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An Ecological Dynamics Approach to ACL Injury Risk Screening in Team Ball Sports

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Pieter Heuvelmans

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Principal supervisor

Prof. Dr. rer. medic. Jochen Baumeister
Exercise Science and Neuroscience Unit
Department of Exercise & Health
Paderborn University
Germany

Secondary supervisor

Prof. Dr. Erik Witvrouw
Department of Rehabilitation Sciences
Faculty of Medicine and Health Sciences
Ghent University
Belgium

Declaration of Authorship

I declare to have read and accepted the Ph.D. regulations of the Faculty of Sciences, University of Paderborn (no. 10.21 / 12, 31-03-2021). Furthermore, I declare that the work presented in the present thesis is original and the result of my own work, except as acknowledged, and has not been submitted, neither in parts nor as a whole, for any other degree or qualification at any University. Content and ideas taken from other sources are - to the best of my knowledge and belief - cited correspondingly. As such, I declare that the research presented in the included studies was conducted in absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Pieter Heuvelmans, 13 March 2025

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Abstract

Team ball sports like football and handball are popular, however, they are also associated with lower limb injuries. Non-contact anterior cruciate ligament (ACL) injury is a well-known example with a large burden. Injury risk factors identified through laboratory-based research have informed the development of injury prevention programmes (IPPs) prescribing neuromuscular training. Reported efficacy shows risk reductions around 67%, however, the number needed to treat (NNT) is between 71 and 120. In order to reduce the NNT and to improve injury prevention, this dissertation argues that the underlying injury risk research may benefit from further developments. Therefore, this dissertation took an ecological dynamics approach (EDA) to studying team ball sport movements with the aim of contributing to knowledge needed for ACL injury risk screening. Study I reviewed the literature and formulated EDA principles. Study II validated the use of an inertial sensor system for team ball sports movements. Study III investigated relationships between constraints, joint coordination, and performance of a football drill in talented youth. Study IV compared traditional computer-based neurocognitive tests to novel agility-based equivalents. Study V examined group- and player-level adaptations to stop-signals in a reactive movement task. Study VI evaluated age- and position-specific agility performance and kinematics of elite handball players in a mobile screening test. This thesis used an ecological dynamics approach to study non-contact ACL injury risk in team ball sports, highlighting individual movement adaptations to constraints. Findings support tailored injury prevention over generalized methods, advocating sport-specific screening with neurocognitive load for better injury risk assessment.

Zusammenfassung

Mannschaftssportarten wie Fußball oder Handball erfreuen sich großer Beliebtheit, sind jedoch mit einem erhöhten Risiko für Verletzungen der unteren Extremität assoziiert. Insbesondere schwere Verletzungen, wie der Riss des vorderen Kreuzbands (ACL), können weitreichende Konsequenzen für die Betroffenen haben. Die Identifikation relevanter Risikofaktoren im Rahmen experimenteller Laboruntersuchungen stellt eine essenzielle Grundlage für die Entwicklung evidenzbasierter Präventionsprogramme dar. Obgleich solche Programme das Verletzungsrisiko um bis zu 67 % reduzieren können, erfordert ihre Umsetzung eine Number Needed to Treat (NNT) von 71 bis 120. Eine Reduktion der NNT und eine Optimierung bestehender Präventionsstrategien erfordern daher weiterführende Forschung zur Verbesserung der Screeningverfahren zur Detektion individueller Risikofaktoren. Vor diesem Hintergrund untersucht die vorliegende Dissertation die Entwicklung neuer Screeningansätze zur Risikoerfassung im Kontext des Mannschaftssports. Als theoretischer Rahmen wurde der *Ecological Dynamics Approach* (EDA) gewählt, um das Verletzungsgeschehen in interaktiven, dynamischen Sportumgebungen zu analysieren und die Prävention von Kreuzbandverletzungen durch optimierte Screeningmethoden zu verbessern. Studie I umfasst ein Literaturreview zur Ableitung zentraler Prinzipien des EDA für das Risikoscreening. In Studie II wurde der Einsatz von Inertialsensoren zur Analyse kinematischer Parameter in Mannschaftssportarten validiert. Studie III analysierte die Wechselwirkungen zwischen Aufgabenrestriktionen, Bewegungskoordination und Leistungsfähigkeit in einem fußballspezifischen Parcours. Studie IV verglich die Leistung zwischen etablierten, computerbasierten kognitiven Tests und bewegungsbasierten, sportartspezifischen Äquivalenten dieser Aufgaben. Studie V untersuchte die Anpassungen in der Bewegungskoordination in Folge von inhibitorischen Reizen (Stop-Signalen). Studie VI analysierte in einer feldbasierten Untersuchung alters- und positionsspezifischer Unterschiede in einer Agilitätsaufgabe mit Fokus auf Leistung und Bewegungskoordination bei Leistungshandballspielern. Alle Studien untersuchten somit spezifische Aspekte des EDA im Kontext des Verletzungsrisikoscreenings und unterstreichen die zentrale Rolle von Aufgabenrestriktionen für die Leistungsfähigkeit und Bewegungskoordination. Die gewonnenen Erkenntnisse tragen zur Entwicklung maßgeschneiderter Präventionsprogramme bei, die insbesondere neurokognitive Elemente zur Optimierung des Verletzungsrisikoscreenings integrieren.

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DOI: 10.1080/14763141.2021.1960419

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Abbreviations

Analysis of Variance — ANOVA

Anterior Cruciate Ligament — ACL

Constraints-Led Approach — CLA

Coordination Pattern Frequency — CPF

Coupling Angle — CA

Dynamical Systems Theory — DST

Ecological Dynamics Approach — EDA

Inertial Measurement Unit — IMU

Injury prevention programme — IPP

Interquartile Range — IQR

Knee Abduction Moment — KAM

Optoelectronic Marker-Based — OMB

Oslo Sports Trauma Research Center — OSTRC

Statistical Parametric Mapping — SPM

Wearable Inertial Sensor — WIS

1 Background

Worldwide, millions of people participate in team ball sports such as football (FIFA 2007), basketball (FIBA 2020), and handball (IHF n.d.). Participation in sports is associated with improved physical and mental health, and it contributes to a better quality of life (Bjørnarå et al. 2021, Eather et al. 2023). Unfortunately, team ball sports are also linked with injuries, many of which affect the lower limbs (Giroto et al. 2017, Mack et al. 2024, Medina-Porqueres et al. 2024). For example, the most common injury in football is an ankle sprain with a rate of 2.6 injuries per 1000 exposure hours (Le Gall et al. 2008, Silvers-Granelli et al. 2015). The knee is the second most commonly injured body part in football with a rate of 2.3 injuries per 1000 exposure hours (Silvers-Granelli et al. 2015). Lower limb injuries can occur in player-to-player contact but also through non-contact mechanisms. Non-contact injuries are the result of the player's movements. For example, rolling an ankle (i.e., forced inversion) can result in an ankle sprain with partial or complete rupture of the lateral collateral ligaments (Flore et al. 2025). The consequences of non-contact injuries vary: clinical intervention and rehabilitation periods are tailored to the severity of an injury and may take anywhere from several days to multiple months or even upwards of one year (Toohey et al. 2022, Cresswell & Barden 2025). After rehabilitation, however, not all injured athletes will return to their competitive level (Lai et al. 2018, Waldén et al. 2016). In professional sports, the impact of a severe injury can thus mean the end of an athlete's career. The anterior cruciate ligament (ACL) rupture is a prominent example of such an injury. A substantial number of ACL ruptures in football (44%) occur in non-contact situations (Della Villa et al. 2020). Non-contact ACL injuries usually occur during rapid deceleration, jump-landing, or change-of-direction (Della Villa et al. 2020, Waldén et al. 2015). The consequences of ACL injury are notoriously impactful. First, ACL injuries result in substantial time loss due to the large number of days of absence from team training and match play, with medical clearance to return typically at over 6 months postoperatively (Waldén et al. 2016, Ardern et al. 2011). Second, even after undergoing ACL reconstruction surgery, only 53% of athletes return to preinjury level of competition (Lindanger et al. 2019, Sandon et al. 2025). Third, ACL injuries result in a significant financial burden to society since operative treatments have an average cost of $18,744 (Stewart et al. 2017). Fourth, injured athletes often suffer from reinjury (30%) and knee osteoarthritis (36%) (Lindanger et al. 2019, Webster & Hewett 2022). Finally, the personal burden of injury includes reduced knee function, occupational limitations, and worse quality of life (Filbay et al. 2022). Taking all of these aspects of burden into consideration, primary prevention of ACL injuries is recognised as essential

(Hewett et al. 2016). The ultimate challenge for ACL injury prevention research is to develop and implement effective programmes aimed at reducing the incidence of injury. Injury prevention researchers have traditionally followed the *sequence of prevention* by van Mechelen et al. (1992) which describes: step 1) establish the extent of the sports injury problem; step 2) establish the aetiology and mechanism of injury; step 3) introduce preventive measures; and step 4) assess the measures' effectiveness. This framework highlights that at the core of injury prevention there is the discipline of injury risk research.

