle, step-specific, and side-specific differences between youth soccer players with and without a history of lower limb injury during soccer-specific field tests. Thirty-two youths (mean age 16.4 years) who were elite soccer players (Females  $n = 13$ , Males  $n = 19$ ) wore IMUs during pre- and postseason soccer-specific change-of-direction assessments. A response feature analysis was used to compare the change in peak resultant acceleration of the groups at a level of significance of  $p < 0.05$ . Statistical analysis revealed significant differences in change of peak resultant acceleration of right leg final foot contact in a  $180^\circ$  pivot turn ( $p = 0.012$ ,  $ES = 1.0$ ) and a  $90^\circ$  cut ( $p = 0.04$ ,  $ES = 0.75$ ) between the two groups. These data suggest that players with a history of lower limb injury might experience greater angle and side-specific change within a season in peak resultant acceleration when compared with injury-free athletes. This study demonstrates that IMUs may present a useful method to analyze youth soccer players' change of direction movement after returning to play. These results can inform future studies investigating player monitoring and may prove to be a useful tool for coaches when designing individualized training programs in this population.

**Keywords:** Change of direction movement; Inertial measurement unit; Youth soccer; Injury

## 4.2 Introduction

Soccer is an evasion sport that requires a multitude of physical performance capacities and soccer-specific skills (Bloomfield, Polman, & Donoghue, 2007; T. Reilly et al., 2000). In evasion sports, the perception–reaction coupling is a determinant of successful attacking and defending, which includes multiple fast change-of-direction (COD) maneuvers. COD ability discriminates between elite and subelite players in soccer (T. Reilly et al., 2000). During a soccer game, players perform approximately 700 turns and swerves of up to 360° (Bloomfield, Polman, & Donoghue, 2007). Most of the COD movements during a game are under 90° (Bloomfield, Polman, & Donoghue, 2007), however, sharper COD angles increase joint loading (Cortes et al., 2011; Havens & Sigward, 2015) and deceleration and reacceleration requirements (Hader et al., 2015; Havens & Sigward, 2015). In relation to increased loading of tissues, COD movements are associated with lower limb injuries in youth and adult soccer (Della Villa et al., 2020; Kristianslund et al., 2014; Light et al., 2021; Serner et al., 2015). For example, anterior cruciate ligament (ACL) injuries typically occur in noncontact pressing and COD situations (Della Villa et al., 2020). In youth players, the highest incidence rates for soccer-related injuries have been reported in the U15 and U18 groups (Read, Oliver, De Ste Croix, et al., 2018). After an injury, the decision of readiness to return to sport (RTS) is complex and related to multiple factors. On-field monitoring methods of COD movement have been recommended to be incorporated into standard RTS criteria (Ardern et al., 2016). However, there is no current consensus on which methods would be recommended for long-term follow up of neuromuscular control or function (Barber-Westin & Noyes, 2011).

Faster COD performance has been linked to greater horizontal and vertical braking forces during the final foot contact (FFC) (Spiteri et al., 2013, 2015). Previous studies have also underlined the importance of penultimate foot contact (PFC – the preparatory step before final foot

contact) in COD for both injury prevention and performance (Dos'Santos et al., 2017; Jones et al., 2016). A greater proportion of braking force applied during PFC is related to faster CODs. Average horizontal ground reaction forces during PFC are significantly related to peak knee abduction moments during FFC. Quantifying lower body interlimb differences in accelerations during PFC and FFC associated with acute angle CODs may provide important information about injury risk. These differences have not been fully investigated in the scientific literature. Previous studies have shown that greater landing force asymmetry in jump tests is associated with an increased risk of lower extremity injuries in youth male soccer players (Read, Oliver, & Lloyd, 2018). In addition, previously injured professional soccer players have significant asymmetries in vertical ground reaction forces (GRF) in both concentric and eccentric phases of countermovement jumping, despite being cleared to RTS (Hart et al., 2019).

Inertial measurement units (IMUs) permit player monitoring on the field of play in game and practice situations. IMUs may provide information based on differences in accelerations related to asymmetries and individual differences during PFC and FFC in COD. Previous studies in running have found tibial accelerations to be a valid proxy for GRF during running (C. D. Johnson et al., 2021; McLean et al., 2011; Sheerin et al., 2019). These studies have looked at horizontal, vertical, and anteroposterior accelerations, however, earlier findings by Lafortune and Hennig (Lafortune & Hennig, 1991) suggest that to accurately quantify the magnitude of tibial acceleration, it would be important to measure all three planes. Peak resultant acceleration (PRA) has been used as a metric in running studies as a surrogate measure for impact loading with moderate to good reliability (Sheerin et al., 2018). IMUs have been used to evaluate COD movement in team sports, however, consensus on sensor placement and appropriate metrics is lacking (Alanen et al., 2021). The variability of these measures on an individual or group level

throughout the season or differences between previously injured and non-injured players in youth soccer has not been studied. Nevertheless, this is an important first step for identifying relevant COD parameters that can be measured with IMU technology. IMU sensor placement is also a key consideration for monitoring COD maneuvers. For example, active (e.g., eccentric muscle action) and passive (e.g., connective tissue, bone, and ligament) musculoskeletal attenuation can decrease or increase the magnitude of the impact (W. B. Edwards et al., 2012; Tamura et al., 2016). This highlights the potential relationship between sensor placement and outcome measures aimed at improving performance, identifying risk for lower limb injury, and monitoring return to sport readiness after injury (W. B. Edwards et al., 2012; Tamura et al., 2017). Shin-level measurements might be expected to reflect impact loading most accurately, whereas the relationship with angle-, side, and step-specific differences are unknown.

Therefore, the purpose of this study was to examine the change in PRA measures in a COD test for PFC and FFC in previously injured and non-injured youth female and male soccer players over the course of a soccer season. The primary aim was to evaluate the change of PRA, measured from shin level, within a season in similar test-retest settings to evaluate if there were significant differences between previously injured and non-injured players. Our hypothesis was that previously injured players would experience higher accelerations in cutting movements when compared with non-injured players. Testing this hypothesis of practical significance in that monitoring peak acceleration values throughout the season with IMUs could prove useful for continuous player evaluation, especially after RTS from a lower extremity injury. Coaches could use this information for determining the need for individualized training and rehabilitation.

## 4.3 Materials and Methods

### 4.3.1 Participants

A convenience sample of two male and two female Tier 1 (top-level) U15-U17 soccer teams from a member club of the Calgary Minor Soccer Association (CMSA) were recruited for this study. These players have soccer training approximately 3 times per week with 1–2 additional strength and conditioning sessions weekly during indoor and outdoor seasons. A total of 32 players ( $n = 13$  females,  $n = 19$  males) finished both inseason and postseason COD tests and were included in the analysis. Players who did not consent, were currently injured, or did not perform either of the tests were excluded. Player age, playing years, position, and previous lower limb injuries (within 12 months from baseline testing) were collected with a questionnaire. Participant height (cm) was measured using a portable height measurement unit (Seca GmbH, Seca 217, Hamburg, Germany) and body mass (kg) was measured using a portable standard electronic scale (Seca GmbH, Seca 437, Hamburg, Germany). Height and body mass measurements were completed barefoot and wearing a t-shirt and shorts. Participant baseline characteristics are presented in Table 1. The study took place at the club’s training facilities in Calgary, Alberta, Canada. The study ethics were approved by the Conjoint Medical Ethics Committee (REB19-0428) and all participants signed a written mature minor consent form prior to participation.

**Table 4.1.** Baseline characteristics.

	<b>Female n =13</b>	<b>Male n=19</b>
Mean age (SD)	16.5 years (0.7)	16.2 years (0.7)
Mean height (SD)	166.0 cm (6.6)	182.7 cm (11.2)
Mean body mass (SD)	59 kg (6)	66 kg (6)
<i>Playing position</i>		
Goalkeeper	0	2
Defender	5	6
Midfielder	4	4
Forward	4	7

Years played (Mean)	8.7	10.6
<i>Leg dominance</i>		
Left	0	4 (injured=1, non-injured=3)
Right	13 (injured =7, non-injured=6)	15 (injured=9, non-injured=6)
<i>Previous injury</i> <sup>1</sup>		
Acute injury	6 (knee=1, ankle=3, thigh=2)	9 (groin=3, ankle=4, thigh=2)
Overuse injury	1 (knee=1)	1 (knee=1)
No injuries	6	9

<sup>1</sup> Lower limb, within 12 months

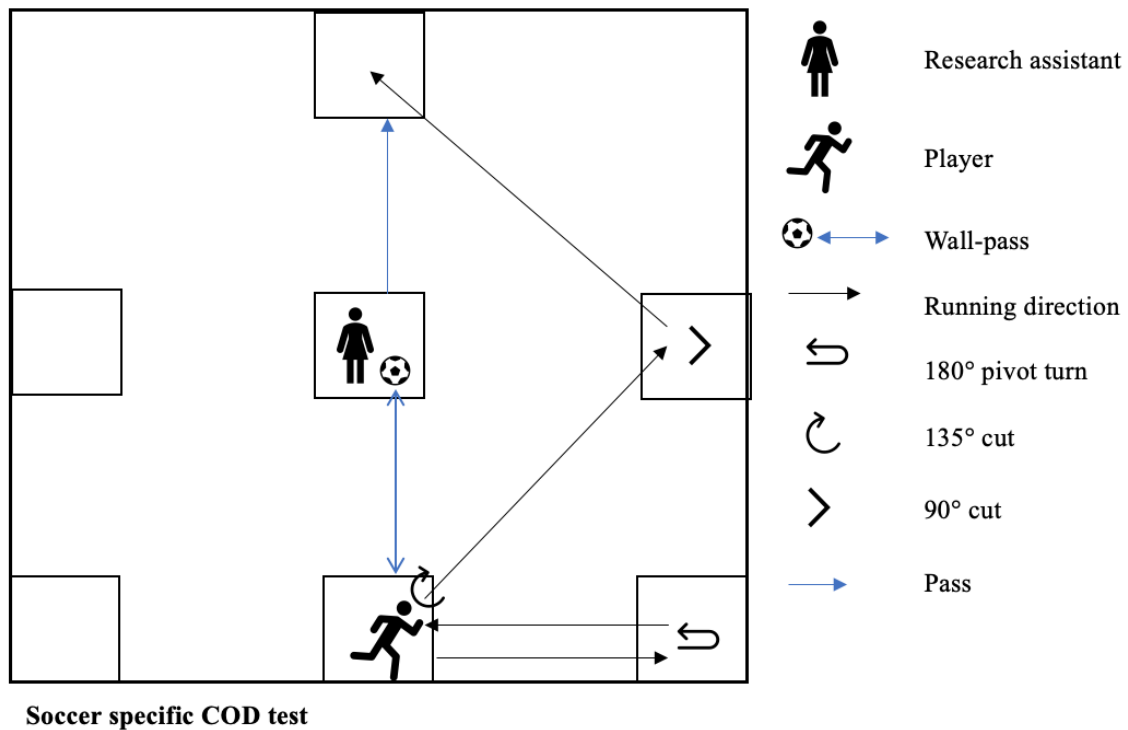
#### 4.3.2 Testing protocol

Players performed a soccer-specific COD test (Pasanen et al., 2015), twice at the club's indoor training facility. Players wore t-shirts, shorts, and soccer cleats, and tests were performed in the afternoon before the regular training session. Players followed their team's normal training schedule (soccer practice 3 times/week, strength and conditioning 1 time/week) before and after the testing sessions. Intense sessions were not scheduled prior to testing sessions. Outdoor soccer season runs from May until October and Test 1 was performed in July 2019 (inseason) and Test 2 in October 2019 (postseason). Two bidirectional maximal effort COD trials were performed at three consecutive cut angles (180° pivot turn, 135° cut, and 90° cut) (Figures 1 and 2). Before the test, players performed a supervised and structured general warmup protocol (5 min running drills including hopping and change of direction movements), led by a research assistant. Players then performed the test first at jogging speed to perform a test-specific warmup and for protocol familiarization. Players did not receive specific instructions about technical execution, in order to run and cut as naturally as possible. After the trial run, players were verbally instructed to complete the test as fast as possible. Each trial was initiated by the player performing a one-touch pass back to the research assistant (Figure 2) and was terminated by receiving a pass (Figure 2) to attempt to simulate the urgency experienced in gameplay.



**Figure 4.1.** Change of direction test: Player making a left turning 180° pivot turn (PFC – left leg, FFC right leg).

Tests that were performed incorrectly (i.e., not stepping into one of the designated cone areas when performing a COD movement) were discarded and repeated. Data were collected by research assistants who had soccer backgrounds and were trained to evaluate the tests by the experienced principal investigator. Values from the successful trials for both directions (i.e., left and right) were used in the analysis. Players needed to complete one successful trial and the trial order (left or right side first) was randomized. The penultimate foot ground contact (PFC) was defined as the last step before the step that initiates the COD (inside leg during the turn). Final foot ground contact (FFC) was defined as the step initiating the COD (outside leg during the turn) (Green et al., 2011; Havens & Sigward, 2015b; Spiteri et al., 2013).



**Figure 4.2.** Map of the test, displaying cuts on the right side.

#### 4.3.3 Accelerometer data

Wireless triaxial IMU devices (Shimmer 3 IMU ( $\pm 16$  g)), Shimmer Sensing, Dublin, Ireland) were used to collect the data with a sampling frequency of 200 Hz (IMU mass = 23.6 g). Each player had an IMU positioned on both of their shins with elastic straps, on top of the lower third of the tibia. The IMUs were placed by research assistants who were trained for the task by the lead investigator. The devices were calibrated prior to each test by turning each sensing axis 180°, based on manufacturer recommendations ([shimmersensing.com/product/shimmer-9dof-calibration/](http://shimmersensing.com/product/shimmer-9dof-calibration/)).

#### 4.3.4 Injury data

Players reported information about previous injuries in the prebaseline questionnaire. Injuries were reported based on the anatomical location, severity, type, and time of injury. In case

of missing or inadequate information, the players were contacted by phone by a research assistant, to ensure data accuracy. Only the injuries that had happened within 12 months before the baseline testing were included. If the players had more than one lower limb injury in this period, the most recent one was used in this analysis (Table 1). Four players reported left leg dominance (kicking) leg and only one injury was reported for the left leg. Due to the fact that most players were right-leg dominant, and to simplify the interpretation of the analysis, it was decided to compare left and right legs and disregard the leg dominance.

#### 4.3.5 Data processing

All trials were video recorded with a 4K camera (Sony, FDR-AX53, 120fps) that was set on a tripod, 5 m behind the setting. The videos were downloaded into the Dartfish video-analysis tool (Dartfish Live S) and tagged for start and stop of PFC and FFC for all angles (180°, 135°, and 90°). The tagging was done by two independent reviewers, who had previous experience with video analysis. To identify touch down and toe off, zooming was used. The tagged video was synchronized with IMU data using a custom script in MATLAB (Version R2011b, MathWorks Inc., Natick, MA, USA).

The start and end of both PFC and FFC were tagged for each limb and each COD angle. The start of the step was defined as the video frame when the foot touched the ground and ended at the video frame when the foot left the ground. Accelerometer data were filtered with a 60 Hz cut-off frequency using a fourth-order Butterworth low-pass filter in MATLAB (Version R2011b, MathWorks Inc., Natick, Massachusetts, USA). The cut-off frequency was chosen based on Fast Fourier analysis, which showed that 99% of signal power was retained below 60 Hz. Peak resultant acceleration for PFC and FFC were extracted and used for analysis.

#### 4.3.6 Statistical analysis

The normal distribution of peak resultant acceleration values was determined with a Shapiro–Wilk’s test, which confirmed the normality of the PRA values. Response feature analysis (Everitt, n.d., 1995) was used to compare the change of peak resultant acceleration in the two tests between the previously injured and non-injured groups. For the response feature analysis, the change in PRA for each participant in each cut and step was calculated and Welch’s t-test was used to compare the mean change of PRA between the injured and non-injured groups. The significance level was set at  $p < 0.05$ . Standardized effect sizes (Cohen’s  $d$ ) were calculated and interpreted as trivial ( $d \leq 0.20$ ), small ( $0.20 \leq d \leq 0.60$ ), moderate ( $0.61 \leq d \leq 1.20$ ), large ( $1.21 \leq d \leq 2.0$ ), very large ( $2.01 \leq d \leq 4.0$ ), or near perfect ( $d \geq 4.0$ ). Tables 2 and 3 include the adjusted  $p$ -values (Bonferroni correction) for multiple comparisons. The PRA data is shown in Table 3. R-software (R-foundation) was used for statistical analysis. All R-packages that were used for data analysis are presented in Appendix A.

**Table 4.2.** Response feature analysis (mean changes) for peak resultant acceleration in all steps.

	Injured, N = 17 <sup>1</sup>	Non-injured, N = 15 <sup>1</sup>	Cohen’s D	95% CI <sup>2</sup>	$p$ -Value <sup>3</sup>	Adjusted $p$ - Value <sup>4</sup>
180° Pivot Turns	Mean Change between the Tests (m/s <sup>2</sup> )					
FFC right leg	33 (36)	−6 (43)	1.0	0.23, 1.7	0.012*	0.14
PFC right leg	1 (65)	3 (80)	−0.02	−0.72, 0.67	>0.9	>0.9
FFC left leg	3 (36)	10 (70)	−0.13	−0.82, 0.57	0.7	>0.9
PFC left leg	14 (53)	−9 (49)	0.44	−0.26, 1.1	0.2	>0.9
135° cuts						
FFC right leg	16 (41)	10 (71)	0.10	−0.60, 0.79	0.8	>0.9
PFC right leg	7 (64)	−2 (96)	0.11	−0.58, 0.81	0.8	>0.9
FFC left leg	1 (54)	8 (30)	−0.17	−0.86, 0.53	0.6	>0.9
PFC left leg	−1 (51)	−8 (56)	0.14	−0.56, 0.83	0.7	>0.9
90° cuts						
FFC right leg	20 (60)	−17 (35)	0.75	0.02, 1.5	0.039 *	0.5
PFC right leg	20 (56)	0 (86)	0.28	−0.42, 1.0	0.4	>0.9
FFC left leg	18 (80)	19 (43)	−0.01	−0.70, 0.69	>0.9	>0.9

PFC left leg	5 (65)	0 (50)	0.08	-0.61, 0.78	0.8	>0.9
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\* Statistically significant; <sup>1</sup> Mean (SD); <sup>2</sup> CI = Confidence Interval for Cohen's *d*; <sup>3</sup> Welch's Two Sample *t*-test; <sup>4</sup> Bonferroni correction for multiple testing.

**Table 4.3.** Comparison of injured and non-injured leg peak resultant acceleration (m/s<sup>2</sup>) differences in the previously injured group.

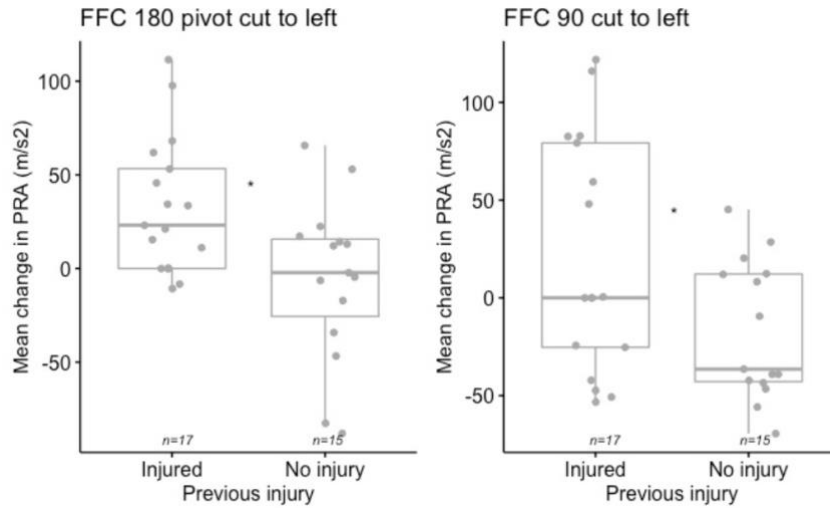
COD	Test 1						Test 2					
			PRA (m/s <sup>2</sup> )						PRA (m/s <sup>2</sup> )			
	Injured Leg, N = 17 <sup>1</sup>	Non-injured Leg, N = 17 <sup>1</sup>	Cohen's <i>d</i> <sup>2</sup>	95% CI <sup>2,3</sup>	<i>p</i> -Value <sup>4</sup>	Adjusted <i>p</i> -Value <sup>5</sup>	Injured Leg, N = 17 <sup>1</sup>	Non-injured Leg, N = 17 <sup>1</sup>	Cohen's <i>d</i> <sup>2</sup>	95% CI <sup>2,3</sup>	<i>p</i> -Value <sup>4</sup>	Adjusted <i>p</i> -Value <sup>5</sup>
FFC180	178 (48)	158 (52)	0.39	-0.29, 1.1	0.3	>0.9	145 (47)	154 (49)	-0.18	-0.85, 0.50	0.6	>0.9
PFC180	156 (53)	180 (61)	-0.43	-1.1, 0.25	0.2	>0.9	159 (43)	162 (37)	-0.10	-0.77, 0.58	0.8	>0.9
FFC135	164 (51)	159 (58)	0.09	-0.58, 0.77	0.8	>0.9	151 (38)	156 (43)	-0.14	-0.81, 0.54	0.7	>0.9
PFC135	136 (49)	163 (58)	-0.52	-1.2, 0.17	0.14	0.9	140 (45)	152 (44)	-0.29	-1.0, 0.39	0.4	>0.9
FFC90	178 (63)	186 (63)	-0.13	-0.81, 0.54	0.7	>0.9	156 (37)	170 (46)	-0.33	-1.0, 0.35	0.3	>0.9
PFC90	173 (64)	183 (61)	-0.16	-0.83, 0.52	0.7	>0.9	157 (46)	175 (37)	-0.43	-1.1, 0.25	0.2	>0.9

<sup>1</sup> Mean (SD); <sup>2</sup> CI = Confidence Interval for Cohen's *d*; <sup>3</sup> Welch's Two Sample *t*-test; <sup>4</sup> Bonferroni correction for multiple testing.

#### 4.4 Results

The mean change in peak resultant acceleration between the two tests for previously injured and noninjured groups showed a statistically significant difference ( $p < 0.05$ ) in FFC 180° and FF C90° when turning left (right foot as final contact foot) with moderate effect sizes of 1.0 and 0.75 (Table 2, Figure 3).

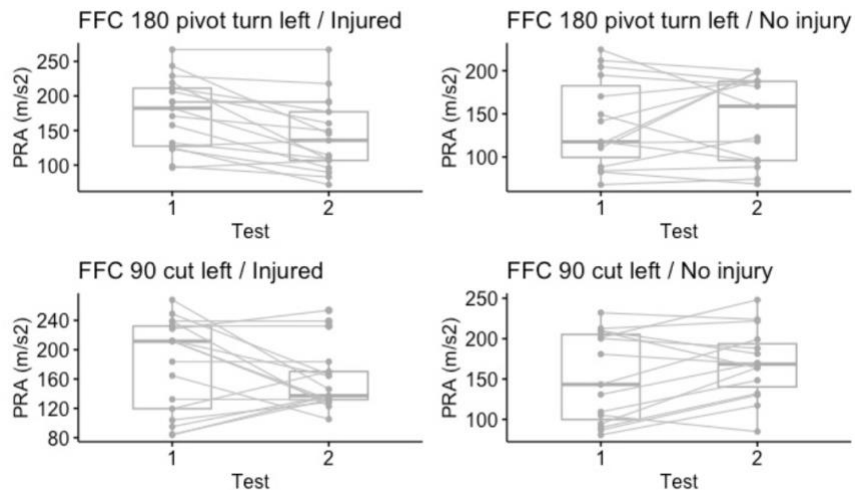
Positive mean change (m/s<sup>2</sup>) indicates that the peak resultant accelerations in the second test were lower. For the other angles or steps, there were no statistically significant differences ( $p > 0.05$ ), and the effect sizes were from small to trivial ( $\leq 0.5$ ).



**Figure 4.3.** Boxplots of differences in peak resultant acceleration (PRA) change between previously injured and non-injured groups for the final foot contact (FFC) in 180°- and 90°- degree left change of direction (COD) maneuvers.

When considering comparisons between injured and non-injured legs, within the previously injured group, no statistical differences between the injured limb and non-injured limb were found ( $p > 0.05$ ). (Table 3).

In addition, notable inseason variation in peak resultant acceleration ( $m/s^2$ ) was visible for both the injured and the non-injured groups between the two tests, with standard deviations between 50–100  $m/s^2$  (Table 3, Figure 4).



**Figure 4.4.** Boxplots showing the individual change of the peak resultant acceleration (PRA) (m/s<sup>2</sup>) for the final foot contact (FFC) in 180° pivot turns and 90° cuts between Test 1 and Test 2.

## 4.5 Discussion

Altered biomechanics are known to be associated with higher injury risks. To the authors' knowledge, this is the first study to assess changes of the side-, angle- and step-specific peak resultant accelerations during change of direction movements. The primary aim of this study was to evaluate within-season change in tibial peak-resultant accelerations during COD tests in previously injured and noninjured players. Substantial inseason variation in peak resultant acceleration between the two timepoints was observed using IMU sensors during PFC and FFC in the COD movements. The injured group seemed to have a greater change in peak resultant accelerations between the tests when performing a 180° pivot cut to the left. In the left turning 90° cut there was also a statistically significant difference between the groups, however, during this COD, the injury-free group had higher peak resultant accelerations in the second test and the previously injured group slightly lower. Additionally, high within-subject variation was observed between test one and test two.

IMU assessments without the orientation of the device have been used to monitor peak resultant accelerations outside laboratory conditions in previous studies (Wundersitz, Gastin, et al., 2015). Giandolini et al. (Giandolini et al., 2015) concluded that speed and terrain increased the variability of peak resultant acceleration values considerably, and in a study by Simons et al. (Simons & Bradshaw, 2016) intraday variability of peak resultant acceleration was good but interday (one week apart) was moderate to good in hopping, drop landings, and rebound jumps. The results of our study show variability in the individual peak resultant acceleration between the two tests. Similar results have been reported also in previous studies examining jumping and landing movements (Bishop et al., 2020; Read et al., 2016). Jump-landing tasks are commonly used to evaluate return-to-play readiness. In the study by Hanzlikova et al. (Hanzlíková et al.,

2021), the authors concluded that rotated jump landing tasks were more closely related to cutting kinematics and more proper to use when identifying risky movement patterns. As cutting is a more complex movement than jumping and landing, the high within-subject variation reflected in our data is not surprising.

Previous studies (Bishop et al., 2020; Grindem et al., 2016) have shown that asymmetries are task and variable specific and tend to change when measured several times during the season. The results of our study suggest that there might be differences between previously injured and non-injured players in tibial peak resultant acceleration while executing cutting movements, especially for 180° pivot turn and 90° cut during final foot contact when turning left. All but one of the players had a previous injury to their right limb, which could explain why only left turning cuts (right foot as outside leg during the cut) were different. COD ability is commonly tested in soccer with agility tests that evaluate the time to complete a specific task, including varying numbers (from 2 to over 10) and varying angles of CODs (Brughelli et al., 2008). One hundred and eighty degree and 90° cutting angles are commonly used in COD testing protocols (Brughelli et al., 2008) and running drills, which could easily be complemented with IMUs. In order to evaluate if peak resultant acceleration could be used to determine the individual baseline, future studies should follow the variability more frequently, for example throughout the season. In addition, injury patterns and risks vary depending on the adolescent growth spurt (Materne et al., 2021; van der Sluis et al., 2013), underlining the importance of continuous movement pattern follow up and research for this age group.

Injured players had consistently higher mean peak resultant acceleration values in both tests which is also in line with the previous literature (McLean et al., 2011). In addition, when looking at the injured limb vs. non-injured limb in the injured group, the peak resultant

accelerations for FFC during sharper CODs (180° and 135°) were higher in the first test. Altered biomechanics, such as more flexed positions in the knee and hip, in the injured limb, can increase the ground impact resulting in higher peak resultant acceleration values (H. Kim et al., 2019). This was supported by our findings on higher peak resultant acceleration values in the injured group and higher peak resultant acceleration values in the injured limb within the injured group. Based on our findings, peak resultant accelerations measured with IMUs could provide a feasible method to screen within-season changes in injured players during rehabilitation and provide useful information to evaluate return to sport readiness. However, this would require reliable measures for “normal” baseline values of peak resultant acceleration. Until the reliability of this test is more thoroughly assessed longitudinally, the usefulness of this method for routine athlete monitoring in soccer players remains unclear. In addition, more injury-specific research is warranted. The injured group in our study had several different types of lower limb injuries with varying times of injury.

There were several limitations to our study. First, biological maturation was not assessed, which may have a profound influence on the agility performance of adolescent soccer players. Further, it is possible that biological maturation may have changed between the two testing sessions. There was an increase in physical test performance due to maturation around peak height velocity in adolescent athletes—especially when looking at consistent acceleration, deceleration, and COD ability. Additionally, the approach speed was not known and since COD ability is both angle and approach velocity dependent (Dugdale et al., 2020), this information could be crucial when comparing in-season differences. The players were instructed to run as fast as possible, though the running speed was not objectively controlled between the two testing sessions. This would not explain the differences between injured and noninjured groups but would most likely explain the substantial individual variability. Variation between and within subjects in approach

velocity would affect also peak resultant accelerations. A larger sample size, and especially a more homogeneous group of injured players, would be recommended for future studies. The testing protocol used in this study is also lacking perception and decision-making factors; the comparison of differences in injured and non-injured players' peak resultant acceleration values should be monitored in game-like situations. Finally, there are several variables that can cause a change in results measured two months apart. Therefore, a reliability analysis of this testing method should be conducted with a shorter time between testing dates, to be able to reliably recommend a similar approach in the future.

#### **4.6 Conclusions**

IMU-measured tibial peak resultant accelerations revealed large between- and within-individual variability between soccer-specific COD tests during the season. This can be affected by several factors that were not controlled in this study, such as training and growth status. However, there seem to be differences between previously injured and non-injured groups, which are angle- and side-specific. Against our hypothesis, players in the injured group exhibited decreased peak resultant acceleration values between the tests in FFC for the previously injured leg in the 180° pivot turn condition. For the 90° cut, the non-injured group exhibited increased values in the second test. COD tests complemented with IMUs could provide a time-efficient tool for practitioners to screen large player groups throughout the season and guide recommendations for individualized training.

**Author Contributions:** Conceptualization, AMA, LCB, MJJ, RF, and KP; methodology, AMA, LCB, MJJ, RF and KP.; software, LCB and OLB; validation, AMA, LCB, and OLB; formal analysis, AMA, LCB and OLB; investigation, AMA, LCB, MC and CVDB; resources, RF and KP; data curation, CVDB and MC.; writing—original draft preparation, AMA.; writing—review

and editing, AMA and KP; visualization, AMA; supervision, KP; project administration, KP.; funding acquisition, KP. All authors have read and agreed to the published version of the manuscript.

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**Institutional Review Board Statement:** The study was conducted in accordance with the Declaration of Helsinki and approved by the Conjoint Medical Ethics Committee (REB19-0428).

**Informed Consent Statement:** Informed consent was obtained from all subjects involved in the study.

**Data Availability Statement:** The participants of this study did not provide consent for their data to be shared publicly.

**Acknowledgments:** The authors would like to thank Stephen Chaudhary, Meghan Critchley, Manraj Kang, Larissa Taddei, Stacey Sick, Haley Young and Valeriya Volkova for their assistance with data collection.

**Conflicts of Interest:** The authors declare no conflict of interest.

## Appendix 4.1

<b>R-package</b>	<b>Version</b>
ggplot2	3.3.3
dplyr	1.0.5
readxl	1.3.1
tidyverse	1.3.1
gtsummary	1.4.1

#### **4.7 Bridge to Chapter Five**

Chapters Three and Four used soccer-specific COD tests in order to measure test-retest reliability or within-season change in youth soccer players. However, several studies have questioned the ability of preplanned tests to help in understanding on-field performance.

Soccer-specific test pattern that was used in Chapters Three and Four did not provide an analysis on playing position specific differences and nor do the other traditional testing methods that are used for COD speed evaluation (Paul et al., 2016; Sheppard & Young, 2006; W. B. Young et al., 2015). There has been a call for context related evaluation of movement patterns for performance, injury prevention and return to play analyses (Ardern et al., 2016; Bittencourt et al., 2016; Paul et al., 2016; W. Young et al., 2021). Previous studies on performance have shown major differences between playing positions in youth and adult soccer; High speed accelerations, decelerations, total distance covered etc. seem all different between playing positions, suggesting that forwards and wingers are experiencing more high-speed running related stress whereas center midfielders generally cover larger distances (Deprez et al., 2015; Granero-Gil, Gómez-Carmona, Bastida-Castillo, Rojas-Valverde, de la Cruz, et al., 2020; Oliva-Lozano, Fortes, et al., 2020; Sariati et al., 2020). Playing position might play an important role in player exposure to different types of CODs during a game, and therefore a playing position analysis during games would provide additional information to understand the individual between-day and within-season variation in COD movement variables, that were reported in Chapters Three and Four.

**Chapter Five: Differences in Situational Patterns During Change of Direction Movements  
Greater than 90° in Youth Male and Female Soccer Players.**

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Alanen, AM., Gibson, E., Critchley, M., Benson, L.C., Ferber, R., Jordan, M.J., & Pasanen, K.  
(Under Review). Differences in Situational Patterns During Change of Direction Movements  
Greater than 90° in Youth Male and Female Soccer Players. *Journal of Human Kinetics*.

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## 5.1 Abstract

Change of direction (COD) maneuvers in soccer create tactical advantages, but also expose the player to an increased risk of injury. COD ability is commonly tested with pre-planned drills including over 90° cuts. These tests do not take into consideration positional differences players encounter during games. This case-series study aimed to use principal component analysis (PCA) to examine situational differences during COD movements between playing positions in youth soccer games. For each of the four teams included (26 females, 27 males), one game was analyzed using video-analysis. Two independent reviewers identified situational patterns and a PCA was used to examine differences between playing positions. Three principal components explained 89% of the variation in the data and were categorized as the total quantity of CODs, attacking/goal-scoring and defensive reacting types of CODs. One-way ANOVA on the individual principal component scores showed statistical differences ( $p < 0.05$ ) between centre midfielders, goalkeepers, and centrebacks in the quantity of CODs (PC1), and between wingers and fullbacks and centre backs in attacking/goal-scoring CODs (PC2), whereas the PC3 was not different between playing positions. Differences between playing positions suggest that training and testing protocols in soccer could be enhanced to better match the individual and playing position-based needs.

**Keywords:** Change of direction, Youth soccer, Playing position

## 5.2 Introduction

During a game, soccer players perform accelerations, decelerations and change of direction (COD) movements with various speeds and in different tactical situations (Bloomfield, Polman, & Donoghue, 2007). Effective COD movement in games requires not only speed, balance, agility and power, but also ability to percept and react to movement of the ball and other players (Bloomfield, Polman, & Donoghue, 2007; T. Reilly et al., 2000). COD ability has been connected with talent identification in youth soccer, with elite players performing faster in COD tests when compared with sub-elite players (Gil et al., 2007; T. Reilly et al., 2000). The number of high-intensity actions in soccer has been steadily increasing in the last years and fast changes of running directions while anticipating and making decision accounts for about 90% of these actions (Andrzejewski et al., 2013; Barnes et al., 2014). Observation of situation-specific CODs during games is warranted to develop player evaluation methods further, for purposes of performance enhancement, injury prevention and rehabilitation.

Previous studies have looked at player movement characteristics during games, but the definition of “change of direction” movement varies within the literature (Brughelli et al., 2008; Sheppard & Young, 2006; W. Young et al., 2021), resulting in different outcomes for the quantity of CODs in a game (Bloomfield, Polman, & Donoghue, 2007; Morgan et al., 2021; Nedelec et al., 2014). Different situational patterns (e.g., direction of movement, playing position, speed, ball possession, competition) influence the number and type of CODs performed and different training configurations have shown to affect results in traditional COD tests (De Villarreal et al., 2023). Studies analyzing inter-limb asymmetries have concluded that COD deficit shows greater asymmetries compared to COD times (Arboix-Alió et al., 2021). Different situational patterns (e.g., direction of movement, playing position, speed, ball possession, competition) influence the

number and type of CODs performed. However, the majority of testing protocols to evaluate player performance or readiness to play after an injury include COD tests that are performed as straight sprint(s) with pre-planned cutting over 90° regardless of playing position (Alanen et al., 2021; Ardern et al., 2016; Dos'Santos et al., 2020; Loturco et al., 2018; Nimphius et al., 2018). These tests have been criticized for having too much effect of straight-line sprinting speed, which has been shown to represent independent performance domain separated from COD interval measures (Nimphius et al., 2018; Willberg et al., 2023). Additionally, differences by playing position might affect player loading during games as previous studies have shown that runs with COD might increase energy expenditure (Ari et al., 2021). Identification and quantification of COD patterns under currently used COD testing conditions is needed to understand how players behave in games according to their playing position and to determine if there is a need for individualization of COD assessments.

The differences between playing positions to COD situational patterns during games in youth soccer have not been studied thoroughly. Thus, an analysis of positional and situational differences in COD movements is warranted to develop a better understanding of the differences of the physical and tactical demands across playing positions. This can provide important information to inform player testing and training related to sport performance and sport injury. The aim of this case-series study was to examine and describe the situational differences in 90° cuts, 135° cuts and 180° pivot turns in games between playing positions in youth female and male soccer players.

## 5.3 Materials and Methods

### 5.3.1 Study design and Participants

Four elite U16-U17 youth soccer teams (2 male teams and 2 female teams) from a local soccer club in Calgary, Alberta, were invited to participate in this cross-sectional study. Team recruitment occurred prior to the outdoor soccer season 2019 (May – October). Final participation was based on a signed mature minor consent of each player and their parent/guardian. All players with a minimum of 30 minutes (1/3 of the game) of playing time were included. Thirty minutes was agreed as a minimum time based on the information from previous studies on playing intensity and performance. As playing time increases, players will cover smaller distance, perform fewer high-intensity actions and situate further away from each other, especially on the second half of play (Barros et al., n.d.; Caetano et al., 2019). Reductions in distance covered will start during the first half, while the first 15 minutes of play includes most high-intensity running and highest intensities have been recorded during first 15-30 minutes (Bradley et al., 2009; Coelho et al., 2016; Mohr et al., 2003). If a player could not be recognized from the video, due to camera angle or other obstructions of the view, they were excluded from the analysis. Ethical approval was granted by the University of Calgary Conjoint Health Research Ethics Board (REB19-0428).

### 5.3.2 Procedures

Player age, playing years, playing position, and previous lower extremity injuries (within 12 months from baseline testing) were collected with a self-reported baseline questionnaire. Playing position was identified as goalkeeper (GK), center back (CB), full back (FB), center midfield (CM), winger (W) or striker (S). All teams used similar formation (4-5-1) on the field which was the base for playing position identification and played against another top-level (Tier 1) opponent in a league-game. Player height (cm) was measured using a portable height

measurement unit (Seca GmbH, Seca 217) and body mass (kg) was measured using portable standard electronic scale (Seca GmbH, Seca 437). Height and body mass measurements were completed barefoot and wearing t-shirt and shorts. Game data were collected by videorecording one game per team with two 4K cameras (Sony, FDR-AX53, 120fps). The cameras were placed on tripods and covered opposite sides of the field. The players were identified based on their jersey numbers.

### 5.3.3 COD Identification

CODs were identified when a player was running forward, changed direction while running (plant and cut) and then continued the run without stopping in the new direction. CODs that included running backwards, side-shuffling or a combination of these with straight running were not identified. Situational patterns were recorded for each identified COD and included the following: ball possession (player/team), running speed before COD movement (low/moderate or fast), contact with other players during COD movement, side (right or left) and the angle of COD movement (90° cut/135° cut/180° pivot turn). Ball possession (player) was identified if the player was dribbling or had control over the ball after receiving a pass. Ball possession (team) was identified if a player from same team had control over the ball or the ball was being passed between players. Contacts were identified from other players to any body part during or right before COD and challenge was identified as an action from opposing player that forced a perception-reaction response. Turning direction was identified as left or right and running speed in two categories, fast or low/moderate. Fast running speed was identified when player was chasing the ball/opponent or being chased with ball possession. Low/moderate speed was identified when player was jogging and/or not pressing/being pressed. All COD movements were identified using video-analysis

software (Dartfish Live S) and a soccer-specific tagging panel designed for identifying situational patterns.

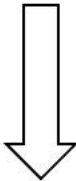
Two independent reviewers (AMA, EG) completed the video tagging task. Reviewer 1 had over ten years of experience in soccer video-analysis through coaching and was responsible for training reviewer 2. After the training period, both reviewers identified the COD movements for seven players from one team (U16 boys) separately to determine interrater reliability and control for misclassification bias. The number of players for the initial identification was determined on playing time; all these players played more than 2/3 of the game. The interrater reliability was excellent, with ICC (3,k) > 0.95 for all situations.

After the initial identification and confirmation of agreement, the reviewers independently identified the rest of the games and players (2 teams per reviewer). The criteria for identification of each situational pattern are presented in Figure 1. To account for unequal playing time, COD situation counts were expressed per 45 minutes (half of a game) of playing time.

- ✓ Player is running and changes direction
- ✓ A plant and cut can be identified
- ✓ The run continues in the forward direction after cutting
- ✓ The angle of the cut is  $\geq 90^\circ$



**Identification of situational patterns**



Criterion	Situations		
COD angle	180°	135°	90°
Ball possession (player)	With ball	Without ball	
Ball possession (team)	Offensive		Defensive
Contact during COD	Contact		No contact
Turning direction	Right		Left
Running speed	Fast		Low/moderate
Challenge during COD	Challenged		Not challenged

**Figure 5.1.** Flowchart of COD and situational pattern identification with example (shadings).

#### 5.3.4 Statistical analysis

Means with standard deviations (SD) were used to describe continuous data, and frequency tables were used for categorical variables. Principal Components Analysis (PCA) was conducted to extract and visualize the information from the original set of situational variables. Before applying PCA to the data, the suitability of the dataset was inspected using Bartlett's test for sphericity and Kayser-Meyer-Olkin (KMO) test for sampling adequacy. The p-value for Bartlett's test was  $<0.001$  and the KMO values for all the variables were over 0.5 (range from 0.69 to 0.87) indicating that the dataset was suitable for PCA.

Before performing the PCA the dataset was first standardized to standard deviation of one and zero mean, because the means and standard deviations for counts between the playing positions were largely different. After Varimax rotation, three principal components explained 89% of the variation between the playing positions. Based on the systematic review by Rojas-Valverde et al. (Rojas-Valverde et al., 2020) there are varying considerations for factor retention, most usual being eigenvalues of  $>1$ . However, there are many methods for determining the number of relevant components and most fail to determine the optimal number (Ferré, 1995). In this study, a method used by Benson et al. (L. C. Benson, Cobb, et al., 2019) was used, where components that contributed modes of variation greater than an equivalently sized input matrix of normally distributed randomly generated numbers, were decided to be retained.

PCA was conducted with R software (R-foundation), using FactoMineR and factoextra packages. Quality criteria for reporting the results of PCA proposed by Rojas-Valverde et al. (Rojas-Valverde et al., 2020) was used as basis for reporting, to increase understanding and future applicability. One-way analysis of variance (ANOVA) was used to determine if playing positions

showed statistically significant differences based on individual PC scores. Statistical significance was set beforehand as  $p < 0.05$  and Tukey's test was used for post-hoc analysis.

## 5.4 Results

Sixty-two players entered the study and 58 played at least 30 minutes in the recorded game. Six players were excluded from the analysis due to inability to identify COD movements (i.e., player too far away, other players obstructing the view). Descriptive characteristics for players who completed the study ( $n=52$ ) are presented in Table 1.

**Table 5.1.** Player characteristics.

	<b>Males (n=25)</b>	<b>Females (n=27)</b>
<i>U17, n</i>	11	13
<i>U16, n</i>	14	14
<i>Age</i>	16.2 (0.7)	16.3 (0.7)
<i>Height</i>	175.7 (9.4)	166.2 (5.8)
<i>Weight</i>	66.9 (5.4)	59.6 (8.7)
<i>Playing years</i>	10.8 (1.7)	10.4 (1.8)
<i>Playing time / game</i>	65 (18)	68 (20)
<b>PLAYING POSITION</b>		
<i>GK, n</i>	2	2
<i>CB, n</i>	4	4
<i>FB, n</i>	5	4
<i>CM, n</i>	5	8
<i>W, n</i>	6	6
<i>S, n</i>	3	3
<b>Lower extremity Injury within 12 months</b>		
<i>Yes, n</i>	10	13
<i>No, n</i>	14	11
<i>Injury report missing, n</i>	1	3

Values are means (SD) unless otherwise indicated. Abbreviations: U17 = Under 17; U16 = Under 16; GK = Goalkeeper; CB = Centre back; FB = Full back; CM = Centre midfield; W = Winger; S = Striker.