1.1 Injury Risk Research

Injury risk factors can be extrinsic: external to the athlete, for example, sport-related elements like opponent behaviour or game rules as well as environmental variables like weather or high/low friction surface (Meeuwisse et al. 2007). Other risk factors are intrinsic: internal to the athlete, for instance, physical attributes like strength and flexibility but also psychological aspects like anxiety or concentration (Meeuwisse et al. 2007). Some risk factors are considered non-modifiable or unchangeable, such as age, sex, genetic predispositions, or previously sustained injuries. By studying the mechanisms of injury, researchers aim to identify modifiable risk factors which could be targeted and changed by some type of intervention. In this manner, biomechanical and neuromuscular ACL injury risk factors have been extensively explored in laboratory experiments in the last 25 years (Besier et al. 2001, Landry et al. 2007, Imwalle et al. 2009, Nguyen et al. 2018). Particularly, knee abduction moment (KAM) during a jump-landing task or change-of-direction was strongly associated with ACL injury in prospective studies, with up to 7.2-fold increased risk (Hewett et al. 2005, Sigurðsson et al. 2024). Furthermore, other injury risk factors were revealed, including lateral trunk flexion (Collings et al. 2022), decreased hip adduction strength (Beynnon et al. 2023), increased joint laxity (Beynnon et al. 2023), and jump-landing strategies with less knee flexion and greater vertical ground reaction force (Leppänen et al. 2017).

These lab-based risk factors have provided information for the development of ACL injury prevention measures (Hewett et al. 2016). Over the years, various prevention programmes were developed including the *OSTRC neuromuscular warm-up* (Olsen et al. 2005), *Prevent Injury and Enhance Performance* (Gilchrist et al. 2008), *FIFA 11+* (Soligard et al. 2008), *Knäkontroll* (Hägglund et al. 2009), and *HarmoKnee* (Kiani et al. 2010). Several systematic reviews and meta-analyses have evaluated the effectiveness of these neuromuscular training interventions in reducing ACL injuries. When compared to control, athletes that participated in an intervention group had a risk reduction between 43.8% and

50% for all ACL injuries (Sugimoto et al. 2012, Webster et al. 2018). For non-contact ACL injuries, this risk reduction was between 67% and 73.4% (Sugimoto et al. 2012, Webster et al. 2018). However, these reports also show that the number needed to treat (NNT) was between 71 and 120, indicating the number of athletes that would need to be trained in order to prevent one ACL injury (Clar et al. 2024, Sugimoto et al. 2012). Although the risk reductions indicate a beneficial effect of these injury prevention programmes, the relatively high NNT means that many athletes would need training to prevent just one injury. In order to reduce the NNT, it has become clear that injury prevention may require further developments. One way to improve injury prevention programmes is to rethink the research approach used to create them. By evaluating potential weaknesses in injury risk research, it may open avenues for improvements that contribute to more effective injury prevention.

Concerns have been raised about several aspects of the traditional approach to injury risk research. These concerns include the tendency of monocausal thinking or oversimplification of injury causality (Bekker & Clark 2016, Bittencourt et al. 2016, Hulme & Finch 2015); the fallacy of the ideal movement template which all athletes should aspire to learn (Seifert et al. 2013); instructions that promote an internal rather than external focus (Benjaminse et al. 2015a); and limited motivation among athletes due to a lack of sport-specific and fun elements (Benjaminse & Verhagen, 2021). Furthermore, the typical biomechanical experiments used in injury risk research are designed to be standardised and to reliably extract singular measures, such as peak KAM or knee flexion angle at initial contact of a prescribed movement task such as a drop-jump or a sidestep cut. The question remains whether these singular measures are a valid way to describe complex human biomechanics (Shultz et al. 2015). In a consensus statement, ACL researchers recommended that to better understand the richness of human biomechanics, research should broaden its scope to alternative approaches to analysis including, for example, statistical parametric mapping (SPM) (Shultz et al. 2015). SPM performs hypothesis testing on time series, also called waveforms, and is therefore a more comprehensive analysis alternative to comparisons of singular biomechanical measures.

Another question that remains is whether lab studies are able to simulate human movement behaviour as it occurs outside the lab environment and whether the assessments are representative of the sports contexts (Dawson & Marcotte 2017). Some researchers have emphasized the importance of preserving the athlete-environment relationship, enabling athletes to generate specific movement solutions tailored to the unique combination of constraints they encounter, thereby reflecting the sports context (Renshaw et al. 2010).

Moreover, concerns have been voiced about the potential lack of transfer from rehearsed movement patterns during practice or warm-up to movement behaviour that occurs during the dynamic events on the field (Benjaminse et al. 2015b). Increasing the retention and transfer to sports activities, for instance via external-focus instruction, are expected to improve the effectiveness of prevention programmes (Benjaminse et al. 2018). Lastly, in many instances it has been shown that the biomechanical and neuromuscular injury event (i.e., the moment of rupture) was the consequence of poor decision making or misjudgement of the playing situation earlier on (Gokeler et al. 2024, Bahr & Krosshaug 2005). Naturally, it stands to reason that prevention research could benefit from considering these behavioural components of injury scenarios. Hence, it is necessary to expand the traditional biomechanical approach and include player behaviour if the objective is to prevent ACL injuries (Bahr & Krosshaug 2005).

Many of the concerns raised about injury risk research highlight weaknesses that may harm the efficacy of preventative interventions. To illustrate, several of the training interventions that were developed have shown to be ineffective in reducing injury-associated knee joint loading during change-of-direction movements (Dos'Santos et al. 2019). Moreover, in some athlete populations, the incidence of ACL injuries has not decreased over a ten-year period despite the incorporation of prevention measures (Webster et al. 2021). Consequently, it has become clear that improvements are desired to further stem the tide of injuries.

1.2 Theoretical Perspective

To enhance injury prevention, it is essential to advance injury risk research, which may necessitate re-evaluating the underlying theories and concepts that form its foundation. This section will introduce the theoretical perspective of this dissertation and explain the elements that constitute it: dynamical systems theory and ecological psychology.

Dynamical systems theory (DST), is a broad mathematical theory with applications in many different scientific fields. A prominent, early application of DST to human movement was published by Bernstein (1967). He described the human body as a mechanical system of which the movements are coordinated by controlling the redundant degrees of freedom that the joints offer. Bernstein's ideas have received many adaptations and expansions, particularly in the domain of motor control, to describe the self-organization of movement coordination (Kelso et al. 1991) through the concept of interacting constraints (Newell 1986). These movement-shaping constraints, wherein human movement emerges naturally, were classified by Newell (1986) to be related to the individual, their environment, or a given task. Individual-related constraints may concern the individual's physical and mental characteristics like height, cardiovascular fitness, strength, and level of fatigue, motivation, or anxiety. Environmental constraints may include features external to the individual like the type of terrain, lighting, and weather conditions. Task constraints may include the goal of the task and any rules or objects that constrain the individual's response dynamics. Subsequently, the DST and its derivative constraints-led approach (CLA) were successfully adopted into sports research to tackle issues in movement variability (Davids et al. 2003), adaptation to training (Torrents & Balagué 2006), and skill acquisition (Davids et al. 2008). The findings from such DST-based sports research layed a foundation of knowledge by dispelling the traditional notion of movement variability as noise and by interpreting training adaptations in athletes as a self-organization process.

In the related domain of motor learning, a theory of ecological psychology emerged. Ecological psychology emphasizes the role of perceptual information in the coordination of human movement (Gibson 1979). The central idea is that perceptual information steers action and that action, in turn, generates perceptual information, resulting in a perception-action coupling (Warren 1990). Gibson (1979) coined the term "affordances" to describe the possibilities for action that an environment offers a particular individual. Affordances can selectively invite behaviours and thereby affect the individual's decisions and subsequent actions (Withagen et al. 2012). The theory of ecological psychology, with affordances as one of its main concepts, has inspired many studies ranging from investigations on stair climbing (Warren 1984) to ball catching (Postma et al. 2018). The findings from such studies have contributed to our understanding of behavioural dynamics and the perceptual mechanisms that underlie motor control strategies.