#### 5.4.1 Principal component analysis

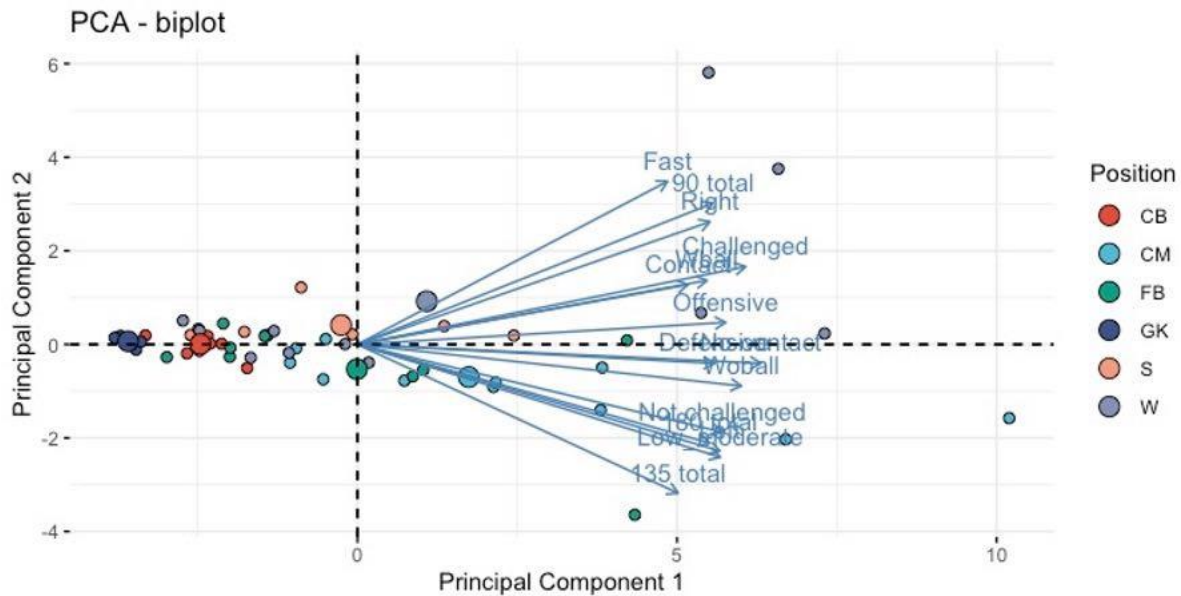
The Eigenvalues for the three PCs were 10.9 (PC1), 1.5 (PC2) and 1.14 (PC3). The first principal component explained most of the variation (72.4%). All 15 variables correlated with PC1 at a significance level of  $p < 0.0001$ , indicating that PC1 was related to the quantity of CODs regardless of situational patterns. All factor loadings except for fast speed for PC1 were  $> 0.75$ , which is usually considered as a strong loading (Rojas-Valverde et al., 2020). Eight variables correlated with PC2 ( $p < 0.05$ ), suggesting that was related to attacking situations (fast, 90°, CODs to the right). Seven variables correlated with PC3 ( $p < 0.05$ ), suggesting that PC3 was related to defensive situations, demanding reacting to opposition movements (fast, without ball, contact, defensive). However, the factor loadings for PC2 and PC3 were between 0.3 and 0.7 and were considered as weak (0.3-0.49) or moderate (0.5-0.75) loadings (Rojas-Valverde et al., 2020).

The results of ANOVA and p-values adjusted for multiple comparisons are presented in Tables 2 and 3. PC1 and PC2 showed statistically significant differences between the playing positions ( $p < 0.05$ ), whereas PC3 did not. Post-hoc (Tukey's test) analysis revealed statistically significant ( $p < 0.05$ ) differences when comparing center midfielders with goalkeepers or center backs in PC1. The differences for PC2 were seen between wingers and center midfielders or wingers and full backs. Table 3 shows the results of post-hoc test (Tukey's test) for the comparisons that were statistically significant ( $p < 0.05$ ).

Center midfielders performed more CODs regardless of situational pattern, than goalkeepers and central defenders (PC1,  $p < 0.05$ ). Wingers seemed to perform fast CODs, doing 90° cuts and turning to their right more often than centre midfielders or fullbacks (PC2,  $p < 0.05$ ). Fullbacks and centre midfielders seemed to perform more 180° pivot turns, 135° cuts, low/moderate speed and

to their left, than wingers (PC2,  $p < 0.05$ ). Centre backs and goalkeepers performed least amount of any types of CODs during a game (PC1).

Biplots (Figures 2 and 3) show the individual PC values for all the players (small dots) and the means per playing position (large dots). Contributions of the original variables are shown with blue arrows (longer arrow indicating stronger contribution).

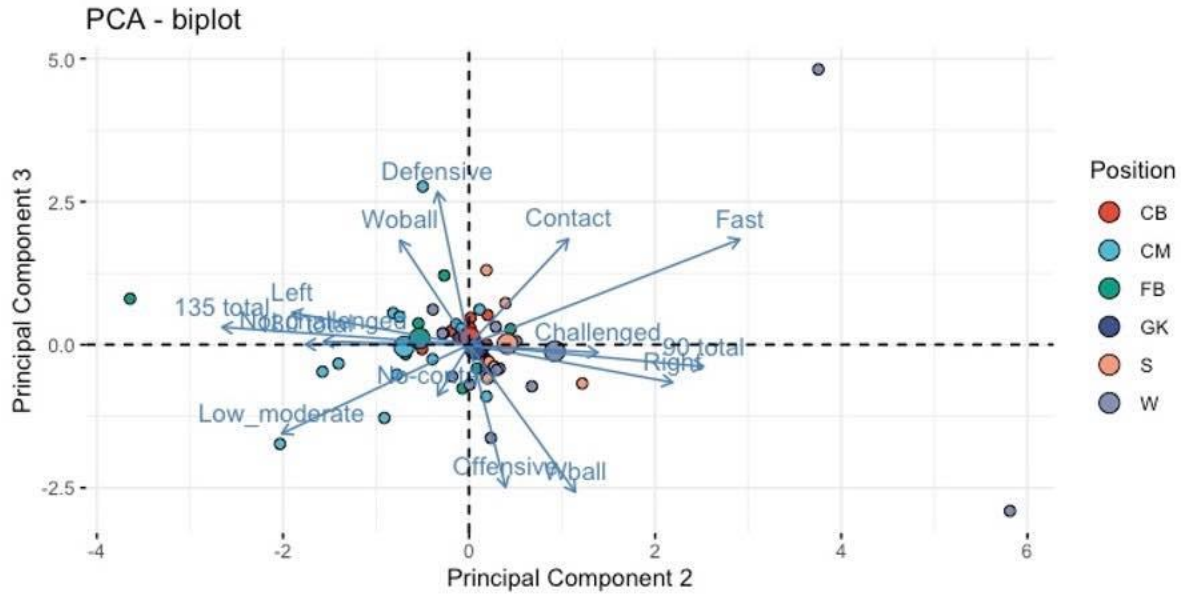


**Figure 5.2.** Biplot of PCs 1 and 2 with playing positions and contributions of different variables.

Small dots = Relation of each individual player to the first two principal components.

Large dots = Means of all the playing positions.

Abbreviations: CB = centre back, CM = centre midfield, FB = full back, GK = goalkeeper, S = striker, W = winger, Wball = with ball, Woball = without ball



**Figure 5.3.** Biplot of PCs 2 and 3 with playing positions and contributions of different variables.

Small dots = Relation of each individual player to the first two principal components.

Large dots = Means of all the playing positions.

Abbreviations: CB = centre back, CM = centre midfield, FB = full back, GK = goalkeeper, S = striker, W = winger

**Table 5.2.** ANOVA for principal components 1-3.

PC1	Degrees of freedom	Sum of squares	Mean square	F-value	p-value
Position	5	153.7	30.745	3.445	0.01*
Residuals	45	410.5	8.924		
PC2					
Position	5	20.07	4.015	3.208	0.01*
Residuals	45	57.57	1.252		
PC3					
Position	5	0.43	0.0864	0.068	0.997
Residuals	45	58.58	1.2734		

\*= statistical significance <0.05

**Table 5.3.** Tukey's multiple comparison of means for playing positions.

Positions	Difference	Lower	Upper	P-adjusted
PC1				
CM-GK	5.33	0.25	10.41	0.03*
CM-CB	4.19	0.21	8.19	0.03*
PC2				
W-FB	1.45	-0.02	2.92	0.05*

W-CM	1.62	0.29	2.95	0.01*
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\*= statistical significance <0.05

Abbreviations: COD = Change of direction, 180 ° = 180 ° pivot turn; 135 ° = 135 ° cut; 90 ° = 90 ° cut; GK = Goalkeeper; CB = Centre back; FB = Fullback; CM = Centre midfielder; W = Wide midfielder/Winger; S = Striker.

## 5.5 Discussion

The aim of this study was to examine the situational differences in 90° cuts, 135° cuts or 180° pivot turns in games between playing positions in youth soccer players during games. Previous studies have discovered differences between playing positions in physical demands and agility (Deprez et al., 2015; Granero-Gil, Gómez-Carmona, Bastida-Castillo, Rojas-Valverde, de la Cruz, et al., 2020). This is the first study to analyze the frequency of CODs used in testing protocols in youth soccer games, including player position specific differentiation. Differences in physical loading between playing positions have been examined in previous studies (Barrett et al., 2018; Panduro et al., 2021) and the results of this study are similar in regards to lower demands for central defenders and playing position specificity in physical demands in general (Bangsbo et al., 2006; Bradley et al., 2009, 2010). The first component, which explained most of the variation, was based on quantity of all the initial variables. Centre midfield players perform more CODs during the game than others, regardless of the type of COD and situation. Previous research has concluded that midfielders cover the most distance during a game (O'Donoghue, 2002; Rienzi et al., 2000) perform less-shuffling and are most involved in ball possession (Bloomfield, Polman, & Donoghue, 2007) which would explain higher quantities of COD movements. The second principal component could be described as attacking/goal-scoring opportunity-based component. It includes positive correlations with “fast”, “90° cuts” and to the “right”. Most of the players were right footed which could explain the dominance for cuts to the right in within this component, since players would want to get their right leg open before shooting or crossing the ball in the attacking zone. The third component was related to reactive situations while defending, with

positive correlations for “without ball”, “fast”, “defensive” and “contact”. The second PC results are supported by previous research showing that strikers perform most high-intensity activity and most often in contact situations (Bangsbo et al., 2006; Bloomfield, Polman, & Donoghue, 2007; Di Salvo et al., 2007) and fullbacks and wingers being involved more often in high-speed situations than other positions (Bangsbo et al., 2006; Barrett et al., 2018)

Based on the means of PCA results, centre midfielders and wingers were involved in CODs more often than other positions, regardless of the situational pattern. Goalkeepers and centre backs on the other hand, did not perform these types of CODs almost at all during games. Regarding more situational specific factors, centre midfielders and full backs seemed to perform more low or moderate speed CODs, 180° or 135° cuts, to the left and while not challenged by the opposition whereas wingers and strikers performed more 90° cuts, to the right, at high speed and while challenged by an opposing player. Winger and striker positions would therefore be involved more in attacking type COD situations than others. However, based on the analysis of the third component, defensive reactive situations were not based on playing positions per se, suggesting perhaps an influence of the opposition characteristics related to tactical formations and individual skills. These situations should be practiced equally, regardless of playing position. In general, our results indicate that practitioners could target testing, training, and physical preparation more effectively by considering playing positional differences.

It should be noted that the count of CODs during games was highly related to the definition of a COD movement. Quantities of CODs in this study are in line with the study by Nedelec et al. (Nedelec et al., 2014) and with study by Baptista et al. (Baptista et al., 2018), but considerably lower than results from studies that included a broader definition for COD movements (Bloomfield, Polman, & Donoghue, 2007; Granero-Gil, Gómez-Carmona, Bastida-Castillo, Rojas-

Valverde, de la Cruz, et al., 2020; Morgan et al., 2021). Based on this fact, a more specific criteria-based definition for COD movements in soccer (and other evasion sports as well) is recommended, to increase the understanding of player loading and quality of analysis on CODs.

Playing position specific differences have been studied earlier based on sprints and accelerations and the results are in line with our findings on COD movements (Borghi et al., 2021). In both youth and adult soccer, wide midfield and wingback positions executed highest number of high-speed accelerations or decelerations and sprints or high-speed running compared to other positions and regardless of playing formation. Centre midfielders performed more low speed accelerations and decelerations, but covered a greater distance compared to other positions, whereas centre defenders have least high and low speed movements (Barron et al., 2014; Oliva-Lozano, Fortes, et al., 2020). Patterns of activity vary during games due to playing positions: fullbacks and forwards cover greater full-speed running distances in U20 female high-level soccer than other positions (Ramos et al., 2017).

The results of our study can be valuable for planning playing position specific training, agility testing or evaluation of readiness for return to play after injury. However, by means of video-analysis it is difficult to determine demands related to velocity and deceleration of the COD movements. This problem could be solved in the future studies by using inertial measurement units.

### 5.5.1 Limitations

This study is not without limitations. Only one game per team was recorded and used for COD identification. There is an effect of the opponent on team and individual player performance. In youth soccer, opponent quality affects match performance – shots, sprints etc. (Varley et al., 2017). In this study, both female teams had “easier” games (4-0, 5-0 wins), whereas the male teams

had more challenging games (2-2 tie and 2-1 win), although all the teams played against other tier 1 opponents in a league game. Field formation and specific tactics used by the coach can also have a great effect on player behaviour. These teams being from the same club and having similar “game philosophy” and playing with similar formation in all games, could bias our data and certainly affect generalizability. The playing time between the two halves was not equal between all of the players and previous studies have concluded that the number of CODs in youth soccer players might differ between the two halves (Morgan et al., 2021). In addition, players with lesser playing time might have played during a period in the game when the concentration of COD movements was lesser or higher. The sample size for PCA was not necessarily large enough (usually recommended to be minimum 100), but the amount of variables in relation to sample size was acceptable (Rojas-Valverde et al., 2020). However, as an analysis method, PCA tends to overfit the data especially with small sample sizes and thus the generalizability of our results should be considered with caution (Osborne & Costello, 2004.). Studies with longer follow-up time, more games and addition of opponent level and tactics used as a variable, is recommended for future to increase understanding on this subject.

## **5.6 Conclusions**

Based on these results, playing position affects the exposure to different types of COD movements during games in youth soccer, when looking at CODs performed in similar way as they are commonly tested. The definition of COD in soccer is not well defined and ranges considerably based on the criteria used. Over 90° COD situations in youth soccer games are depended on playing position and understanding these position specific demands can be helpful when testing youth players for performance or return to play readiness after injury. In addition, this information can assist in developing better testing protocols that meet gameplay demands of

individual players. To increase the understanding and quality of future studies on COD movements, a more comprehensive criteria and definition of change of direction movement is needed.

### **Disclosure statement**

No potential conflict of interest was reported by the authors.

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## **5.7 Bridge to Chapter Six**

The results of Chapter Five suggest that there are differences between playing positions regarding COD movements during soccer games. Center midfielders perform most CODs in general, whereas center defenders and goalkeepers are hardly involved in COD situations. Wingers and forwards are performing more CODs in high-speed and with ball (attacking type CODs), whereas defending type CODs can't be differentiated by playing position.

Previous studies have looked at running speeds and distances during soccer games (Barros et al., 2007; Caetano et al., 2019; Dellal et al., 2011) and also used IMUs to calculate total numbers of high-speed actions or individual external loading, based on accelerations (Burland et al., 2021; Nobari et al., 2022; Roell et al., 2019; Taylor et al., 2017). In Chapter Five, the differences of playing positions regarding situational patterns were explored. However, the correlation between specific situational patterns and kinetic variables during COD movements has not been studied earlier. Understanding which situational patterns are related to higher forces during CODs, could be valuable in developing more context specific testing and training methods for soccer players.

Additionally, majority of studies on COD movements in soccer have been done with male participants. Conducting a study specifically on youth female players would add into the knowledge of COD movement demands for female players.

**Chapter Six: The Effects of Situational Patterns on Accelerations During Change of Direction Movements: Game-Analysis of Youth Female Soccer.**

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Alanen, AM., Benson, L.C., Jordan, M.J., Ferber, R., & Pasanen, K. (Under Review). The Effects of Situational Patterns on Accelerations During Change of Direction Movements: Game-Analysis of Youth Female Soccer. *Biomechanics*, 3(2), 250-257, 2023.

<https://doi.org/10.3390/biomechanics3020021>

## 6.1 Abstract

The aim of this study was to assess center of mass (COM) acceleration and movement during change of direction (COD) maneuvers during competitive soccer game to elucidate situation specific demands of COD performance. This information can assist in developing soccer-specific tests and training methods. Fifteen elite-level female youth soccer players were tracked for one game with inertial measurement units (IMU) attached on the lower back. COD movements in combination with situational patterns were identified using high-speed video. LASSO regression was used to identify the most important predictors associated with higher vertical peak accelerations ( $PA_v$ ) of the COM during COD movements. COD angle, running speed, contact and challenge from the opposition were identified as important features related to higher  $PA_v$ . This study adds to the literature on the demands of COD performance in soccer match play. The unique approach with game-specific situational data of youth female players provides increased insight on the game-demands of COD and agility performance.  $PA_v$  in games was higher when with larger COD angles, increased running speed, or with contact when the player was challenged by the opposition. A larger study including more games is warranted to increase confidence in using these variables as a basis for training or testing agility.

**Keywords:** Football; soccer; change of direction; game-analysis; situational patterns

## 6.2 Introduction

Change of direction (COD) performance is an important discriminator of elite players in youth soccer and is also associated with common mechanisms of injury (King et al., 2021; Lucarno et al., 2021; Paul et al., 2016; Trecroci et al., 2019). Common COD tests in youth soccer include test-patterns like the Illinois agility test, 5-0-5 test, Arrowhead test or T-test, which all include straight sprinting and preplanned COD movement(s) (Altmann et al., 2019; Nimphius et al., 2018). These tests assess COD speed rather than agility, which incorporates a perceptual-motor component (W. B. Young et al., 2015). COD ability can also be masked by straight sprinting speed (Nimphius et al., 2018) and COD movements within a game are dissimilar because of flux in playing situations. Previous research has shown that the requirement for high-speed running, total distance and CODs are position specific (Borghini et al., 2021; Deprez et al., 2015; Sariati et al., 2020) but little is known about the situational factors involved in COD maneuvers that could increase biomechanical demands during the final foot contact. Analysis of biomechanical variables during CODs in a game would provide more specific information on the physical demands of game-play and better guide training and testing tasks to match game requirements. Furthermore, most performance analysis studies in soccer involving COD biomechanics and wearables have been conducted with male participants, with only handful of studies on youth female athlete populations (Chambers et al., 2015; Dos'Santos et al., 2019; Okholm Kryger et al., 2022; Pino-Ortega et al., 2021).

Wearable technology is used widely to monitor soccer players (Akenhead et al., 2016; Dalen et al., 2016; McLaren et al., 2018; Taylor et al., 2017) including in professional leagues. However, the use of this data has been so far limited to estimating external load parameters or counts of specific movements (e.g., jumps, CODs) (Barron et al., 2014; B. Reilly et al., 2021) with

limited analysis of the biomechanical determinants of COD performance during game-play matched with situational patterns. IMUs allow real-world data-collection, but there is no current consensus on how this information should be used to support player development. There has been a call for more soccer-specific testing and monitoring including a multi-dimensional approach for performance evaluations (Forsman et al., 2016; T. Reilly et al., 2000), which could be done in games with IMUs. IMUs could be utilized to provide information about the quality of not only whole-body movements, but also individual segments during a COD movement (Chambers et al., 2015a). In previous studies, this potential has been shown when analyzing walking, running and postural control (L. C. Benson et al., 2018; Johnston et al., 2019).

Laboratory based studies have examined forces during COD movements and provided information about accelerations and ground reaction forces during the antepenultimate, penultimate and final foot contacts (Dos'Santos et al., 2017; Dos'Santos, Thomas, Comfort, et al., 2019a; Jones et al., 2017; Santoro et al., 2021; Thomas et al., 2020). The final foot contact (FFC) is the part of a COD that initiates the movement and allows the player to start accelerating in a new direction. Players who are able to enter FFC phase with higher speed and greater ground reaction forces have been shown to perform better in traditional COD tests (Dos'Santos et al., 2017; Jones et al., 2017). In addition, forces during the final step seem to be angle and side specific, meaning that the forces a player experiences while performing a COD will increase when the COD angle increases and alternate individually based on possible differences in leg-dominance (Dos'Santos et al., 2018). Laboratory based studies with force plates have identified peak impact forces (braking and propulsive) as indicators of better performance (Dos'Santos et al., 2017, 2018). Peak acceleration measured with IMUs has been shown to have capacity to predict impact forces (Wundersitz et al., 2013b) and higher accelerations during on-field movements in team sports have

been related to increased muscle damage and fatigue (W. B. Young et al., 2012). Based on a recent study the vertical acceleration had the largest contribution to total acceleration during soccer games (Oliva-Lozano et al., 2023) and trunk mounted IMUs have shown acceptable validity to measure peak vertical and resultant force (Wundersitz et al., 2013).

Studies analyzing female populations during real-world challenges in evasion sports that require perception and reaction to other players movements are limited (Díaz-Soto et al., 2022; Dos'Santos et al., 2019; Mandorino et al., 2023; Okholm Kryger et al., 2022). Considering larger incidence rates in anterior cruciate ligament (ACL) and ankle injuries in youth female players (De Ste Croix et al., 2015; Lucarno et al., 2021), there is a need for analyzing biomechanical determinants of COD during games in female populations. Previous studies have shown that knee joint loading during the FFC is reduced when greater braking forces are applied during prior steps while decelerating (Dos'Santos, Thomas, Comfort, et al., 2019a; Jones et al., 2017; Thomas et al., 2020). Additionally, reduced decision times during tasks requiring reaction and presence of a simulated defensive opponent have been shown to increase factors related to injury risk, such as knee abduction moments and knee valgus angles (Bill et al., 2022; Mclean et al., 2004; McLean et al., 2010). COD movement in soccer games is affected by approach speed, angle, anticipation, and positional requirements, which have not been studied earlier thoroughly in female populations (Griffin et al., 2022). Lack of evaluation of demands for skill-capacities in female athletes can lead to conclusions that disregard the multifactorial nature of high-speed movements (Nimphius, 2019).