Sometime after the two theories were first formulated, it became clear that ecological psychology and DST are complementary in their views on human movement (Figure 1) (Shaw & Turvey 1999). The first sport science research to explicitly adopt a hybrid "ecological dynamics perspective" investigated expert performance and decision making in team ball sports (Seifert et al. 2013, Renshaw et al. 2009, Araújo et al. 2006). These investigations produced insights into the key properties of experts (e.g., adaptive movement variability) as well as the understanding that, although athletes should develop basic movement patterns, there exists no ideal movement template towards which they should all train. Instead, the interaction of constraints creates many unique scenarios which encourage distinct functional movement solutions. This ecological dynamics perspective was later formalised in a book chapter, describing its two constituents ecological psychology and DST before using it to detail how sport expertise is acquired (Davids et al. 2015). The holistic and multidisciplinary nature of the ecological dynamics perspective makes it a potential advancement over the traditional biomechanical approach to ACL injury risk research.

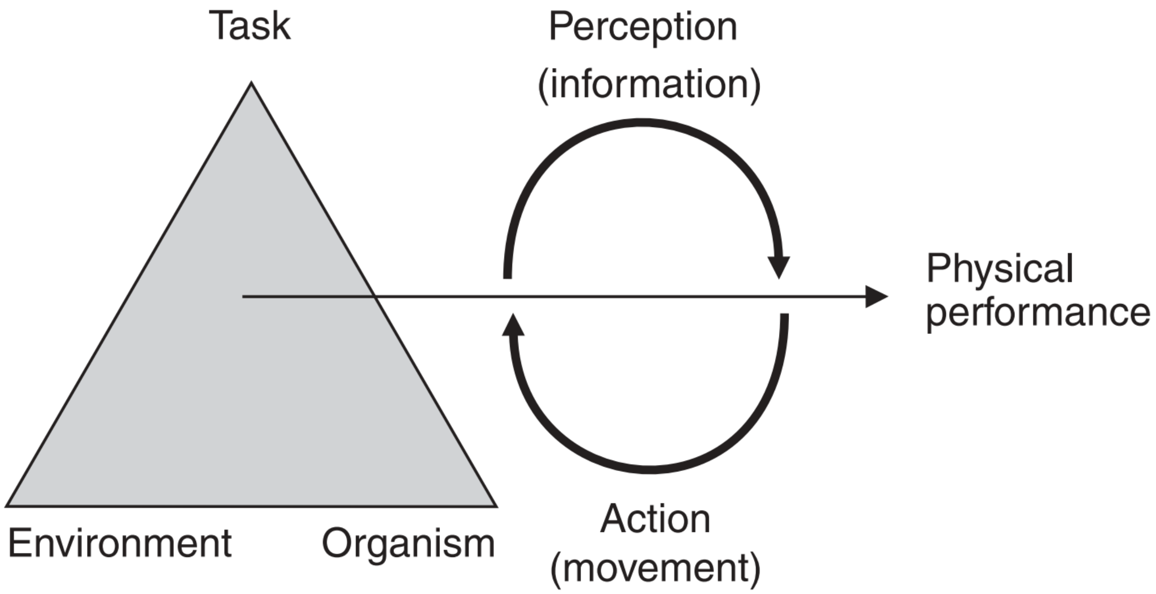

Figure 1. Ecological dynamics perspective. This diagram from Davids et al. (2003) includes Newell's constraints model and the coupling between perception and action.

1.3 Rationale

The rationale of this thesis is based on an 'ecological dynamics' perspective which considers the athlete as a complex adaptive system that interacts with its environment, which is best studied at the athlete-environment level of analysis (Renshaw et al. 2019). Although the ecological dynamics perspective is already prominent in the fields of sports performance (Davids et al. 2015, Seifert et al. 2013, Woods et al. 2019) and sport psychology (Araújo et al. 2019, Otte et al. 2020, Renshaw et al. 2019), there is a paucity in injury risk research. Movement behaviour is complex and in order to grasp the underlying mechanisms it should be studied incrementally from environments in the laboratory to the sports field, allowing the gradual introduction of more variables (Figure 2) (Parada 2018).

Despite receiving valid criticisms, laboratory studies still have their place in ACL injury risk research. Namely, lab-based experiments allow for the dissection of otherwise confounding relationships due to the relatively high control over variables, which facilitates the interpretability of findings (Parada 2018). Thus, lab-based science can give direction for more applied field-based work. The scientific transition "from lab to field", which has started to gain popularity in the domain of human biomechanics (Di Paolo et al. 2023, Spörri et al. 2016, Tamburini et al. 2018, Verheul et al. 2020), is not a one-way road nor should it be seen as a replacement strategy. Instead, field-based research is a natural extension of lab-proven concepts, working to improve the generalisability of findings due to the relaxed control over variables and increased behavioural freedom for the athletes (Parada 2018). This thesis first prioritised a thorough literature review and the validation of measurement tools. Following this fundamental work, the thesis progresses step-by-step in different studies that investigate behavioural, performance, and movement dynamics in team ball sport populations. These studies range from lab-based neurocognitive experiments to applied field-based testing, covering a large part of the "lab to field" spectrum.

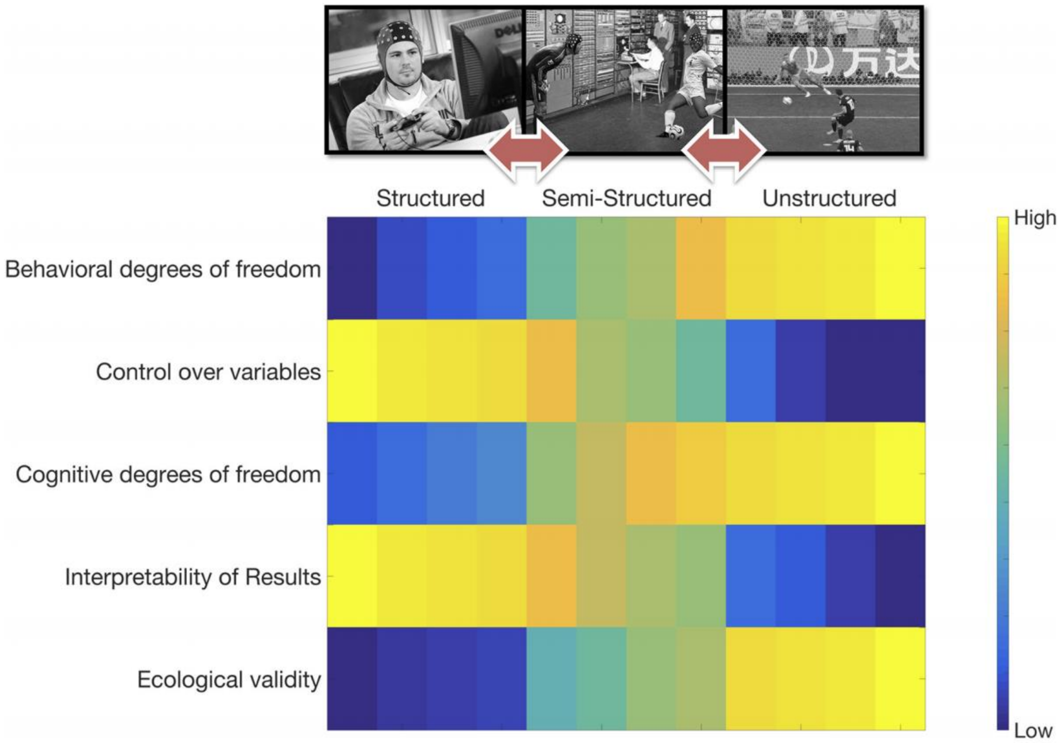

Figure 2. The spectrum between lab and field-based experimental designs. This diagram from Parada (2018) visualises the impact of the lab-to-field transition on behavioural degrees of freedom, control over variables, cognitive degrees of freedom, interpretability of results, and ecological validity.

1.4 Objectives

The research presented here aims to contribute to injury risk screening for non-contact ACL injuries in team ball sports. In particular, this thesis hopes to advance the perspective of researchers by adopting an ecological dynamics approach to studying human movement in team ball sports. While this dissertation covers the topic of non-contact ACL injury, this approach may also be applicable to other non-contact injuries. Specifically, the objectives of this cumulative work are as follows. In the lab, the purpose was to investigate the concurrent validity of IMUs in quantifying joint kinematics during team ball sport movements. Subsequently, additional lab-based work aimed to determine the construct validity of agility-based neurocognitive tests; and to examine how team ball sport players adapt to stop signals when performing a reactive movement task. On the field, this dissertation aimed to uncover effects of additional task- and athlete-constraints on the performance and joint coordination of talented youth football players; and to evaluate the execution times and kinematics of elite handball players between planned and reactive agility tasks in a proof-of-concept screening protocol.