To understand better game-specific demands for COD movement and to inform stakeholders working with youth female players for injury prevention or performance enhancement purposes, on-field evaluation of COD movements is warranted. Understanding the differences in on-field demands of different COD situations may lead to more soccer-specific

training and testing methods that can support player development and injury prevention processes. For these reasons, the purpose of this study was to evaluate the importance of situational features during CODs that predict IMU measured  $PA_v$  during the final foot contact phase while turning in youth female soccer players. A secondary aim was to describe the factors that explained the greatest variance in  $PA_v$  and thus changing physical demands of COD movement.

## **6.3 Methods**

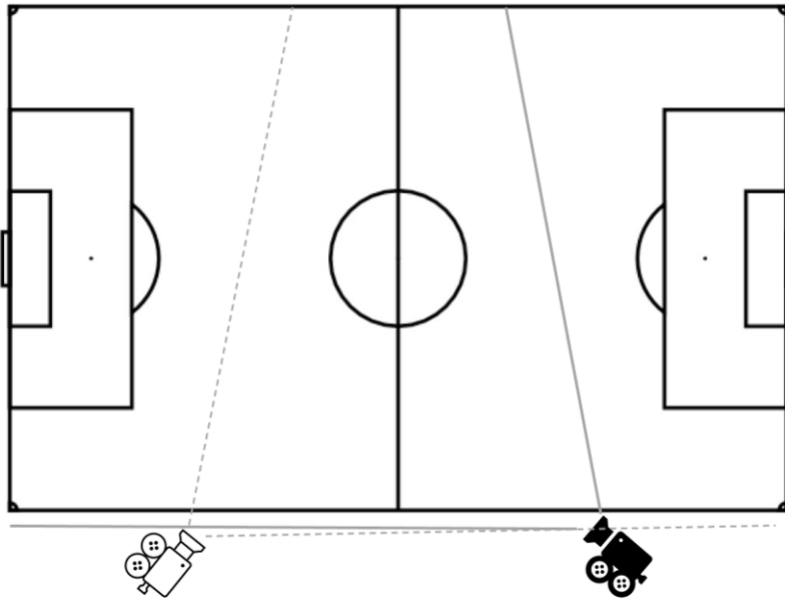
### **6.3.1 Participants and design**

A convenience sample of one elite U16-U17 youth soccer team from a local soccer club in Calgary, Alberta, participated in this case-series study. A total of 15 players played in the game and were included in the study. The mean age of players was 16.9 years (SD  $\pm 0.36$ ), height 163.9 cm (SD  $\pm 6.4$ ), body mass 59.7 kg (SD  $\pm 9.5$ ) and years played 10.6 (SD  $\pm 2.1$ ). Team recruitment occurred prior to the outdoor soccer season 2019 (May – October). Final participation was based on a signed mature minor consent of each player and their parent/guardian. Ethical approval was granted by the University of Calgary Conjoint Health Research Ethics Board (REB19-0428).

### **6.3.2 Data collection**

Two trained research assistants equipped the players with wireless triaxial IMU device (Shimmer 3 IMU  $\pm 16g$ , Shimmer Sensing, Dublin, Ireland, L4 level, in a pocket of an elastic strap) before the game. The devices were calibrated prior to data-collection based on manufacturer recommendations. Players performed a general warm-up before the start whistle. Videomaterial was collected by videorecording the game with two 4K cameras (Sony, FDR-AX53, 120fps). The cameras covered opposite sides of the field (Figure 1). The player identification from video was done based on their jersey numbers. Additionally, research assistants marked distinctive features

of players (hair and cleat color) to an information sheet that was double-checked while conducting the video-analysis.



**Figure 6.1.** Videorecording set-up.

The criteria for COD identification included that the player was running forward, changed direction while running and continued the run without stopping towards the new direction. CODs that included backwards running, side-shuffling or a combination of these with straight running were excluded. Situational patterns were identified for each identified COD and included following features: (1) ball possession (player/team), (2) running speed (low/moderate or fast), (3) body contact with other players during COD movement, (4) turning side (right or left); and (5) the angle of COD movement (90° cut/135° cut/180° pivot turn). Ball possession (player/team) was based on the ball possession definition presented by Link et al. (Link & Hoernig, 2017) Contacts were identified from other players to any body part during or right before the COD maneuver and a challenge was identified as an action from opposing player that forced a perception-reaction response. Fast running speed was identified when the player was chasing the ball/opponent or

being chased with ball possession. Low/moderate speed was identified when player was jogging and/or not pressing/being pressed. All COD movements, including field position (left/right, attacking/defensive half/field coordinates) for each COD and time of game (minute, first/second half) were identified using a soccer-specific tagging panel (Dartfish Live S). One reviewer (AMA) who had over ten years of experience in soccer coaching and game-analysis completed the video-analysis.

Vertical plane raw peak accelerations ( $PA_v$ ,  $m/s^2$ ) for the final foot contact were derived from IMU data using a specific Matlab script (Version R2011b, MathWorks Inc., Natick, Massachusetts, USA) which synchronized the tagged situational datapoints with IMU data.

### 6.3.3 Statistical analysis

Least absolute shrinkage and selection operator (LASSO) was used for the feature importance analysis.  $PA_v$  during final foot contact was the outcome measure and categorical situational patterns including playing position, player ID and time of game (13 variables in total) were the predictor variables. Model performance was optimized by using a 10-fold cross-validation to obtain a model penalisation parameter  $\lambda$ . Optimal value of  $\lambda$  was used to identify the key factors contributing towards  $PA_v$  during COD. All statistical analysis were done using R-software, Version 2022.12.0+353 (*R Core Team. R: A Language and Environment for Statistical Computing; R Foundation for Statistical Computing, 2020*), specifically ‘glmnet’ -package.

## 6.4 Results

LASSO regression identified four important features for increase in  $PA_v$  during CODs (Table 1). LASSO regression uses L1 regularization which adds a penalty to the features and as a result eight of the variable were shrunk to zero and were eliminated from the final model. The

important features were contact before or during COD, running speed, challenge from opponent and the angle of COD (Table 1).

**Table 6.1.** Important situational features affecting  $PA_v$ .

<b>Feature</b>	<b><math>\beta</math>-coefficient</b>
Body contact before/during COD	1.95
Running speed	2.78
Challenge from opponent	3.45
COD angle	7.15

COD = Change of Direction,  $PA_v$  = Vertical Peak Acceleration

Based on the  $\beta$ -coefficient values, COD-angle seems to have the greatest importance for  $PA_v$  during COD movements, followed by challenge from opponent, running speed and body contact before/during COD. The final LASSO model with these four parameters could be used to make predictions of accelerations on new set of data. As the dataset in this case-series study was small, all the datapoints were used to determine the best predictors for  $PA_v$ , and the accuracy of the model in a test data set was not examined further.

Detailed information on the quantities of the CODs and different situational patterns are presented in Table 2. Playing time, half or position on the field were not related to changes in  $PA_v$  and were left out of the table.

**Table 6.2** Quantities of different CODs with corresponding  $PA_v$  (mean).

<b>Type of COD</b>	<b>Quantity</b>	<b><math>PA_v</math> (Mean, <math>m/s^2</math>)</b>
180°	107	41
135°	85	33.66
90°	144	25.2
With ball	138	32.1
Without ball	198	32.7
Offensive	187	32.5
Defensive	151	32.2
Contact	92	30.8
No-contact	245	37.5

Right	150	33
Left	186	31.5
Fast	104	30.5
Low_moderate	232	36.9
Challenged	173	35.1
Not challenged	163	29.4

COD = Change of Direction,  $PA_v$  = Vertical Peak Acceleration

## 6.5 Discussion

This case-study evaluated the effects of situational features during COD movements on  $PA_v$  in a youth female soccer game. The results of this study revealed higher  $PA_v$  during COD being related to steeper turning angle, higher running speed, player being challenged or having a contact before/during COD. The results of this research agree with the hypothesis set beforehand, which argued that impact forces during COD are angle and speed dependent, as shown in previous laboratory-based research. However, the results interestingly revealed additional factors that may increase accelerations during COD movement and potentially contributing to an increased neuromuscular demand.

Previous studies have shown angle and speed dependent changes in COD demands in laboratory conditions (Dos'Santos et al., 2017, 2018; Hader et al., 2015; Havens & Sigward, 2015; Spiteri et al., 2015). Sharper angles increased the COD demand measured by increased ground reaction forces (Thomas et al., 2020), increased ground contact times and decreased velocity profiles that reduced player COD performance (Dos'Santos et al., 2019). These results support our findings that higher accelerations during CODs were associated with higher running speed and a steeper COD angle.

The results of this study show also that contact or challenge prior to or during a COD movement led to increased  $PA_v$ . Both having a contact prior or during COD and being challenged

by another player affected the players' ability to anticipate and achieve a more rapid perception-reaction. In an unanticipated COD task the muscle contraction strategy will change as well as the hip-flexion angle, resulting in mechanical disadvantage, which most likely increases acceleration (Beaulieu et al., 2009; Lee et al., 2013), which would explain the results seen in this study. Additionally, in unanticipated tasks, players have been shown to decelerate later, leading to higher accelerations during FFC (Dos'Santos et al., 2018; Lee et al., 2013; W. B. Young et al., 2015). Previous studies on anticipated and unanticipated tests have concluded that perception-action type activities need to be developed to ensure players readiness for demands of games. This is supported by the results of our study.

Previous studies have shown that greater horizontal forces during the FFC lead to faster 180° pivot turns (Dos'Santos et al., 2017) and faster approach velocities are beneficial for better performance (Dos'Santos et al., 2018; Jones et al., 2017). On the other hand, higher injury risk has been related to these same parameters (Dos'Santos, Thomas, Comfort, et al., 2019a). Our study supported similar conclusions for on-field, non-anticipated movements. This indicates the need for previously suggested modifications for strength training regarding more efficient and safe COD movement, but also introducing game-like elements to both training and testing that include varying running speeds and COD angles, pressing and contacts.

This study is not without limitations, which should be considered when applying the results to practice. Only one game for one youth female team was included in the analysis. A longer follow-up and larger sample size would better capture potential variation inherent in competitive soccer games. However, this study can provide valuable information for planning future studies for similar purposes and the results were supported by previous laboratory-based studies.

Coaches and sport science professionals should consider COD training and testing from a context-specific view and modifications to player testing are suggested. Including perception-reaction components, specifically opposition challenge and/or contact, to COD testing in addition with completing tasks with ball possession, would match better game-play demands. In addition, COD training should include varying combinations of these elements for the purposes of player development and player evaluation. Consideration could also be given to development of more sport-specific return to play testing protocols after injury.

## **6.7 Conclusions**

This study showed that running speed, COD angle, contact and challenge from opposing player were all related to higher  $PA_v$  in final step of COD movement during a soccer game. To better prepare youth soccer players for game-demands, these factors should be included in COD training and testing.

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## Chapter Seven: Overall Discussion

### 7.1 Summary

The aim of this thesis was to contribute novel findings to the change of direction (COD) assessment literature. In more detail, this thesis sought to provide novel contributions to soccer player testing, by using wearable sensors in game-play situations which would help to identify game-specific needs for youth soccer player training and testing. Five studies in total were conducted to fulfill this objective, in traditional testing settings and by analyzing actual game-play. The first study was a scoping review of the use of IMUs in COD analysis, followed by a reliability study on specific IMU variables and an in-season follow-up study analyzing the effect of previous injury on the change in IMU metrics. Finally, situational pattern and playing position analysis while executing CODs during games and analysis of effect of situational patterns to accelerations during games tied the results with game-specific needs.

The current evidence on the use of IMUs in COD movement analysis was summarized in Chapter Two. The primary aim was to evaluate the reliability and validity of IMU sensors to detect COD movement and quantify aspects related to COD movements, such as COD heading angles, and accelerations during COD movement. The detection of COD events and identification of COD heading angles was on acceptable level of validity. When compared with gold-standard methods, IMUs more likely over-estimate variables such as forces, acceleration and mechanical loading and the results were inconsistent in general. The reliability was found to be good or high when measuring COD angles and moderate to high when measuring participant test-retest differences in player load. However, more research has been published on the subject after this literature review.

Studies aiming to quantify running kinetics in soccer players and knee-kinematics during COD tasks in soccer players have concluded that the reliability of IMU derived measurements is

poor and have not recommended IMU measures for kinematic analyses (Chia et al., 2021; T. Hughes et al., 2019; Zeng et al., 2022). The reliability of cumulative impact loading has been reported to be acceptable as well as workload measures across playing positions in soccer players (Burland et al., 2021; Nobari et al., 2022). In addition, the intra-unit reliability for evaluation of step-metrics in team sport based tasks and concurrent validity for ball touches and releases in soccer have been reported to be acceptable (Armitage et al., 2021; Marris et al., 2022).

Therefore, the recommendations for the use of IMUs for soccer-based tasks like COD remain inconclusive and more game-play analysis including wearable technology are recommended. As it seems that isolated IMU metrics might overestimate or be unreliable in general, machine learning methods could be tested in future studies to handle more efficiently large amounts of data that wearable technology systems are able to provide.

In Chapters Three and Four the reliability and in-season variability of peak resultant acceleration and peak angular velocity values was analyzed. These studies concluded that neither peak resultant acceleration (PRA) nor peak angular velocity (PAV) is a reliable metric for youth soccer players' 180° pivot cut analysis. However, interesting difference between male and female players was presented and as discussed earlier, might be additionally related to maturational status of the players. Recent studies have concluded the considerable effects on postural control of maturation (John et al., 2019) as well as differences of maturational effects between the sexes in soccer players (Pletcher et al., 2021). These results can help explaining the results of Chapter Three and underline the importance of considering the maturational status while working with youth soccer players. Light et al. (Light et al., 2021) have additionally concluded that injuries in youth soccer are specific in specific ages, but injury pattern does not necessarily relate to maturational status. Being aware of players' maturational status and injury-risks related to specific ages can

assist stakeholders working with youth players in more effective injury prevention and maximizing athletic potential. Several European soccer academies have already implemented maturational status monitoring into their programs to guide training methods in respect of periods of peak height velocity.

As mentioned in Chapter Two, there are no current recommendations for metrics to be used for COD assessment with IMUs. Even though the results of Chapter Four suggest that PRA could provide information on differences between injured and non-injured groups, this metric and methods combined need more research. In general, based on the results of Chapters Three and Four, PRA is not necessarily the best metric for COD quality assessment. Poor between-day reliability and considerable within-subject variation within season proves that PRA should not at least be used *per se*, but perhaps evaluate if there are for example individual thresholds for altered biomechanical patterns, that could be recognized with IMUs and PRA values. However, this would need longer and more comprehensive follow-up periods that could perhaps be combined with injury data. Studies on soccer injuries and return-to-play (RTP) have equally recommended long term evaluations and continuous risk assessments, due to for example the fact that significant number of re-injuries occur later than the routine follow-up during/after rehabilitation (Lindanger et al., 2019). Studies evaluating changes in players after RTP have found that long-term risk assessments are important, because there are individual, position specific differences between soccer players regarding decreased field-time after injury and more importantly, biomechanical differences after moderate/major injuries leading to for example decreased maximum speed (Lavoie-Gagne et al., 2021; McCann et al., 2019; Raya-González et al., 2022). All these factors will affect overall and tissue-specific loading, possibly increasing injury risk. Combining IMU

data with long-term athlete follow-ups could provide additional data to support decisions during return-to-play periods.

In Chapters Five and Six the focus was on COD movements during game-play. Majority of previous studies on CODs with IMU data have been conducted in laboratory settings and in addition with adult-male participants (Alanen et al., 2021b). The primary aim of Chapters Five and Six was to provide game-play specific information about situational patterns during CODs and their relation to playing position and PRA during the final foot contact. Studies on playing style have shown differences between playing positions and specific characteristics related to specific positions (Li et al., 2022). This was supported by the results of Chapter Five, where the playing position specific needs were analyzed using video-analysis methods. Observed positional differences during CODs raise an important question if youth soccer player testing and training should be guided more in relation to position specific demands. Chapter Five concluded that Strikers and Wingers are more often involved in “attacking type” CODs and Center Midfielders perform most CODs in general during a game. In addition, the low number of CODs performed by Center Defenders and Goalkeepers raises the question if this ability is truly discriminative when evaluating players on these positions, or should they be tested in other ways that represent their movement patterns during the games better. This brings us back to the results of Chapters Three and Four and raises the question if testing and monitoring of players should be playing position specific. In recent studies, Panduro et al. (Panduro et al., 2022) have concluded that in general Center Defenders have lower physical demands during games in youth elite soccer and these differences could be taken into account in player evaluations. Playing position affects soccer-specific skills across a wide age range, which suggests that maturational status should be considered in addition (Saward et al., 2019).

The results of Chapter Six provide interesting base for future studies and suggest how differing and changing constraints during game-play can have prominent effects on biomechanics in soccer players, especially for complex movements that require perception-reaction components, that are never the same within a game. As position specific demands are different for CODs and situational variables might change the forces experienced during the CODs in games, it is not surprising that recent studies on soccer injuries have reported differences in incidence, type, location and severity between playing positions in youth soccer (Chena Sinovas et al., 2020). Additionally, there have been recommendations already to introduce more position specific strength training based on monitored differences in physical performance and player loading in both youth male and female players (Borghi et al., 2021; Diaz-Seradilla et al., 2022). There have been promising results to develop automatic classification of CODs in soccer games with the use of machine learning methods (B. Reilly et al., 2021). Based on the kinematic analysis with IMUs of postural demands in soccer, Oliva-Lozano et al. (Oliva-Lozano, Maraver, et al., 2020) recommended position specific training with perception-reaction demands, which is the same conclusion as provided by the results of this thesis. However, more research is needed in order to provide clear recommendations for IMU metrics, data analysis methods like sampling frequencies (Gómez-Carmona et al., 2021) and addition of potential important movements related to perception-reaction moments within soccer game (McGuckian et al., 2019). There have been suggestions to provide accelerometer thresholds for movement intensities in soccer to help understanding player loading better (Díaz-Soto et al., 2022) and this is a good start for providing similar information for stakeholder use, regarding COD movements in youth soccer.

## **7.2 Limitations and future directions**

The data collection for this study started in May 2019 with recruitment of four youth soccer teams. Data was collected during testing, practices, and games, complimented with information on injuries with a questionnaire. The initial plan was to continue injury surveillance throughout the year and recruit four more teams the following spring. However, in the end of the year first news about potentially dangerous wide-spreading respiratory illness spread around the world and our study was affected obviously after all restrictions and cancellations of sports came true, starting March 2020. Eventually, we were able to continue data collection in fall 2021, but injury surveillance part had to be left out, and additionally treat the two groups (2019 and 2021 participants) as separate samples. This led to major changes to sample sizes in our manuscripts and especially less focus on youth soccer injuries, which was the initial plan. All in all, everything worked out well – we were able to collect most of the data that was originally in the plan and there was no need for complete change of analyses.

### **7.2.1 Sample size**

A convenience sample of four teams was used for each of the studies in this thesis. The justification for the use of convenience sample was based on resources. Collecting the data with IMUs for tests, practices, and games for four teams was in the limits of the budget and timeline of this small pilot study. However, it is quite common in sport science and medicine research that sample sizes do not achieve necessarily the traditional benchmarks as power of 80% at an 0.05 alpha (Lohse et al., 2020). In addition, in sport science studies the median sample size in a random selection in past three years was 19 and only approximately 10% of papers included a priori sample size calculation (Abt et al., 2020). Small sample size in studies that include hypothesis testing, like Chapters Three and Four, increases the risk of Type I and Type II errors, decreases the statistical

power, and increases the chance of higher variability in the data. However, the sample sizes for studies Three and Four are higher than usually seen in sport science studies, and since one of the aims was to inform future studies with larger sample sizes, the sample sizes used were justified. Studies on running biomechanics have concluded that in order to present small or medium effect sizes >25 participants are needed (Oliveira & Pircoveanu, 2021) and both Chapter Three and Four had sample sizes higher than 25.

With machine learning methods like PCA and LASSO that were used in Chapters Five and Six, small sample size can lead into overfitting if these models are used to perform on new data. In PCA analysis of Chapter Five, the dataset was inspected using Bartlett's test for sphericity, to make sure that the variables are not correlated, and that the data reduction could compress the analyzed data in a meaningful way. A Kaiser-Meyer-Olkin test was also used to ensure that the sampling adequacy was acceptable. All the variables showed adequately high KMO-values, indicating that the proportion of variance among variables could be common variance and therefore suited for PCA analysis. The sample size was not necessarily large enough but the amount of variables in relation to sample size was acceptable based on the criteria presented by Rojas-Valverde et al (Rojas-Valverde et al., 2020). In Chapter Six, LASSO technique was used which has a greater chance of selecting insignificant variables to the outcome or having unstable feature selection when sample size is small. These issues can be addressed by using appropriate regularization techniques and cross-validation of the data. In Chapter Six, model performance was optimized using 10-fold cross-validation as recommended (Tibshirani, 1996), and therefore the results of this small case-study can be used as a basis for future studies with confidence.

### **7.2.2 Generalizability**

Another issue related to the small sample size is the generalizability of the results. Especially Chapters Five and Six which analyzed the games and only included one game per team, are questionable in their generalizability to other teams. All the teams were from Calgary, Alberta, which can raise the question if the teams are representative to teams in other countries, especially when thinking about playing styles and tactical solutions. All the teams played on the highest level in their age group, but even in the highest level the level of the opposition can be varying. Future studies should include several games against varying oppositions and perhaps include an analysis comparing the different challenges based on the opponent level.

Both clubs included in these studies have a clear coaching curriculum and philosophy of playing, which means that teams across the same age groups will play in similar way tactically and have similar formation on the field. However, this is of course not the case with all the other youth clubs and thus calls for addition of playing tactic and formation into future analyses. In Chapter Five all the teams represented the same club, used the same formation and style of play, which justifies the combining of all the teams into same analysis.

### **7.2.3 IMU variables and sensor placement**

Several different variables, including exploitation of 1D or 3D accelerometers or integrated measures with gyroscopes and magnetometers, have been used in prior studies analyzing sport-specific movements. The number of IMUs in previous studies has been most commonly one, but up to five or more sensors have also been used. Typical sensor placement has been on the trunk inside a vest or insertion to sport equipment. Several different options to attach the sensors have included double-sided tapes, elastic bands, straps and customized vests (Camomilla et al., 2018a). Up to date, there has been no standardization of data collection procedures or data-analysis

procedures to be used with IMUs. COD movement analysis have utilized sensor placements from feet to upper back and validation studies have looked at accelerometer derived variables that have been compared with force plates or motion capture systems (Alanen et al., 2021b). Peak resultant acceleration has been used previously in for example running studies with good reliability and is commonly used to describe external loading during sports. As there are no recommendations for specific variables to be used, PRA and additionally PAV were used in Chapters Three and Four to measure impact loading during the PFC and FFC during CODs. However, as the movement variability in multiplanar movements like COD is plentiful, PRA does not capture the movement variability on different planes as it only provides the combined acceleration for certain timepoint. Pros for this approach are the feasibility of data analysis as the calculation does not require complicated algorithms and professional data analysts, but on the other hand only using the resultant will likely lead to loss of information. As one the aims was to provide feasible methods for coaches working with youth soccer players, this approach was justified and as seen in the results of Chapter Three and Four, provided information for future studies regarding the use of PRA or PAV when analyzing COD movements. Based on the results of Chapters Three and Four, especially the poor or unacceptable reliability of PRA and PAV, it was decided to approach the game-analysis with just single plane acceleration measure of  $PA_v$ . This approach has also its limitations, because accelerometer will record values based on the local reference frame, meaning that vertical acceleration is collected in regards with the sensors frame. To be able to transform this to global frame (in relation to earth), additional sensor fusion algorithms would be needed. This would be more accurate measurement for vertical forces but would not be feasible for stakeholders working in youth soccer. Additionally, the aim of Chapter Six was to provide

information about features related to higher accelerations in general, and not necessarily inform about the accelerations/forces per se.