2 Methods

This section first provides a general overview of the methods used for each study. Second, it explains common concepts and methodologies between the studies in more detail.

2.1 Overview

Study I is an opinion paper reviewing the literature of ACL injury risk research. It provides three principles that address common methodological limitations of ACL injury risk research. It formulates guidelines for injury risk researchers with regards to three main aspects: 1) poor preservation of the athlete-environment relationship, 2) strictly biomechanical approach to injury causation, 3) the use of reductionist analysis. Study II follows up on the need for more research on inertial sensors identified in study I. It recognises that inertial measurement unit (IMU) systems allow measurements under more ecologically valid conditions when compared to human movement laboratory settings (Camomilla et al. 2018). However, there is a paucity in literature regarding the concurrent validity of these systems in measuring kinematics of dynamic manoeuvres. This study evaluates the concurrent validity of a Noraxon Myomotion IMU system in quantifying lower extremity kinematics in change-of-direction and jump-landing tasks when compared to a Vicon optoelectronic marker-based (OMB) motion analysis system. Study III applies the methodological principles from study I in an experimental study. In order to create complex sport-specific settings for injury screening purposes, it is important to know how movements are coordinated and controlled in such dynamic environments. In this study, talented youth football players are exposed to additional task and athlete-related constraints whilst performing a football-specific drill. The primary aim of this study was to investigate the changes in lower extremity coordination that players present in response to the different constraints. The brain represents a vital link in the mechanisms between constraints, movement behaviour, and performance. Study IV delves deeper into understanding how executive functioning contributes to performance in constraint-rich scenarios. Fast reaction and inhibitory control have been linked to elite athletic performance (Loureiro & Freitas 2012; Kida et al. 2005) and are likely also relevant for injury prevention, as deficits in reaction time and processing speeds have been shown to indicate a potential neurocognitive predisposition to non-contact ACL injury (Swanik et al. 2007). Despite this evidence, cognitive function remains an under researched area in ACL injury prevention literature (Giesche et al. 2020). Therefore, this study evaluates the validity of agility-based tests for executive functioning compared to traditional computer-based tests. Study V continues from the previous study and further exposes the relationships between constraints, executive functioning, and changes-of-direction. It focuses on how players adapt to maintain performance when they are tasked with a scenario that features stop-signals. In doing so, this study follows the principles of study I by making an incremental step in terms of athlete-environment preservation, albeit in a laboratory environment for enhanced control and standardisation. Study VI converges the knowledge obtained from the previous studies. It introduces a new experimental protocol of reactive multi-directional movements and this is applied to a cohort of elite handball players. The main goal was to evaluate performance measures and movement quality in a reactive agility drill between age groups and playing positions. It also serves as a proof of concept for what an ecological dynamics-based screening test could look like.

2.2 Population

Athletes from various team ball sports, with different levels of experience, ages, and competitive backgrounds, were recruited as participants for the studies in this dissertation (N_{total} = 146). Study II evaluated the validity of an IMU system with female (*N* = 5, mean ± SD: age 21.4 ± 1.8 years, height 176.3 ± 7.5 cm, weight 66.8 ± 7.8 kg) and male (*N* = 5, mean ± SD: age 22.2 ± 1.6 years, height 182.8 ± 6.9 cm, weight 75.4 ± 11.1 kg) participants who were recreationally active in sports. Study III investigated talented male youth football players (*N* = 17, mean ± SD: age 13.9 ± 0.3 years, height 164.0 ± 9.0 cm, weight 50.9 ± 7.4 kg). Study IV was conducted with a study population of male and female players (*N* = 27, 5 females, mean ± SD: age 24.2 ± 4.7 years, height 183.6 ± 9.1 cm, weight 77.5 ± 11.2 kg) from various team ball sports (14 football, 7 basketball, 5 handball, 1 rugby). Study V was similarly performed with a mixed population of team ball sport players, using a subset of the study population in study IV (*N* = 24, 3 females, mean ± SD: age 22.4 ± 5.7 years, height 186.0 ± 11.0 cm, weight 78.6 ± 11.9 kg). Study VI examined a study population consisting of elite male handball players, competing at the first or second national level, including adults (*N* = 66, median ± IQR: age 24.0 ± 5.0 years, height 192.5 ± 7.0 cm, weight 95.9 ± 15.4 kg) and youths (*N* = 26, median ± IQR: age 17.0 ± 1.0 years, height 186.0 ± 13.3 cm, weight 83.8 ± 19.0 kg).

2.3 Protocols

The experimental protocols that were investigated in the studies feature several different motor tasks. These motor tasks were carefully chosen so that they represent movements that naturally occur when practicing a team ball sport. By selecting a sport-related motor task and subsequently introducing additional constraints, it simulates the dynamics between a player and a changing playing situation. This allows for the investigation of adaptations that occur in the player's movement behaviour and performance outcomes when they are faced with a different set of constraints. The experimental protocols of studies III, V, and VI follow this design philosophy. Specifically, study III included a football drill where players manoeuvred around a variable layout of cones and passed a stationary ball to a dummy teammate (Figure 3). Study V featured a choice-reaction task on the SpeedCourt system where participants reacted to arrow stimuli, moved to the left or right, and planted a foot on a contact plate (Figure 6). The protocol of study VI was based on study V: with the use of the FitLight system, the choice-reaction task was redesigned to be mobile (Figure 8). This made it suitable for measurement on the handball court, and it included four different directions of travel rather than the original two.

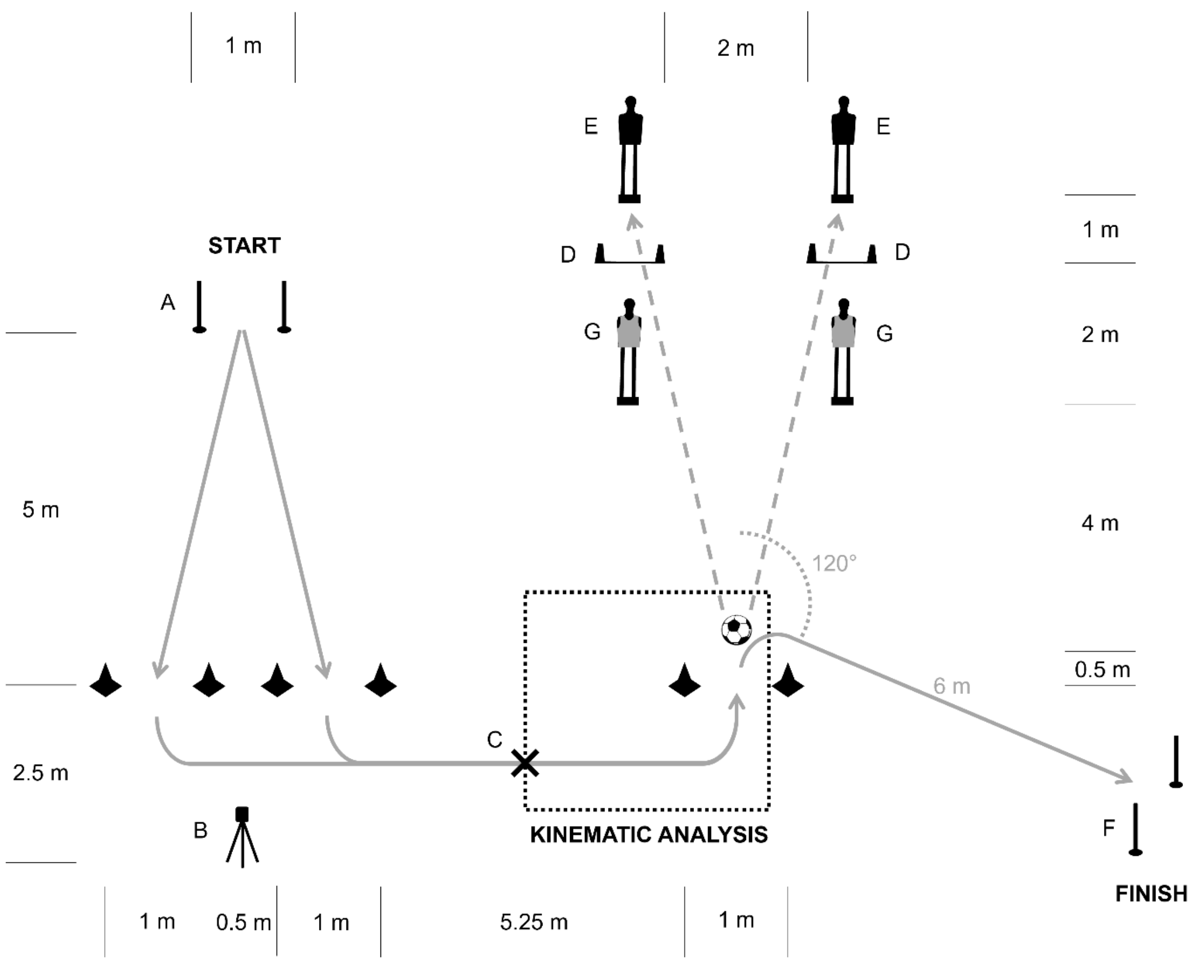

Figure 3. Illustration of the football-specific drill. Figure from study III.

2.4 Tools and Instruments

Inertial measurement units (IMUs) are a type of motion capture system that uses small wearable sensors that are placed on segments of the body. Each sensor collects accelerometer, gyroscope, and magnetometer data. Through a process called sensor fusion, IMU systems calculate the relative position and orientation of different body segments which allows the calculation of three-dimensional joint angles. Studies II, V, and VI used the Noraxon Myomotion IMU system (Noraxon U.S.A. Inc., Scottsdale, AZ). The IMUs were attached to the body at the feet, shanks, thighs, pelvis, T12, and C7, according to the manufacturer's instructions (Figure 4). Study III used a MVN lycra suit with seventeen Xsens IMUs (Xsens Technologies, Netherlands).

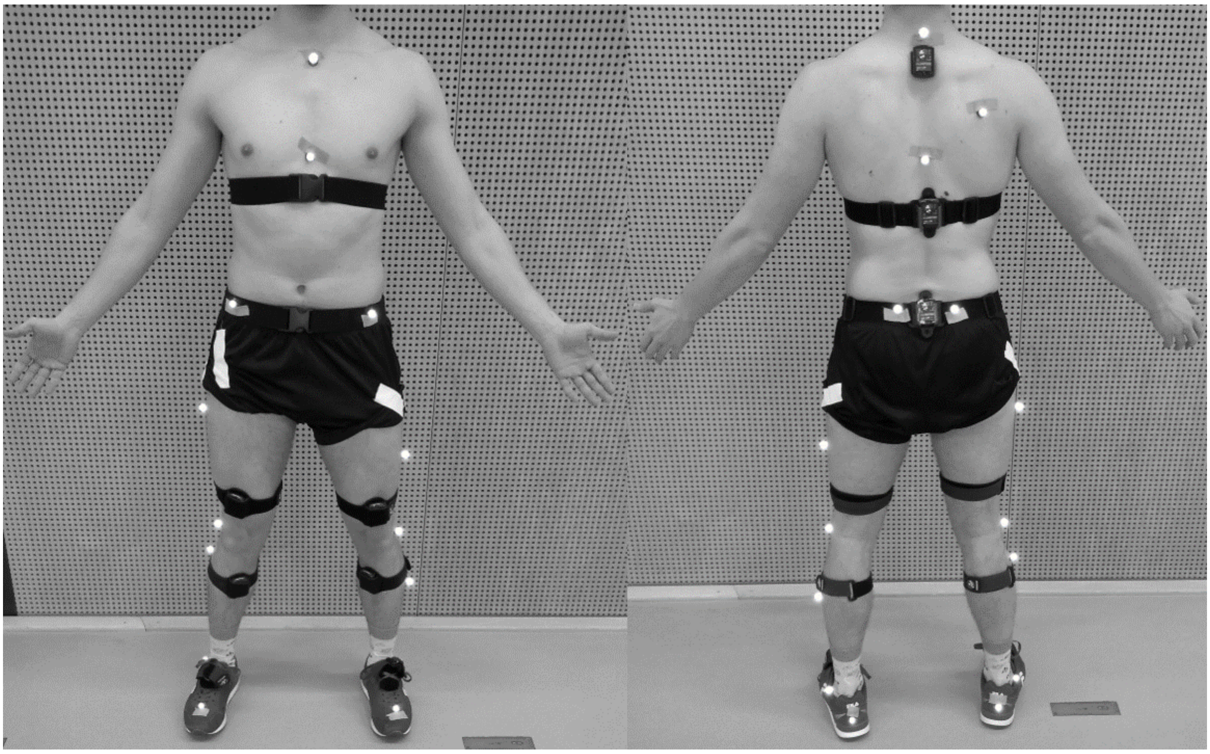

Figure 4. Reflective markers and wearable inertial sensors. These images are from study II but the same sensor placements were used in studies V and VI.

The SpeedCourt system (SC650 Q10, Globalspeed GmbH, Hemsbach, Germany) is a 6.3 m by 6.5 m interactive training platform with integrated contact plates (Figure 5). The participant manoeuvres on the platform and they are instructed to run towards and place a foot on a target contact plate when it appears on the TV monitor. The SpeedCourt can be programmed to present different types of stimuli and in different sequences. Studies IV and V used the SpeedCourt in experiments that were designed to combine change-of-direction motor tasks with different neurocognitive demands related to response inhibition (Figure 6) and working memory (Figure 7).

Figure 5. The SpeedCourt system. The TV monitor displays the target plate.

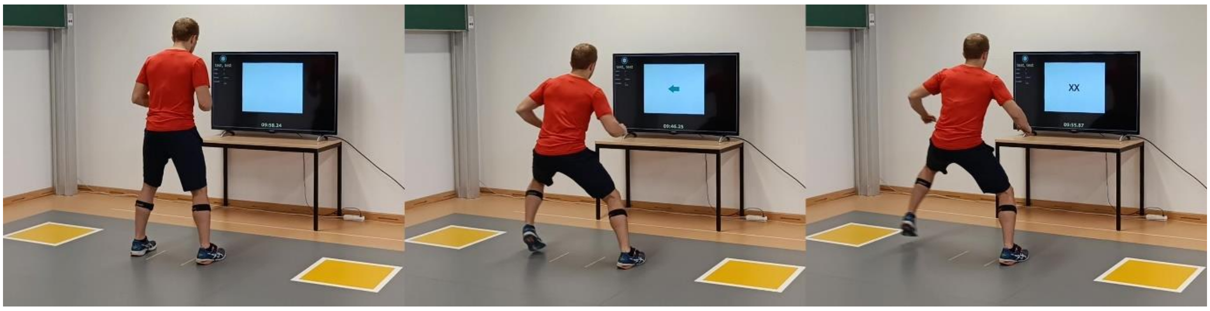

Figure 6. Stop-signal task on the SpeedCourt. From left to right: starting position, go-signal, and stop-signal. Figure from study V.