#### **7.2.4 Signal processing of IMU data**

The sensors used in Chapters Three, Four and Six had slightly different sampling frequencies, which means the number of datapoints the sensor records in a second. Shimmer 3 IMUs have a sampling frequency of 1024 Hz, whereas the Vicon Blue Trident has a sampling frequency of 1125Hz. Signal processing techniques are used to remove the influence of noise from the data, to improve the accuracy of variables. Optimal smoothing frequencies have been analyzed in previous studies using IMUs in running and COD tasks (Wundersitz et al., 2013b). Sampling frequencies in previous COD studies have been between 10Hz and 40Hz in general (Nedergaard et al., 2014a; Wundersitz, Gastin, et al., 2015a) and based the smoothing frequency most commonly on examination of the raw accelerometer data with a Fast Fourier Transformation and deciding the cut-off frequency based on retaining 99% of the signal data. The importance of correct cut-off frequency is related to being able to remove unnecessary noise and at the same time preserving the peak values. In Chapters Three and Four, we used a similar approach, by examining the acceleration and angular velocity raw data with FFT. If the cut-off frequency is too low, important data might be lost and on the other hand if the cut-off frequency is too high, additional noise could be included into the data. Our cut-off frequencies were based on previous studies that had examined different cut-off frequencies and applied similar methods. Even though the cut-off frequencies in Chapters Three and Four were higher than the ones used by Wundersitz et al (Wundersitz et al., 2013b) and Nedergaard et al (Nedergaard et al., 2014a), they were justified by the frequency content analysis, and most likely were able to cut-off most of the possible noise included in the raw data.

### 7.3 Conclusion

Based on these results presented on this thesis, PRA or PAV can't be recommended to be used as individual factors of COD repeatability. However, these metrics might prove useful in combination with other variables, especially when trying to explain differences between males and females and changes throughout the maturational status. Machine learning methods could be utilized in future studies to analyze combinations of IMU recorded variables and their contribution to differences between soccer players' COD movements, that might increase injury risk or influence performance.

Longer follow-up periods are warranted, and COD tests complimented with IMUs could provide a time-efficient tool for practitioners to screen large player groups throughout the season and guide recommendations for individualized training. Long-term data, looking into fluctuations in individual player values from games and practices can assist in developing better testing protocols with thresholds that meet gameplay demands of individual players. To increase the understanding and quality of future studies on COD movements, a more comprehensive criteria and definition of COD movement is needed.

Lastly, coaches and sport science professionals should consider COD training and testing from a context-specific view and modifications to player testing are suggested. Including perception-reaction components, specifically opposition challenge and/or contact, to COD testing in addition with completing tasks with ball possession, would match better game-play demands. In addition, COD training should include varying combinations of these elements for the purposes of player development and player evaluation. Consideration could also be given to development of more sport-specific return to play testing protocols after injury.

## References

- Abdollahi, M., Kuber, P. M., Shiraishi, M., Soangra, R., & Rashedi, E. (2022). Kinematic Analysis of 360° Turning in Stroke Survivors Using Wearable Motion Sensors. *Sensors*, 22(1), 385. <https://doi.org/10.3390/s22010385>
- Abt, G., Boreham, C., Davison, G., Jackson, R., Nevill, A., Wallace, E., & Williams, M. (2020). Power, precision, and sample size estimation in sport and exercise science research. *Journal of Sports Sciences*, 38(17), 1933–1935. <https://doi.org/10.1080/02640414.2020.1776002>
- Achenbach, L., Krutsch, W., Koch, M., Zeman, F., Nerlich, M., & Angele, P. (2019). Contact times of change-of-direction manoeuvres are influenced by age and the type of sports: A novel protocol using the SpeedCourt ® system. *Knee Surgery, Sports Traumatology, Arthroscopy*, 27(3), 991–999. <https://doi.org/10.1007/s00167-018-5192-z>
- Ahamed, N. U., Benson, L. C., Clermont, C. A., Pohl, A. J., & Ferber, R. (2019). New Considerations for Collecting Biomechanical Data Using Wearable Sensors: How Does Inclination Influence the Number of Runs Needed to Determine a Stable Running Gait Pattern? *Sensors*, 19(11), 2516. <https://doi.org/10.3390/s19112516>
- Ahmadi, A., Mitchell, E., Richter, C., Destelle, F., Gowing, M., O'Connor, N. E., & Moran, K. (2015). Toward automatic activity classification and movement assessment during a sports training session. *IEEE Internet of Things Journal*, 2(1), 23–32. <https://doi.org/10.1109/JIOT.2014.2377238>
- Akenhead, R., Harley, J. A., & Twedde, S. P. (2016). Examining the External Training Load of an English Premier League Football Team With Special Reference to Acceleration.

*Journal of Strength and Conditioning Research*, 30(9), 2424–2432.

<https://doi.org/10.1519/JSC.0000000000001343>

Alanen, A., Räsänen, A., Benson, L., & Pasanen, K. (2021). The use of inertial measurement units for analyzing change of direction movement in sports: A scoping review.

*International Journal of Sports Science & Coaching*, 174795412110030.

<https://doi.org/10.1177/17479541211003064>

Altmann, S., Ringhof, S., Neumann, R., Woll, A., & Rumpf, M. C. (2019). Validity and reliability of speed tests used in soccer: A systematic review. *PLOS ONE*, 14(8),

e0220982. <https://doi.org/10.1371/journal.pone.0220982>

Ancillao, A., Tedesco, S., Barton, J., & O'flynn, B. (2018). Indirect measurement of ground reaction forces and moments by means of wearable inertial sensors: A systematic review.

*Sensors (Switzerland)*, 18(8). <https://doi.org/10.3390/s18082564>

Andrzejewski, M., Chmura, J., Pluta, B., Strzelczyk, R., & Kasprzak, A. (2013). Analysis of Sprinting Activities of Professional Soccer Players. *Journal of Strength and Conditioning*

*Research*, 27(8), 2134–2140. <https://doi.org/10.1519/JSC.0b013e318279423e>

Arboix-Alió, J., Bishop, C., Benet, A., Buscà, B., Aguilera-Castells, J., & Fort-Vanmeerhaeghe, A. (2021). Assessing the Magnitude and Direction of Asymmetry in Unilateral Jump and

Change of Direction Speed Tasks in Youth Female Team-Sport Athletes. *Journal of Human Kinetics*, 79, 15–27. <https://doi.org/10.2478/hukin-2021-0061>

Ardern, C. L., Glasgow, P., Schneiders, A., Witvrouw, E., Clarsen, B., Cools, A., Gojanovic, B., Griffin, S., Khan, K. M., Moksnes, H., Mutch, S. A., Phillips, N., Reurink, G., Sadler, R.,

Grävare Silbernagel, K., Thorborg, K., Wangensteen, A., Wilk, K. E., & Bizzini, M.

(2016). 2016 Consensus statement on return to sport from the First World Congress in

- Sports Physical Therapy, Bern. *British Journal of Sports Medicine*, 50(14), 853–864.  
<https://doi.org/10.1136/bjsports-2016-096278>
- Ari, E., Cihan, H., & Cetindemir, A. (2021). The effect on critical velocity of runnings with change of direction in soccer. *Baltic Journal of Health and Physical Activity*, 13(3), 11–21. <https://doi.org/10.29359/BJHPA.13.3.02>
- Armitage, M. (2021). Inter-unit reliability of IMU Step metrics using IMeasureU Blue Trident inertial measurement units for running-based team sport tasks. *J Sports Sci*. 39(13), 1512–1518. doi: 10.1080/02640414.2021.1882726
- Armitage, M., Beato, M., & McErlain-Naylor, S. A. (2021). Inter-unit reliability of IMU Step metrics using IMeasureU Blue Trident inertial measurement units for running-based team sport tasks. *Journal of Sports Sciences*, 39(13), 1512–1518.  
<https://doi.org/10.1080/02640414.2021.1882726>
- Arpinar-Avsar, P., & Celik, H. (2020). Does minimizing co-contraction increase agility test performance? *Isokinetics and Exercise Science*, 28(2), 111–118.  
<https://doi.org/10.3233/IES-192217>
- Atkinson, G., & Nevill, A. M. (1998). Statistical Methods For Assessing Measurement Error (Reliability) in Variables Relevant to Sports Medicine: *Sports Medicine*, 26(4), 217–238.  
<https://doi.org/10.2165/00007256-199826040-00002>
- Atkinson, M., Rosalie, S., & Netto, K. (2016). Physical demand of seven closed agility drills. *Sports Biomechanics*, 15(4), 473–480. <https://doi.org/10.1080/14763141.2016.1179781>
- Bahr, R., & Krosshaug, T. (2005). Understanding injury mechanisms: A key component of preventing injuries in sport. In *British Journal of Sports Medicine* (Vol. 39, Issue 6).  
<https://doi.org/10.1136/bjism.2005.018341>

- 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. <https://doi.org/10.1519/JSC.0000000000003064>
- Bangsbo, J., Mohr, M., & Krstrup, P. (2006). Physical and metabolic demands of training and match-play in the elite football player. *Journal of Sports Sciences*, 24(7), 665–674. <https://doi.org/10.1080/02640410500482529>
- Baptista, I., Johansen, D., Seabra, A., & Pettersen, S. A. (2018). Position specific player load during match-play in a professional football club. *PLOS ONE*, 13(5), e0198115. <https://doi.org/10.1371/journal.pone.0198115>
- Barber-Westin, S. D., & Noyes, F. R. (2011). Factors Used to Determine Return to Unrestricted Sports Activities After Anterior Cruciate Ligament Reconstruction. *Arthroscopy: The Journal of Arthroscopic & Related Surgery*, 27(12), 1697–1705. <https://doi.org/10.1016/j.arthro.2011.09.009>
- Barnes, C., Archer, D., Hogg, B., Bush, M., & Bradley, P. (2014). The Evolution of Physical and Technical Performance Parameters in the English Premier League. *International Journal of Sports Medicine*, 35(13), 1095–1100. <https://doi.org/10.1055/s-0034-1375695>
- Barreira, P., Robinson, M. A., Drust, B., Nedergaard, N., Raja Azidin, R. M. F., & Vanrenterghem, J. (2017). Mechanical Player Load<sup>TM</sup> using trunk-mounted accelerometry in football: Is it a reliable, task- and player-specific observation? *Journal of Sports Sciences*, 35(17), 1674–1681. <https://doi.org/10.1080/02640414.2016.1229015>
- Barrett, S., McLaren, S., Spears, I., Ward, P., & Weston, M. (2018). The Influence of Playing Position and Contextual Factors on Soccer Players' Match Differential Ratings of

- Perceived Exertion: A Preliminary Investigation. *Sports*, 6(1), 13.  
<https://doi.org/10.3390/sports6010013>
- Barron, D. J., Atkins, S., Edmundson, C., & Fewtrell, D. (2014). Accelerometer derived load according to playing position in competitive youth soccer. *International Journal of Performance Analysis in Sport*, 14(3), 734–743.  
<https://doi.org/10.1080/24748668.2014.11868754>
- Barros, R. M. L., Misuta, M. S., Menezes, R. P., Figueroa, P. J., Cunha, S. A., Anido, R., & Leite, N. J. (2007). *Analysis of the distances covered by first division Brazilian soccer players obtained with an automatic tracking method.*
- Beaulieu, M. L., Lamontagne, M., & Xu, L. (2009). Lower limb muscle activity and kinematics of an unanticipated cutting manoeuvre: A gender comparison. *Knee Surgery, Sports Traumatology, Arthroscopy*, 17(8), 968–976. <https://doi.org/10.1007/s00167-009-0821-1>
- Benjaminse, A., Gokeler, A., Fleisig, G. S., Sell, T. C., & Otten, B. (2011). What is the true evidence for gender-related differences during plant and cut maneuvers? A systematic review. *Knee Surgery, Sports Traumatology, Arthroscopy*, 19(1), 42–54.  
<https://doi.org/10.1007/s00167-010-1233-y>
- Benson, L. C., Ahamed, N. U., Kobsar, D., & Ferber, R. (2019). New considerations for collecting biomechanical data using wearable sensors: Number of level runs to define a stable running pattern with a single IMU. *Journal of Biomechanics*.  
<https://doi.org/10.1016/j.jbiomech.2019.01.004>
- Benson, L. C., Clermont, C. A., Bošnjak, E., & Ferber, R. (2018). The use of wearable devices for walking and running gait analysis outside of the lab: A systematic review. *Gait and Posture*, 63(April), 124–138. <https://doi.org/10.1016/j.gaitpost.2018.04.047>

- Benson, L. C., Cobb, S. C., Hyngstrom, A. S., Keenan, K. G., Luo, J., & O'Connor, K. M. (2019). A Principal Components Analysis Approach to Quantifying Foot Clearance and Foot Clearance Variability. *Journal of Applied Biomechanics*, *35*(2), 116–122. <https://doi.org/10.1123/jab.2018-0187>
- Benson, L. C., Räsänen, A. M., Clermont, C. A., & Ferber, R. (2022). Is This the Real Life, or Is This Just Laboratory? A Scoping Review of IMU-Based Running Gait Analysis. *Sensors*, *22*(5), 1722. <https://doi.org/10.3390/s22051722>
- Benson, L., Raisanen, A., Volkova, V., & Pasanen, K. (2020). Workload a-WEAR-ness: Monitoring Workload in Team Sports With Wearable Technology. A Scoping Review. *Journal of Orthopaedic and Sports Physical Therapy*, *50*(10), 549–564.
- Berber, E., McLean, S., Beanland, V., Read, G. J. M., & Salmon, P. M. (2020). Defining the attributes for specific playing positions in football match-play: A complex systems approach. *Journal of Sports Sciences*, *38*(11–12), 1248–1258. <https://doi.org/10.1080/02640414.2020.1768636>
- Bill, K., Mai, P., Willwacher, S., Krosshaug, T., & Kersting, U. G. (2022). Athletes with high knee abduction moments show increased vertical center of mass excursions and knee valgus angles across sport-specific fake-and-cut tasks of different complexities. *Frontiers in Sports and Active Living*, *4*, 983889. <https://doi.org/10.3389/fspor.2022.983889>
- Bishop, C., Abbott, W., Brashill, C., Turner, A., Lake, J., & Read, P. (2020). *Bilateral vs. Unilateral Countermovement Jumps: Comparing the Magnitude and Direction of Asymmetry in Elite Academy Soccer Players*. 7.
- Bishop, C., Lake, J., Loturco, I., Papadopoulos, K., Turner, A., & Read, P. (2020). Interlimb Asymmetries: The Need for an Individual Approach to Data Analysis. *Journal of*

*Strength and Conditioning Research*, 35(3), 695–701.

<https://doi.org/10.1519/JSC.0000000000002729>

Bittencourt, N. F. N., Meeuwisse, W. H., Mendonça, L. D., Nettel-Aguirre, A., Ocarino, J. M., & Fonseca, S. T. (2016). Complex systems approach for sports injuries: Moving from risk factor identification to injury pattern recognition—narrative review and new concept. *British Journal of Sports Medicine*, 50(21), 1309–1314. <https://doi.org/10.1136/bjsports-2015-095850>

Bloomfield, J., Polman, R. C. J., & Donoghue, P. O. (2007). *Physical Demands of Different Positions in FA Premier League Soccer Do individual differences in working memory capacity influence skill acquisition? View project Coaching View project.*  
<https://www.researchgate.net/publication/258035296>

Borges, T. O., Moreira, A., Bacchi, R., Finotti, R. L., Ramos, M., Lopes, C. R., & Aoki, M. S. (2017). Validation of the VERT wearable jump monitor device in elite youth volleyball players. *Biology of Sport*, 34(3), 239–242. <https://doi.org/10.5114/biolSport.2017.66000>

Borghi, S., Colombo, D., La Torre, A., Banfi, G., Bonato, M., & Vitale, J. A. (2021). Differences in GPS variables according to playing formations and playing positions in U19 male soccer players. *Research in Sports Medicine*, 29(3), 225–239.  
<https://doi.org/10.1080/15438627.2020.1815201>

Born, D.-P., Zinner, C., Düking, P., & Sperlich, B. (n.d.). *Multi-Directional Sprint Training Improves Change-Of-Direction Speed and Reactive Agility in Young Highly Trained Soccer Players.*

- Brachet, P., Blackburn, S., Nicol, A. C., & Walker, C. (2003). *Body and Limb Accelerations During Football Activities on Artificial Turf*.  
<https://doi.org/10.1017/CBO9781107415324.004>
- Bradley, P. S., Di Mascio, M., Peart, D., Olsen, P., & Sheldon, B. (2010). High-Intensity Activity Profiles of Elite Soccer Players at Different Performance Levels. *Journal of Strength and Conditioning Research*, 24(9), 2343–2351.  
<https://doi.org/10.1519/JSC.0b013e3181aeb1b3>
- Bradley, P. S., Sheldon, W., Wooster, B., Olsen, P., Boanas, P., & Krstrup, P. (2009). High-intensity running in English FA Premier League soccer matches. *Journal of Sports Sciences*, 27(2), 159–168. <https://doi.org/10.1080/02640410802512775>
- Brooks, E. R., Benson, A. C., Fox, A. S., & Bruce, L. M. (2020). Physical movement demands of elite-level netball match-play as measured by an indoor positioning system. *Journal of Sports Sciences*, 38(13), 1488–1495. <https://doi.org/10.1080/02640414.2020.1745504>
- Brughelli, M., Cronin, J., Levin, G., & Chaouachi, A. (2008). *Understanding Change of Direction Ability in Sport A Review of Resistance Training Studies*.
- Buchheit, M., & Simpson, B. M. (2017). Player-tracking technology: Half-full or half-empty glass? In *International Journal of Sports Physiology and Performance* (Vol. 12).  
<https://doi.org/10.1123/ijsp.2016-0499>
- Buchheit, M., Simpson, B. M., & Mendez-Villanueva, A. (2013). Repeated high-speed activities during youth soccer games in relation to changes in maximal sprinting and aerobic speeds. *International Journal of Sports Medicine*, 34(1), 40–48. <https://doi.org/10.1055/s-0032-1316363>

- Burland, J. P., Outerleys, J. B., Lattermann, C., & Davis, I. S. (2021). Reliability of wearable sensors to assess impact metrics during sport-specific tasks. *Journal of Sports Sciences*, 39(4), 406–411. <https://doi.org/10.1080/02640414.2020.1823131>
- Bush, M., Barnes, C., Archer, D. T., Hogg, B., & Bradley, P. S. (2015). Evolution of match performance parameters for various playing positions in the English Premier League. *Human Movement Science*, 39, 1–11. <https://doi.org/10.1016/j.humov.2014.10.003>
- Caetano, F. G., Silva, V. P. da, Torres, R. da S., Anido, R. de O., Cunha, S. A., & Moura, F. A. (2019). Analysis of Match Dynamics of Different Soccer Competition Levels Based on The Player Dyads. *Journal of Human Kinetics*, 70(1), 173–182. <https://doi.org/10.2478/hukin-2019-0030>
- Camomilla, V., Bergamini, E., Fantozzi, S., & Vannozzi, G. (2018). Trends Supporting the In-Field Use of Wearable Inertial Sensors for Sport Performance Evaluation: A Systematic Review. *Sensors*, 18(3), 873. <https://doi.org/10.3390/s18030873>
- Chambers, R., Gabbett, T. J., Cole, M. H., & Beard, A. (2015). The Use of Wearable Microsensors to Quantify Sport-Specific Movements. *Sports Medicine*, 45(7), 1065–1081. <https://doi.org/10.1007/s40279-015-0332-9>
- Chena Sinovas, M., Rodríguez Hernández, M. L., & Bores Cerezal, A. (2020). Epidemiology of injuries in young Spanish soccer players according to the playing positions (Epidemiología de las lesiones en futbolistas jóvenes españoles según la demarcación). *Retos*, 38, 459–464. <https://doi.org/10.47197/retos.v38i38.74649>
- Chia, L., Andersen, J. T., McKay, M. J., Sullivan, J., Megalaa, T., & Pappas, E. (2021). Evaluating the validity and reliability of inertial measurement units for determining knee and trunk kinematics during athletic landing and cutting movements. *Journal of*

*Electromyography and Kinesiology*, 60, 102589.

<https://doi.org/10.1016/j.jelekin.2021.102589>

- Claudino, J. G., Capanema, D. de O., de Souza, T. V., Serrão, J. C., Machado Pereira, A. C., & Nassis, G. P. (2019). Current Approaches to the Use of Artificial Intelligence for Injury Risk Assessment and Performance Prediction in Team Sports: A Systematic Review. In *Sports Medicine—Open* (Vol. 5, Issue 1). Springer. <https://doi.org/10.1186/s40798-019-0202-3>
- Coelho, D. B., Paixão, R. C. da, Oliveira, E. C. de, Becker, L. K., Ferreira-Júnior, J. B., Coelho, L. G., Dias, J. C., & Silami-Garcia, E. (2016). Exercise intensity during official soccer matches. *Brazilian Journal of Kinanthropometry and Human Performance*, 18(6), 621. <https://doi.org/10.5007/1980-0037.2016v18n6p621>
- Condello, G., Kernozek, T. W., Tessitore, A., & Foster, C. (2016). Biomechanical analysis of a change-of-direction task in college soccer players. *International Journal of Sports Physiology and Performance*, 11(1), 96–101. <https://doi.org/10.1123/ijsp.2014-0458>
- Cooper, A. (2021). An investigation into the factors affecting player development within each phase of the academy pathway in english football academies. *Soccer & Society*, 22(5), 429–441. <https://doi.org/10.1080/14660970.2020.1822342>
- Cortes, N., Onate, J., & Van Lunen, B. (2011). Pivot task increases knee frontal plane loading compared with sidestep and drop-jump. *Journal of Sports Sciences*, 29(1), 83–92. <https://doi.org/10.1080/02640414.2010.523087>
- Cummins, C., Orr, R., O'Connor, H., & West, C. (2013). Global positioning systems (GPS) and microtechnology sensors in team sports: A systematic review. *Sports Medicine*, 43(10), 1025–1042. <https://doi.org/10.1007/s40279-013-0069-2>

- Dalen, T., Jørgen, I., Gertjan, E., Geir Havard, H., & Ulrik, W. (2016). Player Load, Acceleration, and Deceleration During Forty-Five Competitive Matches of Elite Soccer. *Journal of Strength and Conditioning Research*, 30(2), 351–359.  
<https://doi.org/10.1519/JSC.0000000000001063>
- Davids, K. (2008). *Dynamics of Skill Acquisition: A Constraints-Led Approach*. Human Kinetics.
- Dawes, J., Jeffreys, I., Spiteri, T., & Nimphius, S. (2014). Broadening the View of Agility: A Scientific Review of the Literature. *Journal of Australian Strength and Conditioning*, 22(3), 6–25.
- De Ste Croix, M. B. A., Priestley, A. M., Lloyd, R. S., & Oliver, J. L. (2015). ACL injury risk in elite female youth soccer: Changes in neuromuscular control of the knee following soccer-specific fatigue: Female youth soccer and fatigue. *Scandinavian Journal of Medicine & Science in Sports*, 25(5), e531–e538. <https://doi.org/10.1111/sms.12355>
- De Villarreal, E. S., Byrne, P. J., & Ramirez-Campillo, R. (2023). Change of Direction Ability as a Sensitive Marker of Adaptation to Different Training Configurations, and Different Populations: Results from Four Experiments. *Journal of Human Kinetics*, 85(1), 63–73.  
<https://doi.org/10.2478/hukin-2022-0110>
- Della Villa, F., Buckthorpe, M., Grassi, A., Nabiuzzi, A., Tosarelli, F., Zaffagnini, S., & Villa, S. D. (2020). Systematic video analysis of ACL injuries in professional male football (soccer): Injury mechanisms, situational patterns and biomechanics study on 134 consecutive cases. *British Journal of Sports Medicine*, 54(23), 1–10.  
<https://doi.org/10.1136/bjsports-2019-101247>
- Dellal, A., Chamari, K., Wong, D. P., Ahmaidi, S., Keller, D., Barros, R., Bisciotti, G. N., & Carling, C. (2011). Comparison of physical and technical performance in European

- soccer match-play: FA Premier League and La Liga. *European Journal of Sport Science*, 11(1), 51–59. <https://doi.org/10.1080/17461391.2010.481334>
- Dellal, A., & Wong, D. (2013). REPEATED SPRINT AND CHANGE-OF-DIRECTION ABILITIES IN SOCCER PLAYERS: EFFECTS OF AGE GROUP. *Journal of Strength and Conditioning Research*, 27(9), 2504–2508. <https://doi.org/10.1519/JSC.0b013e31827f540c>
- Deprez, D., Franssen, J., Boone, J., Lenoir, M., Philippaerts, R., & Vaeyens, R. (2015). Characteristics of high-level youth soccer players: Variation by playing position. *Journal of Sports Sciences*, 33(3), 243–254. <https://doi.org/10.1080/02640414.2014.934707>
- Di Salvo, V., Baron, R., Tschan, H., Calderon Montero, F., Bachl, N., & Pigozzi, F. (2007). Performance Characteristics According to Playing Position in Elite Soccer. *International Journal of Sports Medicine*, 28(3), 222–227. <https://doi.org/10.1055/s-2006-924294>
- Díaz-Seradilla, E., Rodríguez-Fernández, A., Rodríguez-Marroyo, J. A., Castillo, D., Raya-González, J., & Villa Vicente, J. G. (2022). Inter- and intra-microcycle external load analysis in female professional soccer players: A playing position approach. *PLOS ONE*, 17(3), e0264908. <https://doi.org/10.1371/journal.pone.0264908>
- Díaz-Soto, F. J., Rico-González, M., Palucci Vieira, L. H., Clemente, F. M., Nobari, H., & Pino-Ortega, J. (2022). A systematic review of velocity and accelerometer thresholds in soccer. *International Journal of Sports Science & Coaching*, 174795412211433. <https://doi.org/10.1177/17479541221143346>
- Donnell-Fink, L. A., Klara, K., Collins, J. E., Yang, H. Y., Goczalk, M. G., Katz, J. N., & Losina, E. (2015). Effectiveness of knee injury and anterior cruciate ligament tear

prevention programs: A meta-analysis. *PLoS ONE*, 10(12).

<https://doi.org/10.1371/journal.pone.0144063>

Dos'Santos, T., Bishop, C., Thomas, C., Comfort, P., & Jones, P. A. (2019). The effect of limb dominance on change of direction biomechanics: A systematic review of its importance for injury risk. In *Physical Therapy in Sport* (Vol. 37, pp. 179–189). Churchill Livingstone. <https://doi.org/10.1016/j.ptsp.2019.04.005>

Dos'Santos, T., McBurnie, A., Thomas, C., Comfort, P., & Jones, P. A. (2020). Biomechanical Determinants of the Modified and Traditional 505 Change of Direction Speed Test. *Journal of Strength and Conditioning Research*, 34(5), 1285–1296. <https://doi.org/10.1519/JSC.0000000000003439>

Dos'Santos, T., Thomas, C., Comfort, P., & Jones, P. A. (2018). The Effect of Angle and Velocity on Change of Direction Biomechanics: An Angle-Velocity Trade-Off. *Sports Medicine*, 48(10), 2235–2253. <https://doi.org/10.1007/s40279-018-0968-3>

Dos'Santos, T., Thomas, C., Comfort, P., & Jones, P. A. (2019a). Role of the Penultimate Foot Contact During Change of Direction: Implications on Performance and Risk of Injury. *Strength & Conditioning Journal*, 41(1), 87–104. <https://doi.org/10.1519/SSC.0000000000000395>

Dos'Santos, T., Thomas, C., Comfort, P., & Jones, P. A. (2019b). The Effect of Training Interventions on Change of Direction Biomechanics Associated with Increased Anterior Cruciate Ligament Loading: A Scoping Review. In *Sports Medicine* (Vol. 49, Issue 12, pp. 1837–1859). Springer International Publishing. <https://doi.org/10.1007/s40279-019-01171-0>

- Dos'Santos, T., Thomas, C., & Jones, P. A. (2021a). How early should you brake during a 180° turn? A kinetic comparison of the antepenultimate, penultimate, and final foot contacts during a 505 change of direction speed test. *Journal of Sports Sciences*, 39(4), 395–405. <https://doi.org/10.1080/02640414.2020.1823130>
- Dos'Santos, T., Thomas, C., & Jones, P. A. (2021b). The effect of angle on change of direction biomechanics: Comparison and inter-task relationships. *Journal of Sports Sciences*, 39(22), 2618–2631. <https://doi.org/10.1080/02640414.2021.1948258>
- Dos'Santos, T., Thomas, C., Jones, P. A., & Comfort, P. (2017). Mechanical Determinants of Faster Change of Direction Speed Performance in Male Athletes. *Journal of Strength and Conditioning Research*, 31(3), 696–705.
- Dos'Santos, T., Thomas, C., Jones, P. A., & Comfort, P. (2019). Assessing Asymmetries in Change of Direction Speed Performance: Application of Change of Direction Deficit. *Journal of Strength and Conditioning Research*, 33(11), 2953–2961. <https://doi.org/10.1519/JSC.0000000000002438>
- Dos'Santos, T., Thomas, C., Comfort, P., & Jones, P. (2019). Role of the Penultimate Foot Contact During Change of Direction: Implications on Performance and Risk of Injury. *Strength and Conditioning Journal*, 41(1), 87–104. <https://doi.org/10.1519/SSC.0000000000000395>
- Downes, M. J., Brennan, M. L., Williams, H. C., & Dean, R. S. (2016). Development of a critical appraisal tool to assess the quality of cross-sectional studies (AXIS). *BMJ Open*, 6(12), 1–7. <https://doi.org/10.1136/bmjopen-2016-011458>

- Dugdale, J. H., Sanders, D., & Hunter, A. M. (2020). Reliability of Change of Direction and Agility Assessments in Youth Soccer Players. *Sports*, 8(4), 51.  
<https://doi.org/10.3390/sports8040051>
- Edwards, S., White, S., Humphreys, S., Robergs, R., & O'Dwyer, N. (2019). Caution using data from triaxial accelerometers housed in player tracking units during running. *Journal of Sports Sciences*, 37(7), 810–818. <https://doi.org/10.1080/02640414.2018.1527675>
- Edwards, W. B., Derrick, T. R., & Hamill, J. (2012). Musculoskeletal Attenuation of Impact Shock in Response to Knee Angle Manipulation. In *Journal of Applied Biomechanics* (Vol. 28, pp. 502–510). [www.JAB-Journal.com](http://www.JAB-Journal.com)
- Eke, C. U., Cain, S. M., & Stirling, L. A. (2017). Strategy quantification using body worn inertial sensors in a reactive agility task. *Journal of Biomechanics*, 64, 219–225.  
<https://doi.org/10.1016/j.jbiomech.2017.09.030>
- Emery, C. A., Meeuwisse, W. H., & Hartmann, S. E. (2005). Evaluation of Risk Factors for Injury in Adolescent Soccer: Implementation and Validation of an Injury Surveillance System. *The American Journal of Sports Medicine*, 33(12), 1882–1891.  
<https://doi.org/10.1177/0363546505279576>
- Everitt, B. S. (2019). *A Handbook of Statistical Analyses using S-Plus*. 18.
- Everitt, B. S. (1995). The Analysis of Repeated Measures: A Practical Review with Examples. *The Statistician*, 44(1), 113. <https://doi.org/10.2307/2348622>
- Ferré, L. (1995). Selection of components in principal component analysis: A comparison of methods. *Computational Statistics & Data Analysis*, 19(6), 669–682.  
[https://doi.org/10.1016/0167-9473\(94\)00020-J](https://doi.org/10.1016/0167-9473(94)00020-J)

- Finocchietti, S., Gori, M., & Souza Oliveira, A. (2019). Kinematic Profile of Visually Impaired Football Players During Specific Sports Actions. *Scientific Reports*, 9(1), 1–8.  
<https://doi.org/10.1038/s41598-019-47162-z>
- Fiorilli, G., Iuliano, E., Mitrotasios, M., Pistone, E. M., Aquino, G., Di Costanzo, A., Calcagno, G., & Di Cagno, A. (2017). Are change of direction speed and reactive agility useful for determining the optimal field position for young soccer players? *Journal of Sports Science and Medicine*, 16(2), 247–253.
- Forsman, H., Gråstén, A., Blomqvist, M., Davids, K., Liukkonen, J., & Kontinen, N. (2016). Development of perceived competence, tactical skills, motivation, technical skills, and speed and agility in young soccer players. *Journal of Sports Sciences*, 34(14), 1311–1318. <https://doi.org/10.1080/02640414.2015.1127401>
- Fox, A., Davidson, S., McGinnis, R., Cain, S., Saunders, N., & McLean, S. (2014). Exploring the use of wireless inertial measurement units for biomechanical analysis of side-step cutting manoeuvres. *Journal of Science and Medicine in Sport*, 18, e144–e145.  
<https://doi.org/10.1016/j.jsams.2014.11.149>
- Fox, A. S. (2018). Change-of-Direction Biomechanics: Is What’s Best for Anterior Cruciate Ligament Injury Prevention Also Best for Performance? *Sports Medicine*, 48(8), 1799–1807. <https://doi.org/10.1007/s40279-018-0931-3>
- Fox, J. L., O’Grady, C. J., & Scanlan, A. T. (2020a). Game schedule congestion affects weekly workloads but not individual game demands in semi-professional basketball. *Biology of Sport*, 37(1), 59–67. <https://doi.org/10.5114/biolSport.2020.91499>

- Fox, J. L., O'Grady, C. J., & Scanlan, A. T. (2020b). The Relationships Between External and Internal Workloads During Basketball Training and Games. *International Journal of Sports Physiology and Performance*, 1–6. <https://doi.org/10.1123/ijsp.2019-0722>
- Fox, J. L., Stanton, R., Sargent, C., O'Grady, C. J., & Scanlan, A. T. (2020). The impact of contextual factors on game demands in starting, semiprofessional, male basketball players. *International Journal of Sports Physiology and Performance*, 15(4), 450–456. <https://doi.org/10.1123/ijsp.2019-0203>
- Franklyn-Miller, A., Richter, C., King, E., Gore, S., Moran, K., Strike, S., & Falvey, E. C. (2017). Athletic groin pain (part 2): A prospective cohort study on the biomechanical evaluation of change of direction identifies three clusters of movement patterns. *British Journal of Sports Medicine*, 51(5), 460–468. <https://doi.org/10.1136/bjsports-2016-096050>
- Fuerst, P., Gollhofer, A., & Gehring, D. (2017). Preparation time influences ankle and knee joint control during dynamic change of direction movements. *Journal of Sports Sciences*, 35(8), 762–768. <https://doi.org/10.1080/02640414.2016.1189084>
- Gabbett, T. J. (2016). The training-injury prevention paradox: Should athletes be training smarter and harder? *British Journal of Sports Medicine*, 50(5), 273–280. <https://doi.org/10.1136/bjsports-2015-095788>
- Giandolini, M., Pavailler, S., Samozino, P., Morin, J.-B., & Horvais, N. (2015). Foot strike pattern and impact continuous measurements during a trail running race: Proof of concept in a world-class athlete. *Footwear Science*, 7(2), 127–137. <https://doi.org/10.1080/19424280.2015.1026944>

- Gil, S. M., Gil, J., Ruiz, F., Irazusta, A., & Irazusta, J. (2007). Physiological and Anthropometric Characteristics of Young Soccer Players According to Their Playing Position: Relevance for the Selection Process. *The Journal of Strength and Conditioning Research*, 21(2), 438. <https://doi.org/10.1519/R-19995.1>
- Gil, S.M., Gil, J., Ruiz, F., & Irazusta, A., Irazusta, J. (2007). Characteristics of Young Soccer Players According To Their Playing Position : *Journal of Strength and Conditioning Research / National Strength & Conditioning Association*, 21(2), 438–445.
- Gómez-Carmona, C. D., Rojas-Valverde, D., Rico-González, M., Ibáñez, S. J., & Pino-Ortega, J. (2021). What is the most suitable sampling frequency to register accelerometry-based workload? A case study in soccer. *Proceedings of the Institution of Mechanical Engineers, Part P: Journal of Sports Engineering and Technology*, 235(2), 114–121. <https://doi.org/10.1177/1754337120972516>
- Granero-Gil, P., Gómez-Carmona, C. D., Bastida-Castillo, A., Rojas-Valverde, D., De La Cruz, E., & Pino-Ortega, J. (2020). Influence of playing position and laterality in centripetal force and changes of direction in elite soccer players. *PLoS ONE*, 15(4), 1–13. <https://doi.org/10.1371/journal.pone.0232123>
- Green, B. S., Blake, C., & Caulfield, B. M. (2011). A Comparison of Cutting Technique Performance in Rugby Union Players. *Journal of Strength and Conditioning Research*, 25(10), 2668–2680. <https://doi.org/10.1519/JSC.0b013e318207ed2a>
- Griffin, J., Horan, S., Keogh, J., Andreatta, M., & Minahan, C. (2022). Time to Be Negative About Acceleration: A Spotlight on Female Football Players. *Journal of Strength and Conditioning Research*, 36(11), 3264–3271. <https://doi.org/10.1519/JSC.0000000000004061>

- Grindem, H., Snyder-Mackler, L., Moksnes, H., Engebretsen, L., & Risberg, M. A. (2016). Simple decision rules can reduce reinjury risk by 84% after ACL reconstruction: The Delaware-Oslo ACL cohort study. *British Journal of Sports Medicine*, *50*(13), 804–808. <https://doi.org/10.1136/bjsports-2016-096031>
- Gurchiek, R. D., Cheney, N., & McGinnis, R. S. (2019). Estimating biomechanical time-series with wearable sensors: A systematic review of machine learning techniques. *Sensors (Switzerland)*, *19*(23). <https://doi.org/10.3390/s19235227>
- Gurchiek, R. D., Choquette, R. H., Beynon, B. D., Slauterbeck, J. R., Tourville, T. W., Toth, M. J., & McGinnis, R. S. (2019). Open-Source Remote Gait Analysis: A Post-Surgery Patient Monitoring Application. *Scientific Reports*, *9*(1), 17966. <https://doi.org/10.1038/s41598-019-54399-1>
- Gurchiek, R. D., McGinnis, R. S., Needle, A. R., McBride, J. M., & van Werkhoven, H. (2017). The use of a single inertial sensor to estimate 3-dimensional ground reaction force during accelerative running tasks. *Journal of Biomechanics*, *61*, 263–268. <https://doi.org/10.1016/j.jbiomech.2017.07.035>
- Hader, K., Palazzi, D., & Buchheit, M. (2015). Change of Direction Speed in Soccer: How Much Braking is Enough? *Kinesiology*, *47*(1), 67–74.
- Häggglund, M., & Waldén, M. (2016). Risk factors for acute knee injury in female youth football. *Knee Surgery, Sports Traumatology, Arthroscopy*, *24*(3), 737–746. <https://doi.org/10.1007/s00167-015-3922-z>
- Hanzlíková, I., Richards, J., Athens, J., & Hébert-Losier, K. (2021). Which jump-landing task best represents lower extremity and trunk kinematics of unanticipated cutting maneuver? *Gait & Posture*, *85*, 171–177. <https://doi.org/10.1016/j.gaitpost.2021.02.003>

- Hart, L. M., Cohen, D. D., Patterson, S. D., Springham, M., Reynolds, J., & Read, P. (2019). Previous injury is associated with heightened countermovement jump force-time asymmetries in professional soccer players. *Transl Sports Med.*, 2, 256–262.  
<https://doi.org/10.1002/tsm2.92>
- Havens, K. L., & Sigward, S. M. (2015). Cutting Mechanics: Relation to Performance and Anterior Cruciate Ligament Injury Risk. *Medicine & Science in Sports & Exercise*, 47(4), 818–824. <https://doi.org/10.1249/MSS.0000000000000470>
- Hawkins, R. D., & Fuller, C. W. (1999). A prospective epidemiological study of injuries in four English professional football clubs. *British Journal of Sports Medicine*, 33(3), 196–203.  
<https://doi.org/10.1136/bjism.33.3.196>
- Hewit, J. K., Cronin, J. B., & Hume, P. A. (2012). Understanding Change of Direction Performance: A Technical Analysis of a 180° Ground-Based Turn and Sprint Task. *International Journal of Sports Science & Coaching*, 7(3), 493–501.  
<https://doi.org/10.1260/1747-9541.7.3.493>
- Hughes, G., & Dally, N. (2015). Gender difference in lower limb muscle activity during landing and rapid change of direction. *Science and Sports*, 30(3), 163–168.  
<https://doi.org/10.1016/j.scispo.2015.02.009>
- Hughes, T., Jones, R. K., Starbuck, C., Sergeant, J. C., & Callaghan, M. J. (2019). The value of tibial mounted inertial measurement units to quantify running kinetics in elite football (soccer) players. A reliability and agreement study using a research orientated and a clinically orientated system. *Journal of Electromyography and Kinesiology*, 44, 156–164.  
<https://doi.org/10.1016/j.jelekin.2019.01.001>

- Hulin, B. T., Gabbett, T. J., Johnston, R. D., & Jenkins, D. G. (2018). Playerload variables: Sensitive to changes in direction and not related to collision workloads in rugby league match play. *International Journal of Sports Physiology and Performance*, *13*(9), 1136–1142. <https://doi.org/10.1123/ijsp.2017-0557>
- Impellizzeri, F. M., Marcora, S. M., & Coutts, A. J. (2019). Internal and external training load: 15 years on. *International Journal of Sports Physiology and Performance*, *14*(2), 270–273. <https://doi.org/10.1123/ijsp.2018-0935>
- Jeffreys, I. (2011). *A Task-Based Approach to Developing Context-Specific Agility*. *33*(4), 52–59.
- John, C., Rahlf, A. L., Hamacher, D., & Zech, A. (2019). Influence of biological maturity on static and dynamic postural control among male youth soccer players. *Gait & Posture*, *68*, 18–22. <https://doi.org/10.1016/j.gaitpost.2018.10.036>
- Johnson, C. D., Outerleys, J., & Davis, I. S. (2021). Relationships between tibial acceleration and ground reaction force measures in the medial-lateral and anterior-posterior planes. *Journal of Biomechanics*, *117*. <https://doi.org/10.1016/j.jbiomech.2021.110250>
- Johnson, W. R., Mian, A., Robinson, M. A., Verheul, J., Lloyd, D. G., & Alderson, J. A. (2019). *Multidimensional ground reaction forces and moments from wearable sensor accelerations via deep learning*. *XX*(X), 1–10. <https://doi.org/10.1109/TBME.2020.3006158>
- Johnston, W., O'Reilly, M., Argent, R., & Caulfield, B. (2019). Reliability, Validity and Utility of Inertial Sensor Systems for Postural Control Assessment in Sport Science and Medicine Applications: A Systematic Review. *Sports Medicine*, *49*(5), 783–818. <https://doi.org/10.1007/s40279-019-01095-9>

- Jones, P., Bampouras, T. M., & Marrin, K. (2009). An investigation into the physical determinants of change of direction speed. *Journal of Sports Medicine and Physical Fitness*, 49(1), 97–104.
- Jones, P., Herrington, L., & Graham-Smith, P. (2016). Braking characteristics during cutting and pivoting in female soccer players. *J*, 30. <https://doi.org/10.1016/j.jelekin.2016.05.006>
- Jones, P., Thomas, C., Dos'Santos, T., McMahon, J., & Graham-Smith, P. (2017). The Role of Eccentric Strength in 180° Turns in Female Soccer Players. *Sports*, 5(4), 42. <https://doi.org/10.3390/sports5020042>
- Junge, A. (2004). Injuries in youth amateur soccer and rugby players—Comparison of incidence and characteristics. *British Journal of Sports Medicine*, 38(2), 168–172. <https://doi.org/10.1136/bjism.2002.003020>
- Kadlubowski, B., Keiner, M., Hartmann, H., Wirth, K., & Frick, U. (2019). The Relationship between Change of Direction Tests in Elite Youth Soccer Players. *Sports*, 7(5), 111. <https://doi.org/10.3390/sports7050111>
- Karcher, C., & Buchheit, M. (2014). On-Court demands of elite handball, with special reference to playing positions. In *Sports Medicine* (Vol. 44, Issue 6, pp. 797–814). Adis International Ltd. <https://doi.org/10.1007/s40279-014-0164-z>
- Keller, S., Koob, A., Corak, D., Von Schoning, V., & Born, D.-P. (2020). HOW TO IMPROVE CHANGE-OF-DIRECTION SPEED IN JUNIOR TEAM SPORT ATHLETES—HORIZONTAL, VERTICAL, MAXIMAL, OR EXPLOSIVE STRENGTH TRAINING? *Journal of Strength and Conditioning Research*, 34(2).