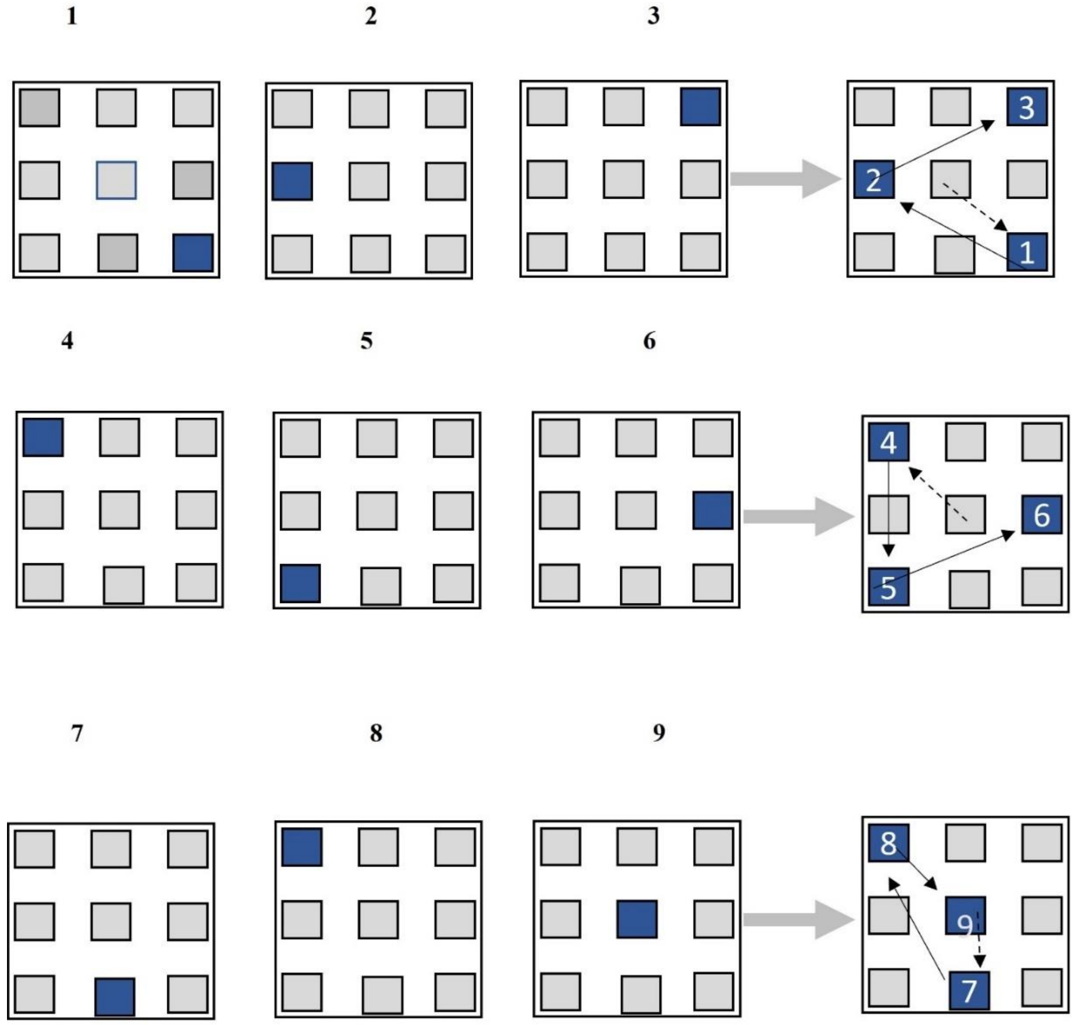

Figure 7. Running routes for the working memory task on the SpeedCourt. The stimuli were presented in sequence and the participant had to repeat the route. Figure from study IV.

The FitLight system (FitLight Corp, Ontario, Canada) comprises a set of wireless LED targets with integrated proximity sensors which can be programmed to activate in different sequences. The objective for the participant is to quickly react to a FitLight activation by deactivating it with a swiping gesture. The FitLights can be arranged spatially to elicit different movement behaviours. The system records the elapsed time between light activation and deactivation, thus representing the execution time (ET). Study VI used the FitLight system in a protocol that compared planned versus reactive agility. In this experiment, four lights were placed on top of cones which were placed in a trapezoid layout (Figure 8). The lights were programmed to activate in a planned or random sequence of ten subsequent light activations.

Figure 8. The FitLight system. These images depict the participant in the starting position (top) and final position (bottom) and four FitLights arranged in a trapezoid layout on top of cones. The distance from the starting position to each FitLight is 2.5 meters.

2.5 Kinematic Data Analysis

The analysis of kinematic data can use different methods to deal with the inherent complexity (i.e., many variables) and dimensionality (i.e., time series). In line with the EDA principle of conducting non-reductionist analysis (Study I), the studies in this dissertation applied analysis methods that deviate from traditional discrete approaches. Study II used measures of agreement (i.e., cross-correlation) and error (i.e., root mean square deviation and amplitude difference) to compare kinematic data between an IMU and OMB system that were simultaneously recording in order to examine concurrent validity. Study III used coordination classification to analyse joint kinematics. Coordination classification is an analysis method that can be used to quantify how two kinematic variables move together or 'coordinate' (Figure 9). It is considered a dimensional reduction technique because it turns two variables (e.g., hip flexion angle and knee flexion angle) into one variable called the 'coupling angle'. The coupling angle is expressed on a polar scale from 0 to 360 degrees and it indicates in which manner the two components relate at any given time point. For example, during a jump-landing, the hip and knee joints are both flexing to control the impact and to decelerate the downwards motion. First, the two joint angles are plotted against each other so that a procedure called 'vector coding' can be applied. Vector coding extracts the direction of the vector between subsequent time points in the joint-joint plot (Chang et al. 2008). In the example, the coupling angle will lie anywhere between 0 and 90 degrees, which corresponds with a positive in-phase coordination between the hip and knee joints (Needham et al. 2015). The exact coupling angle depends on the relative angular velocities of the hip and knee joints; hence the coupling angle is able to quantify which joint was the dominant mover at each time point. Study VI used statistical parametric mapping (SPM) to analyse joint kinematics. SPM is an analytical procedure for hypothesis testing with time series data. The application of nonlinear SPM to kinematic data grants insights into spatiotemporal adaptations by identifying both if and when waveforms are significantly different, respectively named amplitude and timing differences (Pataky et al. 2022).

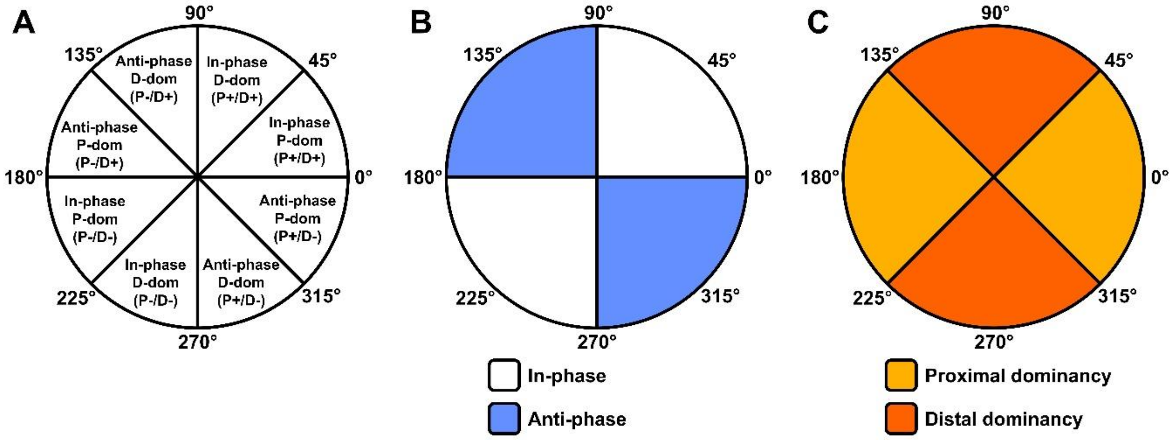

Figure 9. Coordination classification polar plots. (A) The classification of coordination patterns based on the convention proposed by Needham et al. (2015); (B) the segments corresponding with in/anti-phase coordination; and (C) the segments corresponding with proximal/distal dominant coordination. P: proximal joint, D: distal joint, dom: dominancy, (+): flexion, (-): extension. Figure from study III.

3 Results

This section provides summaries of the results of each study, accompanied by a figure or table. For the comprehensive results, please refer to the manuscripts included in the Appendix.

3.1 Study I: An ecological dynamics approach to ACL injury risk research: a current opinion

Study I argued for three methodological principles that facilitate an ecological dynamics approach to conducting ACL injury risk research (Figure 10). The principles include 1) preserving the athlete-environment relationship, 2) including behaviour and playing situation in the model of injury causation, and 3) conducting non-reductionist analysis. In this study, examples are discussed of research that would follow these principles. It is hypothesised that research which follows these principles is more holistic and it would hence expand our understanding of injury risk.