- Khobkhun, F., Hollands, M. A., Richards, J., & Ajjimaporn, A. (2020). Can We Accurately Measure Axial Segment Coordination during Turning Using Inertial Measurement Units (IMUs)? *Sensors*, *20*(9), 2518. <https://doi.org/10.3390/s20092518>
- Kim, H., Son, S. J., Seeley, M. K., & Hopkins, J. T. (2019). Altered movement strategies during jump landing/cutting in patients with chronic ankle instability. *Scandinavian Journal of Medicine & Science in Sports*, *29*(8), 1130–1140. <https://doi.org/10.1111/sms.13445>
- Kim, K. J. A. E., Gailey, R., Agrawal, V., Gaunard, I., Feigenbaum, L., Bennett, C., Felt, V., & Best, T. M. (2020). Quantification of agility testing with inertial sensors after a knee injury. *Medicine and Science in Sports and Exercise*, *52*(1), 244–251. <https://doi.org/10.1249/MSS.0000000000002090>
- King, E., Richter, C., Daniels, K. A. J., Franklyn-Miller, A., Falvey, E., Myer, G. D., Jackson, M., Moran, R., & Strike, S. (2021). Can Biomechanical Testing After Anterior Cruciate Ligament Reconstruction Identify Athletes at Risk for Subsequent ACL Injury to the Contralateral Uninjured Limb? *The American Journal of Sports Medicine*, *49*(3), 609–619. <https://doi.org/10.1177/0363546520985283>
- King, E., Richter, C., Franklyn-Miller, A., Daniels, K., Wadey, R., Jackson, M., Moran, R., & Strike, S. (2018). Biomechanical but not timed performance asymmetries persist between limbs 9 months after ACL reconstruction during planned and unplanned change of direction. *Journal of Biomechanics*, *81*, 93–103. <https://doi.org/10.1016/j.jbiomech.2018.09.021>
- Kozinc, Ž., & Šarabon, N. (2021). Different change of direction tests assess different physical ability parameters: Principal component analysis of nine change of direction tests.

*International Journal of Sports Science & Coaching*, 174795412110516.

<https://doi.org/10.1177/17479541211051676>

- Kristianslund, E., Faul, O., Bahr, R., Myklebust, G., & Krosshaug, T. (2014). Sidestep cutting technique and knee abduction loading: Implications for ACL prevention exercises. *British Journal of Sports Medicine*, 48(9), 779–783. <https://doi.org/10.1136/bjsports-2012-091370>
- Kristianslund, E., & Krosshaug, T. (2013). Comparison of drop jumps and sport-specific sidestep cutting: Implications for anterior cruciate ligament injury risk screening. *American Journal of Sports Medicine*, 41(3), 684–688. <https://doi.org/10.1177/0363546512472043>
- Krosshaug, T., Steffen, K., Kristianslund, E., Nilstad, A., Mok, K. M., Myklebust, G., Andersen, T. E., Holme, I., Engebretsen, L., & Bahr, R. (2015). The Vertical Drop Jump Is a Poor Screening Test for ACL Injuries in Female Elite Soccer and Handball Players. *American Journal of Sports Medicine*, 44(4). <https://doi.org/10.1177/0363546515625048>
- Lafortune, M. A., & Hennig, E. M. (1991). Contribution of angular motion and gravity to tibial acceleration. *Medicine & Science in Sports & Exercise*, 23(3). [https://journals.lww.com/acsm-msse/Fulltext/1991/03000/Contribution\\_of\\_angular\\_motion\\_and\\_gravity\\_to.15.aspx](https://journals.lww.com/acsm-msse/Fulltext/1991/03000/Contribution_of_angular_motion_and_gravity_to.15.aspx)
- Lander, N., Nahavandi, D., Mohamed, S., Essiet, I., & Barnett, L. M. (2020). Bringing objectivity to motor skill assessment in children. *Journal of Sports Sciences*, 38(13), 1539–1549. <https://doi.org/10.1080/02640414.2020.1747743>
- Lavoie-Gagne, O. Z., Retzky, J., Diaz, C. C., Mehta, N., Korrapati, A., Forlenza, E. M., Knapik, D. M., & Forsythe, B. (2021). Return-to-Play Times and Player Performance After Medial Collateral Ligament Injury in Elite-Level European Soccer Players. *Orthopaedic*

*Journal of Sports Medicine*, 9(9), 232596712110339.

<https://doi.org/10.1177/23259671211033904>

Le Gall, F., Carling, C., & Reilly, T. (2008). Injuries in Young Elite Female Soccer Players: An 8-Season Prospective Study. *The American Journal of Sports Medicine*, 36(2), 276–284.

<https://doi.org/10.1177/0363546507307866>

Le Gall, F., Carling, C., Reilly, T., Vandewalle, H., Church, J., & Rochcongar, P. (2006).

Incidence of Injuries in Elite French Youth Soccer Players: A 10-Season Study. *The American Journal of Sports Medicine*, 34(6), 928–938.

<https://doi.org/10.1177/0363546505283271>

Lee, M. J. C., Lloyd, D. G., Lay, B. S., Bourke, P. D., & Alderson, J. A. (2013). Effects of Different Visual Stimuli on Postures and Knee Moments during Sidestepping. *Medicine & Science in Sports & Exercise*, 45(9), 1740–1748.

<https://doi.org/10.1249/MSS.0b013e318290c28a>

Li, Y., Zong, S., Shen, Y., Pu, Z., Gómez, M.-Á., & Cui, Y. (2022). Characterizing player's playing styles based on player vectors for each playing position in the Chinese Football Super League. *Journal of Sports Sciences*, 40(14), 1629–1640.

<https://doi.org/10.1080/02640414.2022.2096771>

Light, N., Johnson, A., Williams, S., Smith, N., Hale, B., & Thorborg, K. (2021). Injuries in youth football and the relationship to player maturation: An analysis of time-loss injuries during four seasons in an English elite male football academy. *Scandinavian Journal of Medicine & Science in Sports*, 31(6), 1324–1334. <https://doi.org/10.1111/sms.13933>

Lindanger, L., Strand, T., Mølster, A. O., Solheim, E., & Inderhaug, E. (2019). Return to Play and Long-term Participation in Pivoting Sports After Anterior Cruciate Ligament

- Reconstruction. *The American Journal of Sports Medicine*, 47(14), 3339–3346.  
<https://doi.org/10.1177/0363546519878159>
- Link, D., & Hoernig, M. (2017). Individual ball possession in soccer. *PLOS ONE*, 12(7), e0179953. <https://doi.org/10.1371/journal.pone.0179953>
- Lohse, K. R., Sainani, K. L., Taylor, J. A., Butson, M. L., Knight, E. J., & Vickers, A. J. (2020). Systematic review of the use of “magnitude-based inference” in sports science and medicine. *PLOS ONE*, 15(6), e0235318. <https://doi.org/10.1371/journal.pone.0235318>
- Loturco, I., Jeffreys, I., Abad, C. C. C., Kobal, R., Zanetti, V., Pereira, L. A., & Nimphius, S. (2019). Change-of-direction, speed and jump performance in soccer players: A comparison across different age-categories. *Journal of Sports Sciences*, 00(00), 1–7. <https://doi.org/10.1080/02640414.2019.1574276>
- Loturco, I., Nimphius, S., Kobal, R., Bottino, A., Zanetti, V., Pereira, L. A., & Jeffreys, I. (2018). Change-of direction deficit in elite young soccer players: The limited relationship between conventional speed and power measures and change-of-direction performance. *German Journal of Exercise and Sport Research*, 48(2), 228–234. <https://doi.org/10.1007/s12662-018-0502-7>
- Lucarno, S., Zago, M., Buckthorpe, M., Grassi, A., Tosarelli, F., Smith, R., & Della Villa, F. (2021). Systematic Video Analysis of Anterior Cruciate Ligament Injuries in Professional Female Soccer Players. *The American Journal of Sports Medicine*, 49(7), 1794–1802. <https://doi.org/10.1177/03635465211008169>
- Lucas, L. A., England, B. S., Mason, T. W., Lanning, C. R., Miller, T. M., Morgan, A. M., & Almonroeder, T. G. (2018). Decision making influences tibial impact accelerations

- during lateral cutting. *Journal of Applied Biomechanics*, 34(5), 414–418.  
<https://doi.org/10.1123/jab.2017-0397>
- Luteberget, L. S., & Spencer, M. (2017). High-intensity events in international women's team handball matches. *International Journal of Sports Physiology and Performance*, 12(1), 56–61. <https://doi.org/10.1123/ijsp.2015-0641>
- Lyle, M. A., Valero-Cuevas, F. J., Gregor, R. J., & Powers, C. M. (2015). Lower extremity dexterity is associated with agility in adolescent soccer athletes: Dexterity predicts agility in soccer athletes. *Scandinavian Journal of Medicine & Science in Sports*, 25(1), 81–88.  
<https://doi.org/10.1111/sms.12162>
- MacDonald, K., Bahr, R., Baltich, J., Whittaker, J. L., & Meeuwisse, W. H. (2017). Validation of an inertial measurement unit for the measurement of jump count and height. *Physical Therapy in Sport*, 25, 15–19. <https://doi.org/10.1016/j.ptsp.2016.12.001>
- Malina, R. M., Cumming, S. P., Rogol, A. D., Coelho-e-Silva, M. J., Figueiredo, A. J., Konarski, J. M., & Kozieł, S. M. (2019). Bio-Banding in Youth Sports: Background, Concept, and Application. *Sports Medicine*, 49(11), 1671–1685. <https://doi.org/10.1007/s40279-019-01166-x>
- Mandorino, M., J. Figueiredo, A., Gjaka, M., & Tessitore, A. (2023). Injury incidence and risk factors in youth soccer players: a systematic literature review. Part II: Intrinsic and extrinsic risk factors. *Biology of Sport*, 40(1), 27–49.  
<https://doi.org/10.5114/biolport.2023.109962>
- Marcotte, R. T., Bassett, D. R., Weinhandl, J. T., & Crouter, S. E. (2018). Application of the ActiGraph GT9X IMU for the assessment of turning during walking and running.

*Biomedical Physics and Engineering Express*, 4(6). <https://doi.org/10.1088/2057-1976/aad0d0>

Marques, J. B., Paul, D. J., Graham-Smith, P., & Read, P. J. (2019). Change of Direction Assessment Following Anterior Cruciate Ligament Reconstruction: A Review of Current Practice and Considerations to Enhance Practical Application. In *Sports Medicine*. Springer International Publishing. <https://doi.org/10.1007/s40279-019-01189-4>

Marris, J., Barrett, S., Abt, G., & Towlson, C. (2022). Quantifying technical actions in professional soccer using foot-mounted inertial measurement units. *Science and Medicine in Football*, 6(2), 203–214. <https://doi.org/10.1080/24733938.2021.1910333>

Marshall, B., Franklyn-Miller, A., King, E., Moran, K., Strike, S., & Falvey, E. (2014). Biomechanical Factors Associated With Time To Complete a Change of Direction Cutting Maneuver. *Journal of Strength and Conditioning Research*, 28(10), 2845–2851.

Materne, O., Chamari, K., Farooq, A., Weir, A., Hölmich, P., Bahr, R., Greig, M., & McNaughton, L. R. (2021). Association of Skeletal Maturity and Injury Risk in Elite Youth Soccer Players: A 4-Season Prospective Study With Survival Analysis. *Orthopaedic Journal of Sports Medicine*, 9(3), 1–11. <https://doi.org/10.1177/2325967121999113>

Matsuyama, H., Hiroi, K., Kaji, K., Yonezawa, T., & Kawaguchi, N. (2019). Ballroom dance step type recognition by random forest using video and wearable sensor. *UbiComp/ISWC 2019- - 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*, 774–780. <https://doi.org/10.1145/3341162.3344852>

- McCann, R. S., Kosik, K. B., Terada, M., & Gribble, P. A. (2019). Prediction of Recurrent Injury in the Same Competitive Sport Season Following Return-to-Play From an Ankle Sprain. *International Journal of Athletic Therapy and Training*, 24(2), 78–84.  
<https://doi.org/10.1123/ijatt.2018-0006>
- McFadden, C., Daniels, K., & Strike, S. (2020). The sensitivity of joint kinematics and kinetics to marker placement during a change of direction task. *Journal of Biomechanics*, 101.  
<https://doi.org/10.1016/j.jbiomech.2020.109635>
- McGinnis, R. S., Cain, S. M., Davidson, S. P., Vitali, R. V., McLean, S. G., & Perkins, N. C. (2017). Inertial sensor and cluster analysis for discriminating agility run technique and quantifying changes across load. *Biomedical Signal Processing and Control*, 32, 150–156. <https://doi.org/10.1016/j.bspc.2016.10.013>
- McGinnis, R. S., Cain, S. M., Tao, S., Whiteside, D., Goulet, G. C., Gardner, E. C., Bedi, A., & Perkins, N. C. (2015). Accuracy of Femur Angles Estimated by IMUs During Clinical Procedures Used to Diagnose Femoroacetabular Impingement. *IEEE Transactions on Biomedical Engineering*, 62(6), 1503–1513.  
<https://doi.org/10.1109/TBME.2015.2392758>
- McGinnis, R. S., Patel, S., Silva, I., Mahadevan, N., DiCristofaro, S., Jortberg, E., Ceruolo, M., & Aranyosi, A. J. (2016). Skin mounted accelerometer system for measuring knee range of motion. *2016 38th Annual International Conference of the IEEE Engineering in Medicine and Biology Society (EMBC)*, 5298–5302.  
<https://doi.org/10.1109/EMBC.2016.7591923>
- McGuckian, T. B., Cole, M. H., Chalkley, D., Jordet, G., & Pepping, G.-J. (2019). Visual Exploration When Surrounded by Affordances: Frequency of Head Movements Is

Predictive of Response Speed. *Ecological Psychology*, 31(1), 30–48.

<https://doi.org/10.1080/10407413.2018.1495548>

McLaren, S. J., Macpherson, T. W., Coutts, A. J., Hurst, C., Spears, I. R., & Weston, M. (2018).

The Relationships Between Internal and External Measures of Training Load and Intensity in Team Sports: A Meta-Analysis. *Sports Medicine*, 48(3), 641–658.

<https://doi.org/10.1007/s40279-017-0830-z>

McLean, S. G., Borotikar, B., & Lucey, S. M. (2010). Lower limb muscle pre-motor time measures during a choice reaction task associate with knee abduction loads during dynamic single leg landings. *Clinical Biomechanics*, 25(6), 563–569.

<https://doi.org/10.1016/j.clinbiomech.2010.02.013>

McLean, S. G., Lipfert, S. W., & Van Den Bogert, A. J. (2004). Effect of Gender and Defensive

Opponent on the Biomechanics of Sidestep Cutting: *Medicine & Science in Sports & Exercise*, 36(6), 1008–1016. <https://doi.org/10.1249/01.MSS.0000128180.51443.83>

McLean, S. G., Oh, Y. K., Palmer, M. L., Lucey, S. M., Lucarelli, D. G., Ashton-Miller, J. A., & Wojtys, E. M. (2011). The Relationship Between Anterior Tibial Acceleration, Tibial Slope, and ACL Strain During a Simulated Jump Landing Task. *Journal of Bone and Joint Surgery*, 93(14), 1310–1317. <https://doi.org/10.2106/JBJS.J.00259>

Meghji, M., Balloch, A., Habibi, D., Ahmad, I., Hart, N., Newton, R., Weber, J., & Waqar, A.

(2019). An Algorithm for the Automatic Detection and Quantification of Athletes' Change of Direction Incidents Using IMU Sensor Data. *IEEE Sensors Journal*, 19(12),

4518–4527. <https://doi.org/10.1109/JSEN.2019.2898449>

- Meylan, C., Trewin, J., & McKean, K. (2017). Quantifying explosive actions in international women's soccer. *International Journal of Sports Physiology and Performance*, *12*(3), 310–315. <https://doi.org/10.1123/ijsp.2015-0520>
- Mohr, M., Krstrup, P., & Bangsbo, J. (2003). Match performance of high-standard soccer players with special reference to development of fatigue. *Journal of Sports Sciences*, *21*(7), 519–528. <https://doi.org/10.1080/0264041031000071182>
- Morgan, O. J., Drust, B., Ade, J. D., & Robinson, M. A. (2021). Change of direction frequency off the ball: New perspectives in elite youth soccer. *Science and Medicine in Football*, 1–10. <https://doi.org/10.1080/24733938.2021.1986635>
- Nagano, Y., Sasaki, S., Higashihara, A., & Ichikawa, H. (2020). Movements with greater trunk accelerations and their properties during badminton games. *Sports Biomechanics*, *19*(3), 342–352. <https://doi.org/10.1080/14763141.2018.1478989>
- Nedelec, M., McCall, A., Carling, C., Legall, F., Berthoin, S., & Dupont, G. (2014). The Influence of Soccer Playing Actions on the Recovery Kinetics After a Soccer Match. *Journal of Strength and Conditioning Research*, *28*(6), 1517–1523. <https://doi.org/10.1519/JSC.0000000000000293>
- Nedergaard, N. J., Dalbø, S., Petersen, S. V., Zebis, M. K., & Bencke, J. (2020). Biomechanical and neuromuscular comparison of single- and multi-planar jump tests and a side-cutting maneuver: Implications for ACL injury risk assessment. *Knee*, *27*(2). <https://doi.org/10.1016/j.knee.2019.10.022>
- Nedergaard, N. J., Kersting, U., & Lake, M. (2014). Using accelerometry to quantify deceleration during a high-intensity soccer turning manoeuvre. *Journal of Sports Sciences*, *32*(20), 1897–1905. <https://doi.org/10.1080/02640414.2014.965190>

- Nedergaard, N. J., Robinson, M. A., Eusterwiemann, E., Drust, B., Lisboa, P. J., & Vanrenterghem, J. (2017). The relationship between whole-body external loading and body-worn accelerometry during team-sport movements. *International Journal of Sports Physiology and Performance*, *12*(1), 18–26. <https://doi.org/10.1123/ijsp.2015-0712>
- Netto, K., Tran, J., Gastin, P., & Aisbett, B. (2010). Validity of GPS housed accelerometer data in running and cutting. *Journal of Science and Medicine in Sport*, *13*(SUPPL. 1): e37).
- Nimphius, S. (2019). Exercise and sport science failing by design in understanding female athletes. *International Journal of Sports Physiology and Performance*, *14*(9), 1157–1158. <https://doi.org/10.1123/ijsp.2019-0703>
- Nimphius, S., Callaghan, S., Bezodis, N., & Lockie, R. (2018). Change of Direction and Agility Tests: Challenging Our Current Measures of Performance. *J*, *40*(1). <https://doi.org/10.1519/SSC.0000000000000309>
- Nimphius, S., Callaghan, S. J., Spiteri, T., & Lockie, R. G. (2016). Change of Direction Deficit: A More Isolated Measure of Change of Direction Performance Than Total 505 Time. *Journal of Strength and Conditioning Research*, *30*(11), 3024–3032. <https://doi.org/10.1519/JSC.0000000000001421>
- Nimphius, S., McBride, J. M., Rice, P. E., Capps, C. L. G., & Capps, C. R. (2019). Comparison of quadriceps and hamstring muscle activity during an isometric squat between strength-matched men and women. *Journal of Sports Science and Medicine*, *18*(1), 101–108.
- Nobari, H., Gonçalves, L. G., Aquino, R., Clemente, F. M., Rezaei, M., Carlos-Vivas, J., Pérez-Gómez, J., Pueo, B., & Ardigò, L. P. (2022). Wearable Inertial Measurement Unit to Measure External Load: A Full-Season Study in Professional Soccer Players. *Applied Sciences*, *12*(3), 1140. <https://doi.org/10.3390/app12031140>

- Nygaard Falch, H., Guldteig Rædergård, H., & van den Tillaar, R. (2019). Effect of Different Physical Training Forms on Change of Direction Ability: A Systematic Review and Meta-analysis. In *Sports Medicine—Open* (Vol. 5, Issue 1). Springer.  
<https://doi.org/10.1186/s40798-019-0223-y>
- O'Donoghue, P. G. (2002). Time-motion analysis of work-rate in English FA Premier League soccer. *International Journal of Performance Analysis in Sport*, 2(1), 36–43.  
<https://doi.org/10.1080/24748668.2002.11868259>
- Odonovan, M. P., Kaplan, J. T., & Hancock, C. L. (2016). IMU Assessment Of Agility Performance While Wearing An Energy-harvesting Backpack. In *ACSM poster presentation*.
- Okholm Kryger, K., Wang, A., Mehta, R., Impellizzeri, F. M., Massey, A., & McCall, A. (2022). Research on women's football: A scoping review. *Science and Medicine in Football*, 6(5), 549–558. <https://doi.org/10.1080/24733938.2020.1868560>
- Oliva-Lozano, J. M., Conte, D., Fortes, V., & Muyor, J. M. (2023). Exploring the Use of Player Load in Elite Soccer Players. *Sports Health: A Multidisciplinary Approach*, 15(1), 61–66.  
<https://doi.org/10.1177/19417381211065768>
- Oliva-Lozano, J. M., Fortes, V., Krstrup, P., & Muyor, J. M. (2020). Acceleration and sprint profiles of professional male football players in relation to playing position. *PLOS ONE*, 15(8), e0236959. <https://doi.org/10.1371/journal.pone.0236959>
- Oliva-Lozano, J. M., Maraver, E. F., Fortes, V., & Muyor, J. M. (2020). Kinematic Analysis of the Postural Demands in Professional Soccer Match Play Using Inertial Measurement Units. *Sensors*, 20(21), 5971. <https://doi.org/10.3390/s20215971>