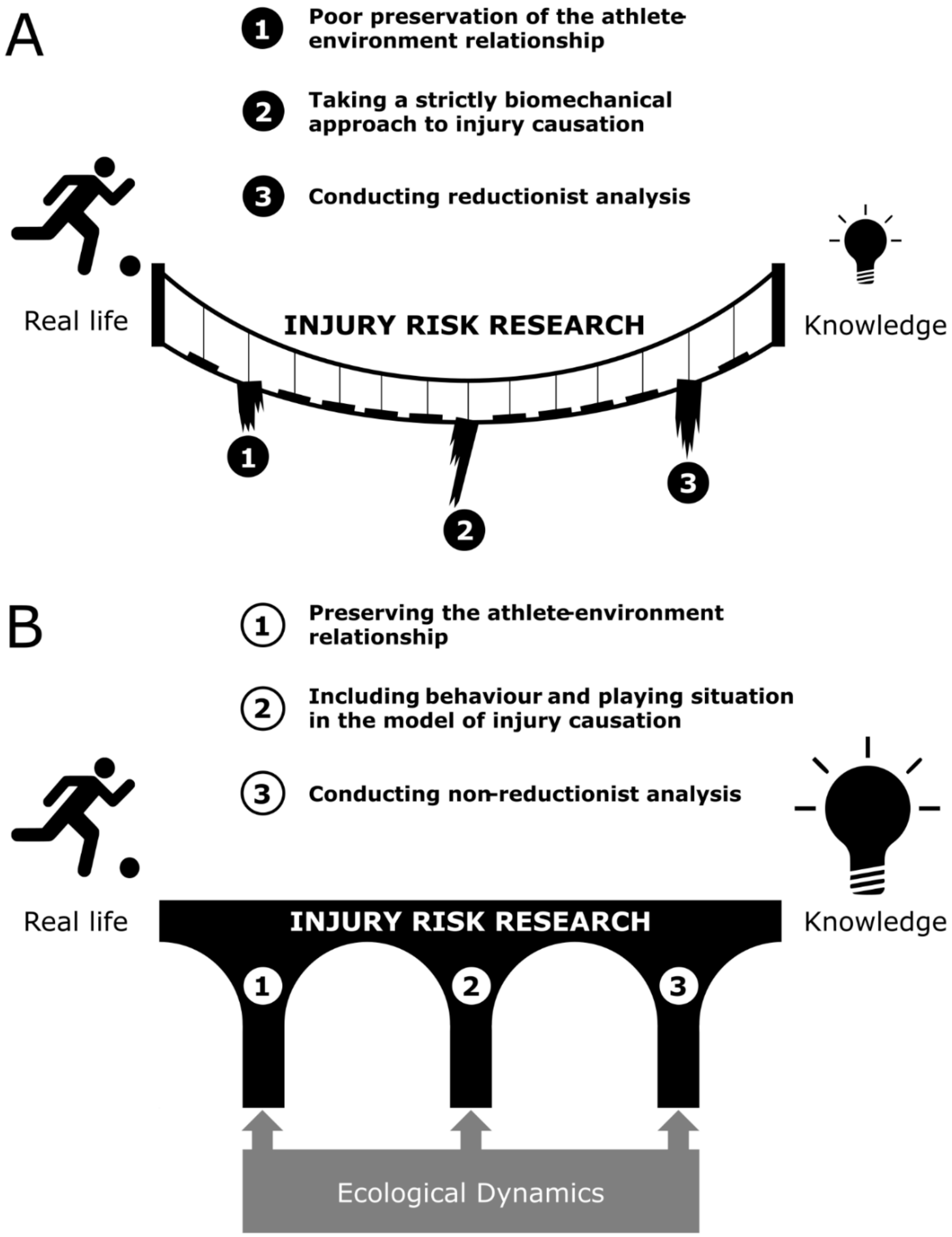

Figure 10. Schematic representation of injury risk research as the bridge between real life and knowledge. (a) Limitations of current injury risk research methods are pitfalls that limit the knowledge obtained from these studies. (b) Principles for an ecological dynamics approach to injury risk research. These principles provide a foundation for research that is more generalisable and less reductionist, expanding the knowledge that is obtained. Figure from study I.

3.2 Study II: Concurrent validation of the Noraxon MyoMotion wearable inertial sensors in change-of-direction and jump-landing tasks

Study II found that Noraxon IMUs produce excellent agreement with a Vicon OMB motion capture system for sagittal plane joint kinematics when recording team ball sport movements (cross-correlation $\geq$ 0.88). Kinematics in the frontal and transverse planes yielded more variable agreements (Table 1). This study provided implications for researchers including the cautious use of frontal and transverse plane kinematics as well as the recommendation to correct for offsets when comparing absolute joint angles between different motion capture systems.

Table 1. Measures of agreement and error between two motion capture systems for five motor tasks.

	Hip			Knee	Ankle		
	Sagittal	Frontal	Transverse	Sagittal	Sagittal	Frontal	Transverse
XCORR							
single-leg hop	0.97 (0.06)	0.62 (0.52)	0.37 (0.27)	0.97 (0.05)	0.94 (0.11)	0.31 (0.29)	0.60 (0.35)
single-leg crossover hop	0.97 (0.06)	0.59 (0.50)	0.40 (0.26)	0.95 (0.05)	0.93 (0.14)	0.31 (0.25)	0.73 (0.36)
double-leg vertical jump	0.99 (0.01)	0.77 (0.37)	0.34 (0.22)	0.98 (0.03)	0.96 (0.05)	0.39 (0.26)	0.26 (0.36)
single-leg deceleration	1.00 (0.01)	0.85 (0.25)	0.27 (0.44)	0.99 (0.02)	0.94 (0.12)	0.34 (0.33)	0.17 (0.27)
sidestep cut	0.98 (0.04)	0.66 (0.67)	0.51 (0.31)	0.94 (0.09)	0.88 (0.14)	0.37 (0.37)	0.21 (0.46)
RMSD							
single-leg hop	11.31° (5.88°)	7.80° (5.69°)	12.31° (6.91°)	14.77° (9.13°)	8.91° (9.23°)	6.22° (2.46°)	9.20° (7.30°)
single-leg crossover hop	11.99° (6.38°)	8.11° (6.25°)	11.60° (6.82°)	16.16° (8.23°)	12.13° (11.09°)	7.58° (3.81°)	9.85° (6.08°)
double-leg vertical jump	7.67° (7.12°)	9.42° (7.09°)	17.00° (7.13°)	15.57° (8.04°)	6.33° (4.37°)	8.26° (4.07°)	13.52° (7.40°)
single-leg deceleration	9.41° (5.37°)	14.43° (11.71°)	17.25° (16.42°)	15.74° (8.00°)	5.49° (2.89°)	7.47° (2.85°)	15.73° (7.50°)
sidestep cut	10.76° (9.82°)	11.15° (8.43°)	16.80° (12.77°)	25.89° (16.50°)	8.12° (5.11°)	7.72° (2.79°)	15.91° (9.31°)
ΔAMP							
single-leg hop	-1.58° (9.22°)	1.90° (3.75°)	4.01° (9.73°)	0.01° (9.50°)	-17.83° (7.31°)	-23.72° (8.90°)	1.02° (9.09°)
single-leg crossover hop	-2.41° (7.44°)	2.12° (3.89°)	2.11° (8.02°)	-2.40° (7.38°)	-16.74° (7.37°)	-24.11° (12.71°)	1.11° (11.50°)
double-leg vertical jump	5.14° (7.72°)	2.67° (4.78°)	10.09° (12.09°)	-2.36° (9.13°)	-26.86° (13.36°)	-29.92° (10.07°)	2.90° (11.10°)
single-leg deceleration	-1.58° (11.66°)	-0.76° (5.61°)	3.26° (13.69°)	-4.26° (9.70°)	-29.27° (9.76°)	-30.49° (10.74°)	0.53° (12.23°)
sidestep cut	1.10° (11.26°)	3.20° (6.58°)	13.39° (18.25°)	-4.34° (11.74°)	-20.56° (12.23°)	-24.62° (8.31°)	1.22° (10.55°)

XCORR = cross-correlation; RMSD = root mean square deviation; ΔAMP = amplitude difference. Values are median (interquartile range).

3.3 Study III: Relationships Between Task Constraints, Visual Constraints, Joint Coordination and Football-Specific Performance in Talented Youth Athletes: An Ecological Dynamics Approach

Study III identified interacting mechanisms between task constraints (defender dummies), visual constraints (stroboscopic vision), lower extremity joint coordination, and football-specific performance (execution time, passing accuracy). In particular, the addition of the constraints affected the performance measures negatively; execution time increased and passing accuracy decreased. Moreover, a relationship was found between joint coordination and execution time (Figure 11). Together, this study provided a field-based exploration into the complex interactions between movement behaviour, varying constraints, and performance dynamics.

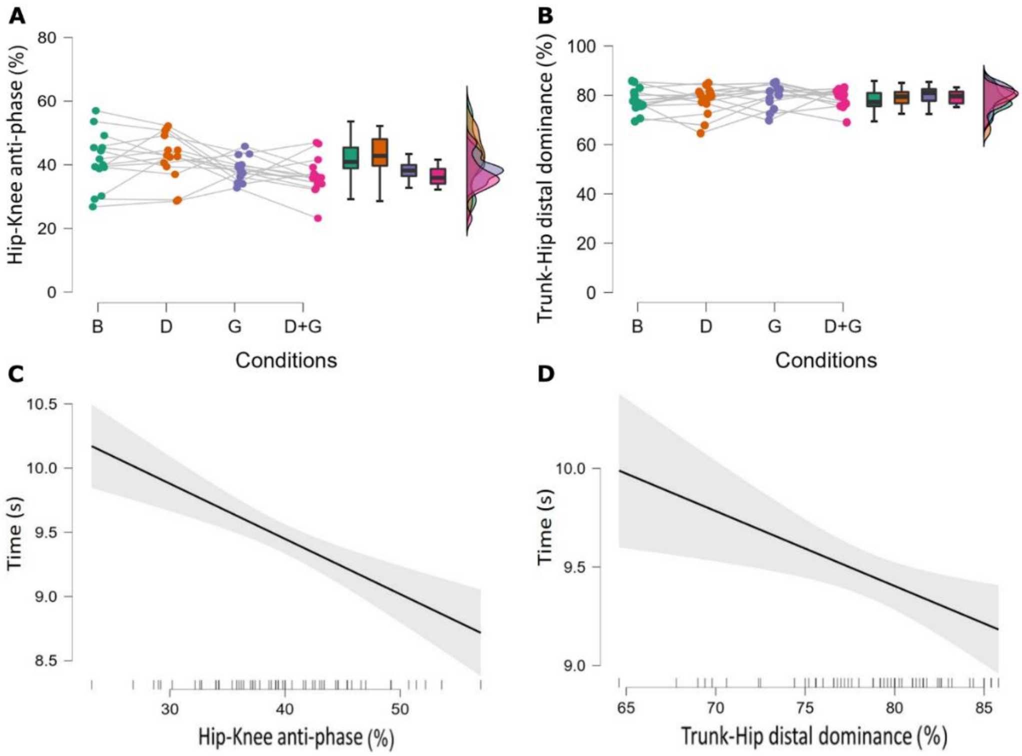

Figure 11. Coordination distributions and regression analysis. Distributions of hip-knee anti-phase coordination (A) and trunk-hip distal dominant coordination (B) per condition with connected dots representing player means. Stepwise linear regression analysis between execution time and hip-knee anti-phase coordination (C) and trunk-hip distal dominant coordination (D), respectively. Note. The explained variance in the regression model was R2 = .30, R2 Adjusted = .28 (p < .001). B: basic constraints, D: defender dummies, G: stroboscopic glasses.