- Oliveira, A. S., & Pircoveanu, C. I. (2021). Implications of sample size and acquired number of steps to investigate running biomechanics. *Scientific Reports*, *11*(1), 3083.  
<https://doi.org/10.1038/s41598-021-82876-z>
- Osborne, J. W., & Costello, A. B. (n.d.). *Sample size and subject to item ratio in principal components analysis*. <https://doi.org/10.7275/KTZQ-JQ66>
- Panduro, J., Ermidis, G., Røddik, L., Vigh-Larsen, J. F., Madsen, E. E., Larsen, M. N., Pettersen, S. A., Krstrup, P., & Randers, M. B. (2021). Physical performance and loading for six playing positions in elite female football: Full-game, end-game, and peak periods. *Scandinavian Journal of Medicine & Science in Sports*, sms.13877.  
<https://doi.org/10.1111/sms.13877>
- Pasanen, K., Rossi, M. T., Parkkari, J., Heinonen, A., Steffen, K., Myklebust, G., Krosshaug, T., Vasankari, T., Kannus, P., Avela, J., Kulmala, J.-P., Perttunen, J., Kujala, U. M., & Bahr, R. (2015). Predictors of lower extremity injuries in team sports (PROFITS-study): A study protocol. *BMJ Open Sport & Exercise Medicine*, *1*(1), e000076.  
<https://doi.org/10.1136/bmjsem-2015-000076>
- Paul, D. J., Gabbett, T. J., & Nassis, G. P. (2016). Agility in Team Sports: Testing, Training and Factors Affecting Performance. *Sports Medicine*, *46*(3), 421–442.  
<https://doi.org/10.1007/s40279-015-0428-2>
- Pereira, L. A., Nimphius, S., Kobal, R., Kitamura, K., Turisco, L. A. L., Orsi, R. C., Cal Abad, C. C., & Loturco, I. (2018). Relationship Between Change of Direction, Speed, and Power in Male and Female National Olympic Team Handball Athletes. *Journal of Strength and Conditioning Research*, *32*(10), 2987–2994.  
<https://doi.org/10.1519/JSC.0000000000002494>

- Pfiffmann, D., Herbst, M., Ingelfinger, P., Simon, P., & Tug, S. (2016). Analysis of Injury Incidences in Male Professional Adult and Elite Youth Soccer Players: A Systematic Review. *Journal of Athletic Training, 51*(5), 410–424. <https://doi.org/10.4085/1062-6050-51.6.03>
- Pino-Ortega, J., Rojas-Valverde, D., Gómez-Carmona, C. D., & Rico-González, M. (2021). Training Design, Performance Analysis, and Talent Identification—A Systematic Review about the Most Relevant Variables through the Principal Component Analysis in Soccer, Basketball, and Rugby. *International Journal of Environmental Research and Public Health, 18*(5), 2642. <https://doi.org/10.3390/ijerph18052642>
- Pletcher, E. R., Dekker, T. J., Lephart, S. M., & Sell, T. C. (2021). Sex and Age Comparisons in Neuromuscular And Biomechanical Characteristics of the Knee in Young Athletes. *International Journal of Sports Physical Therapy, 16*(2). <https://doi.org/10.26603/001c.21358>
- Pojskic, H., Åslin, E., Krolo, A., Jukic, I., Uljevic, O., Spasic, M., & Sekulic, D. (2018). 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. *Frontiers in Physiology, 9*, 506. <https://doi.org/10.3389/fphys.2018.00506>
- Pol, R., Hristovski, R., Medina, D., & Balague, N. (2019). From microscopic to macroscopic sports injuries. Applying the complex dynamic systems approach to sports medicine: A narrative review. *British Journal of Sports Medicine, 53*(19), 1214–1220. <https://doi.org/10.1136/bjsports-2016-097395>

- R Core Team. *R: A Language and Environment for Statistical Computing; R Foundation for Statistical Computing*. (2020). <https://www.R-project.org/>
- Ramos, G., Nakamura, F., Pereira, L., Junior, W., Mahseredjian, F., Wilke, C., Garcia, E., & Coimbra, C. (2017). Movement Patterns of a U-20 National Women's Soccer Team during Competitive Matches: Influence of Playing Position and Performance in the First Half. *International Journal of Sports Medicine*, 38(10), 747–754. <https://doi.org/10.1055/s-0043-110767>
- Raya-González, J., Pulido, J. J., Beato, M., Ponce-Bordón, J. C., López del Campo, R., Resta, R., & García-Calvo, T. (2022). Analysis of the Effect of Injuries on Match Performance Variables in Professional Soccer Players: A Retrospective, Experimental Longitudinal Design. *Sports Medicine - Open*, 8(1), 31. <https://doi.org/10.1186/s40798-022-00427-w>
- Read, P. J., Oliver, J. L., de Ste Croix, M. B. A., Myer, G. D., & Lloyd, R. S. (2016). Reliability of the Tuck Jump Injury Risk Screening Assessment in Elite Male Youth Soccer Players. *Journal of Strength and Conditioning Research*, 30(6), 1510–1516. <https://doi.org/10.1519/JSC.0000000000001260>
- Read, P. J., Oliver, J. L., De Ste Croix, M. B. A., Myer, G. D., & Lloyd, R. S. (2018). An audit of injuries in six english professional soccer academies. *Journal of Sports Sciences*, 36(13), 1542–1548. <https://doi.org/10.1080/02640414.2017.1402535>
- Read, P. J., Oliver, J. L., & Lloyd, R. S. (2018). A prospective investigation to evaluate risk factors for lower extremity injury risk in male youth soccer players. *Scand J Med Sci Sports*, 28, 1244–1251. <https://doi.org/10.1111/sms.13013>

- Reilly, B., Morgan, O., Czanner, G., & Robinson, M. A. (2021). Automated Classification of Changes of Direction in Soccer Using Inertial Measurement Units. *Sensors*, *21*(14), 4625. <https://doi.org/10.3390/s21144625>
- Reilly, T., Williams, A. M., Nevill, A., & Franks, A. (2000). A multidisciplinary approach to talent identification in soccer. *Journal of Sports Sciences*, *18*(9), 695–702. <https://doi.org/10.1080/02640410050120078>
- Renshaw, I., Chow, J. Y., Davids, K., & Hammond, J. (2010). A constraints-led perspective to understanding skill acquisition and game play: A basis for integration of motor learning theory and physical education praxis? *Physical Education & Sport Pedagogy*, *15*(2), 117–137. <https://doi.org/10.1080/17408980902791586>
- Rienzi, E., Drust, B., Reilly, T., Carter, J. E., & Martin, A. (2000). Investigation of anthropometric and work-rate profiles of elite South American international soccer players. *The Journal of Sports Medicine and Physical Fitness*, *40*(2), 162–169.
- Roell, M., Mahler, H., Lienhard, J., Gehring, D., Gollhofer, A., & Roecker, K. (2019). Validation of wearable sensors during team sport-specific movements in indoor environments. *Sensors (Switzerland)*, *19*(16), 1–13. <https://doi.org/10.3390/s19163458>
- Roell, M., Roecker, K., Gehring, D., Mahler, H., & Gollhofer, A. (2018). Player monitoring in indoor team sports: Concurrent validity of inertial measurement units to quantify average and peak acceleration values. *Frontiers in Physiology*, *9*(FEB), 1–13. <https://doi.org/10.3389/fphys.2018.00141>
- Rojas-Valverde, D., Pino-Ortega, J., Gómez-Carmona, C. D., & Rico-González, M. (2020). A Systematic Review of Methods and Criteria Standard Proposal for the Use of Principal

- Component Analysis in Team's Sports Science. *International Journal of Environmental Research and Public Health*, 17(23), 8712. <https://doi.org/10.3390/ijerph17238712>
- Ryan, C., Uthoff, A., McKenzie, C., & Cronin, J. (2022). Traditional and Modified 5-0-5 Change of Direction Test: Normative and Reliability Analysis. *Strength & Conditioning Journal*, 44(4), 22–37. <https://doi.org/10.1519/SSC.0000000000000691>
- Sankey, S. P., Robinson, M. A., & Vanrenterghem, J. (2020). Whole-body dynamic stability in side cutting: Implications for markers of lower limb injury risk and change of direction performance. *Journal of Biomechanics*, 104, 109711. <https://doi.org/10.1016/j.jbiomech.2020.109711>
- Santoro, E., Tessitore, A., Liu, C., Chen, C.-H., Khemtong, C., Mandorino, M., Lee, Y.-H., & Condello, G. (2021). The Biomechanical Characterization of the Turning Phase during a 180° Change of Direction. *International Journal of Environmental Research and Public Health*, 18(11), 5519. <https://doi.org/10.3390/ijerph18115519>
- Sariati, D., Hammami, R., Chtara, M., Zagatto, A., Boullosa, D., Clark, C. C. T., Hackney, A. C., Granacher, U., Souissi, N., & Zouhal, H. (2020). Change-of-Direction Performance in Elite Soccer Players: Preliminary Analysis According to Their Playing Positions. *International Journal of Environmental Research and Public Health*, 17(22), 8360. <https://doi.org/10.3390/ijerph17228360>
- Saward, C., Morris, J. G., Nevill, M. E., & Sunderland, C. (2019). The effect of playing status, maturity status, and playing position on the development of match skills in elite youth football players aged 11–18 years: A mixed-longitudinal study. *European Journal of Sport Science*, 19(3), 315–326. <https://doi.org/10.1080/17461391.2018.1508502>

Schreurs, M. J., Benjaminse, A., & Lemmink, K. A. P. M. (2017). Sharper angle, higher risk?

The effect of cutting angle on knee mechanics in invasion sport athletes. *Journal of Biomechanics*, *63*, 144–150. <https://doi.org/10.1016/j.jbiomech.2017.08.019>

Serner, A., Tol, J. L., Jomaah, N., Weir, A., Whiteley, R., Thorborg, K., Robinson, M., &

Hölmich, P. (2015). Diagnosis of Acute Groin Injuries: A Prospective Study of 110 Athletes. *American Journal of Sports Medicine*, *43*(8), 1857–1864.

<https://doi.org/10.1177/0363546515585123>

Seshadri, D. R., Li, R. T., Voos, J. E., Rowbottom, J. R., Alfes, C. M., Zorman, C. A., &

Drummond, C. K. (2019). Wearable sensors for monitoring the internal and external workload of the athlete. *Npj Digital Medicine*, *2*(1), 71. <https://doi.org/10.1038/s41746-019-0149-2>

Sheerin, K. R., Besier, T. F., Reid, D., & Hume, P. A. (2018). The one-week and six-month

reliability and variability of three-dimensional tibial acceleration in runners. *Sports Biomechanics*, *17*(4), 531–540.

Sheerin, K. R., Reid, D., & Besier, T. F. (2019). The measurement of tibial acceleration in

runners—A review of the factors that can affect tibial acceleration during running and evidence-based guidelines for its use. *Gait & Posture*, *67*, 12–24.

<https://doi.org/10.1016/j.gaitpost.2018.09.017>

Sheppard, J. M., & Young, W. B. (2006). Agility literature review: Classifications, training and

testing. *Journal of Sports Sciences*, *24*(9), 919–932.

<https://doi.org/10.1080/02640410500457109>

- Simons, C., & Bradshaw, E. J. (2016). Reliability of accelerometry to assess impact loads of jumping and landing tasks. *Sports Biomechanics*, *15*(1), 1–10.  
<https://doi.org/10.1080/14763141.2015.1091032>
- Simpson, M. J., Jenkins, D. G., Scanlan, A. T., & Kelly, V. G. (2020). Relationships between external- And internal-workload variables in an elite female netball team and between playing positions. *International Journal of Sports Physiology and Performance*, *15*(6), 841–846. <https://doi.org/10.1123/ijssp.2019-0619>
- Sinclair, J. K. (2017). Effects of Court Specific and Minimalist Footwear on the Biomechanics of a Maximal 180° Cutting Manoeuvre. *Human Movement*, *18*(1), 29–36.  
<https://doi.org/10.1515/humo-2017-0001>
- Skazalski, C., Whiteley, R., Hansen, C., & Bahr, R. (2018). A valid and reliable method to measure jump-specific training and competition load in elite volleyball players. *Scandinavian Journal of Medicine & Science in Sports*, *28*(5), 1578–1585.  
<https://doi.org/10.1111/sms.13052>
- Spencer, K., Paget, N., Kilding, A., & McErlain-Naylor, S. A. (2020). Physical, physiological, and technical demands of national netball umpires at different competition levels. *Journal of Sports Sciences*, *38*(14), 1660–1665. <https://doi.org/10.1080/02640414.2020.1754718>
- Spiteri, T., Cochrane, J. L., Hart, N. H., Haff, G. G., & Nimphius, S. (2013). Effect of strength on plant foot kinetics and kinematics during a change of direction task. *European Journal of Sport Science*, *13*(6), 646–652. <https://doi.org/10.1080/17461391.2013.774053>
- Spiteri, T., Newton, R. U., Binetti, M., Hart, N., Sheppard, J., & Nimphius, S. (2015). Mechanical Determinants of Faster Change of Direction and Agility Performance in

- Female Basketball Athletes. *Journal of Strength and Conditioning Research*, 29(8), 2205–2214.
- Spiteri, T., Nimphius, S., Hart, N. H., Specos, C., Sheppard, J. M., & Newton, R. U. (2014). The Contribution of Strength Characteristics To Change of Direction and Agility Performance in Female Basketball Athletes. *J Strength Cond Res.*, 28(9), 2415–2423.
- Sporis, G., Jukic, I., Milanovic, L., & Vucetic, V. (2010). Reliability and Factorial Validity of Agility Tests for Soccer Players. *Journal of Strength and Conditioning Research*, 24(3), 679–686. <https://doi.org/10.1519/JSC.0b013e3181c4d324>
- Staunton, C., Wundersitz, D., Gordon, B., & Kingsley, M. (2017). Construct Validity of Accelerometry-Derived Force to Quantify Basketball Movement Patterns. *International Journal of Sports Medicine*, 38(14), 1090–1096. <https://doi.org/10.1055/s-0043-119224>
- Stetter, B. J., Krafft, F. C., Ringhof, S., Stein, T., & Sell, S. (2020). A Machine Learning and Wearable Sensor Based Approach to Estimate External Knee Flexion and Adduction Moments During Various Locomotion Tasks. *Frontiers in Bioengineering and Biotechnology*, 8(January). <https://doi.org/10.3389/fbioe.2020.00009>
- Stetter, B. J., Ringhof, S., Krafft, F. C., Sell, S., & Stein, T. (2019). Estimation of knee joint forces in sport movements using wearable sensors and machine learning. *Sensors (Switzerland)*, 19(17), 1–12. <https://doi.org/10.3390/s19173690>
- Stirling, L., Eke, C., & Cain, S. M. (2018). Examination of the perceived agility and balance during a reactive agility task. *PLoS ONE*, 13(6), 1–14. <https://doi.org/10.1371/journal.pone.0198875>

- Suzuki, Y., Ae, M., Takenaka, S., & Fujii, N. (2014). Comparison of support leg kinetics between side-step and cross-step cutting techniques. *Sports Biomechanics*, *13*(2), 144–153. <https://doi.org/10.1080/14763141.2014.910264>
- Svilar, L., Castellano, J., & Jukić, I. (2019). Comparison of 5vs5 Training Games and Match-Play Using Microsensor Technology in Elite Basketball. *Journal of Strength and Conditioning Research*, *33*(7), 1897–1903.
- Svilar, L., Castellano, J., Jukic, I., & Casamichana, D. (2018). Positional differences in elite basketball: Selecting appropriate training-load measures. *International Journal of Sports Physiology and Performance*, *13*(7), 947–952. <https://doi.org/10.1123/ijsp.2017-0534>
- Svilar, L., & Jukić, I. (2018). Load monitoring system in top-level basketball team. *Kinesiology*, *50*(1), 25–33. <https://doi.org/10.26582/k.50.1.4>
- Tamura, A., Akasaka, K., Otsudo, T., Sawada, Y., Okubo, Y., Shiozawa, J., Toda, Y., & Yamada, K. (2016). Fatigue Alters Landing Shock Attenuation During a Single-Leg Vertical Drop Jump. *Orthopaedic Journal of Sports Medicine*, *4*(1), 1–7. <https://doi.org/10.1177/2325967115626412>
- Tamura, A., Akasaka, K., Otsudo, T., Shiozawa, J., Toda, Y., & Yamada, K. (2017). Dynamic knee valgus alignment influences impact attenuation in the lower extremity during the deceleration phase of a single-leg landing. *PLOS ONE*, *12*(6), 1–12. <https://doi.org/10.1371/journal.pone.0179810>
- Taylor, J. B., Wright, A. A., Dischiavi, S. L., Townsend, M. A., & Marmon, A. R. (2017). Activity Demands During Multi-Directional Team Sports: A Systematic Review. *Sports Medicine*, *47*(12), 2533–2551. <https://doi.org/10.1007/s40279-017-0772-5>

- Tedesco, S., Crowe, C., Ryan, A., Sica, M., Scheurer, S., Clifford, A. M., Brown, K. N., & O'Flynn, B. (2020). 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)*, 20(11). <https://doi.org/10.3390/s20113029>
- Thomas, C., Dos'Santos, T., Comfort, P., & Jones, P. A. (2020). Male and female soccer players exhibit different knee joint mechanics during pre-planned change of direction. *Sports Biomechanics*, 1–14. <https://doi.org/10.1080/14763141.2020.1830160>
- Tibshirani, R. (1996). Regression and Shrinkage via the Lasso. *J R Stat Soc.*, 58(1), 267–288.
- Trama, R., Hautier, C., & Blache, Y. (2020). Input and soft-tissue vibration characteristics during sport-specific tasks. *Medicine and Science in Sports and Exercise*, 52(1), 112–119. <https://doi.org/10.1249/MSS.0000000000002106>
- Trecroci, A., Longo, S., Perri, E., Iaia, F. M., & Alberti, G. (2019). Field-based physical performance of elite and sub-elite middle-adolescent soccer players. *Research in Sports Medicine*, 27(1), 60–71. <https://doi.org/10.1080/15438627.2018.1504217>
- van der Sluis, A., Elferink-Gemser, M., Coelho-e-Silva, M., Nijboer, J., Brink, M., & Visscher, C. (2013). Sport Injuries Aligned to Peak Height Velocity in Talented Pubertal Soccer Players. *International Journal of Sports Medicine*, 35(04), 351–355. <https://doi.org/10.1055/s-0033-1349874>
- Varley, M. C., Gregson, W., McMillan, K., Bonanno, D., Stafford, K., Modonutti, M., & Di Salvo, V. (2017). Physical and technical performance of elite youth soccer players during international tournaments: Influence of playing position and team success and opponent quality. *Science and Medicine in Football*, 1(1), 18–29. <https://doi.org/10.1080/02640414.2016.1230676>

- Waldén, M., Atroshi, I., Magnusson, H., Wagner, P., & Häggglund, M. (2012). Republished research: Prevention of acute knee injuries in adolescent female football players: Cluster randomised controlled trial. *British Journal of Sports Medicine*, *46*(13), 904.  
<https://doi.org/10.1136/bjsports-2012-e3042rep>
- Waldén, M., Häggglund, M., Magnusson, H., & Ekstrand, J. (2016). 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. *British Journal of Sports Medicine*, *50*(12), 744–750. <https://doi.org/10.1136/bjsports-2015-095952>
- Willberg, C., Kohler, A., & Zentgraf, K. (2023). Construct Validity and Applicability of a Team-Sport-Specific Change of Direction Test. *Journal of Human Kinetics*, *85*(1), 115–126.  
<https://doi.org/10.2478/hukin-2022-0115>
- Williams, A. M., & Reilly, T. (2000). Talent identification and development in soccer. *Journal of Sports Sciences*, *18*(9), 657–667. <https://doi.org/10.1080/02640410050120041>
- Wundersitz, D. W. T., Gastin, P. B., Robertson, S., Davey, P. C., & Netto, K. J. (2015). Validation of a Trunk-mounted Accelerometer to Measure Peak Impacts during Team Sport Movements. *International Journal of Sports Medicine*, *36*(9), 742–746.  
<https://doi.org/10.1055/s-0035-1547265>
- Wundersitz, D. W. T., Josman, C., Gupta, R., Netto, K. J., Gastin, P. B., & Robertson, S. (2015). Classification of team sport activities using a single wearable tracking device. *Journal of Biomechanics*, *48*(15), 3975–3981. <https://doi.org/10.1016/j.jbiomech.2015.09.015>
- Wundersitz, D. W. T., Netto, K. J., Aisbett, B., & Gastin, P. B. (2013). Validity of an upper-body-mounted accelerometer to measure peak vertical and resultant force during running

- and change-of-direction tasks. In *Sports Biomechanics* (Vol. 12, Issue 4, pp. 403–412). Taylor & Francis. <https://doi.org/10.1080/14763141.2013.811284>
- Yanci, J., Los Arcos, A., Castillo, D., & Cámara, J. (2017). Sprinting, Change of Direction Ability and Horizontal Jump Performance in Youth Runners According to Gender. *Journal of Human Kinetics*, *60*(1), 199–207. <https://doi.org/10.1515/hukin-2017-0103>
- Young, W. B., Dawson, B., & Henry, G. J. (2015). Agility and change-of-direction speed are independent skills: Implications for training for agility in invasion sports. *International Journal of Sports Science and Coaching*, *10*(1), 159–169. <https://doi.org/10.1260/1747-9541.10.1.159>
- Young, W. B., Hepner, J., & Robbins, D. W. (2012). Movement Demands in Australian Rules Football as Indicators of Muscle Damage. *Journal of Strength and Conditioning Research*, *26*(2), 492–496. <https://doi.org/10.1519/JSC.0b013e318225a1c4>
- Young, W., & Farrow, D. (2013). The importance of a sport-specific stimulus for training agility. *Strength and Conditioning Journal*, *35*(2), 39–43. <https://doi.org/10.1519/SSC.0b013e31828b6654>
- Young, W., Rayner, R., & Talpey, S. (2021). It's Time to Change Direction on Agility Research: A Call to Action. *Sports Medicine - Open*, *7*(1), 12. <https://doi.org/10.1186/s40798-021-00304-y>
- Zaferiou, A. M., Ojeda, L., Cain, S. M., Vitali, R. V., Davidson, S. P., Stirling, L., & Perkins, N. C. (2017). Quantifying performance on an outdoor agility drill using foot-mounted inertial measurement units. *PLoS ONE*, *12*(11), 1–15. <https://doi.org/10.1371/journal.pone.0188184>

Zago, M., Sforza, C., Dolci, C., Tarabini, M., & Galli, M. (2019). Use of machine learning and wearable sensors to predict energetics and kinematics of cutting maneuvers. *Sensors (Switzerland)*, *19*(14), 9–11. <https://doi.org/10.3390/s19143094>

Zeng, Z., Liu, Y., Hu, X., Tang, M., & Wang, L. (2022). Validity and Reliability of Inertial Measurement Units on Lower Extremity Kinematics During Running: A Systematic Review and Meta-Analysis. *Sports Medicine - Open*, *8*(1), 86. <https://doi.org/10.1186/s40798-022-00477-0>