3.4 Study IV: Unveiling the Distinctions: Computer versus Sport-Specific Neurocognitive Tests

Study IV found poor to moderate validity between computer-based and sport-specific assessments of the executive functions. Specifically, response inhibition (r = 0.179, p > 0.05) and working memory capacity (r = 0.465, p< 0.05) were assessed (Figure 12). Importantly, this study discusses the inherent difference in behavioural degrees-of-freedom and it provides the implication that research should develop more sport-specific assessments.

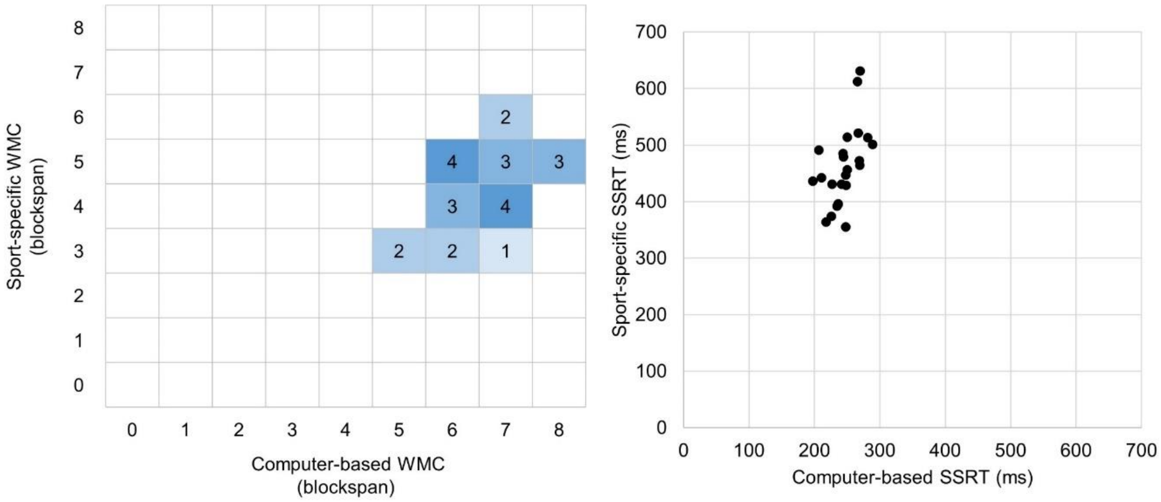

Figure 12. Distributions of computer-based versus sport-specific performance of neurocognitive assessment. Working memory capacity (WMC) and stop-signal reaction time (SSRT).

3.5 Study V: Stop-Signal Task on a Training Platform Induces Player-Level Adaptations in Team Sport Athletes

Study V found delayed reaction times when athletes performed a choice-reaction lateral stepping task in a scenario with random stop-signals, compared to the same task without stop-signals. Interestingly, when analysis was conducted at the player-level, rather than the conventional group-level, distinct performance profiles were identified with significant implications for task performance (Figure 13).

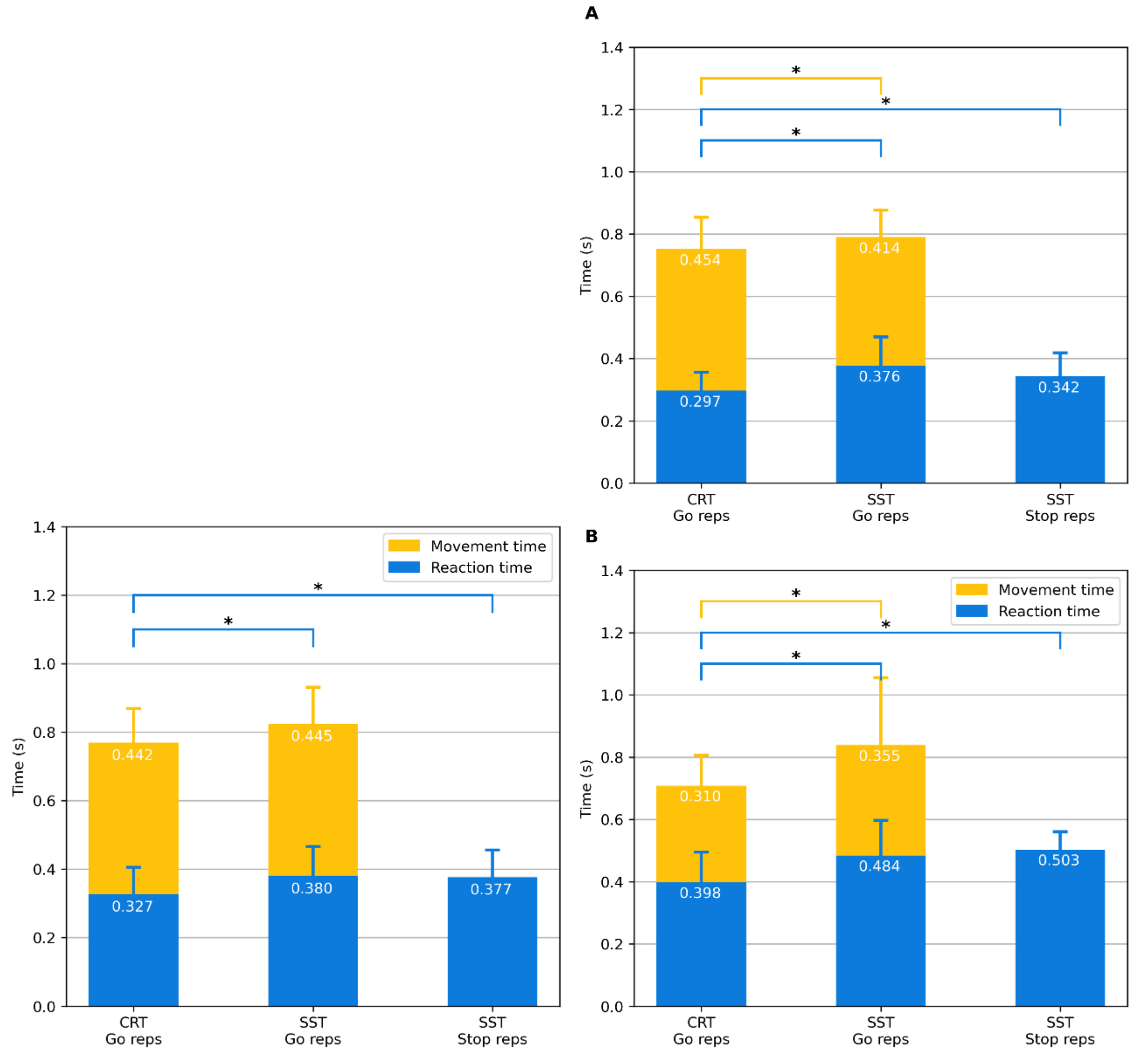

Figure 13. Reaction time and movement time for choice reaction task (CRT) and stop-signal task (SST). Group-level analysis on the left and individual performance profiles (A and B) on the right.

3.6 Study VI: Agility in Handball: Position- and Age-Specific Insights in Performance and Kinematics using Proximity and Wearable Inertial Sensors

Study VI identified significant differences in execution time of an agility drill between conditions (planned vs. reactive), age group (adult vs. youth), and playing positions (Figure 14). These performance differences were accompanied by quantifiable changes in movement behaviour. Comparisons of lower extremity joint kinematics found amplitude and timing differences which suggest distinct movement coordination strategies (Figure 15).

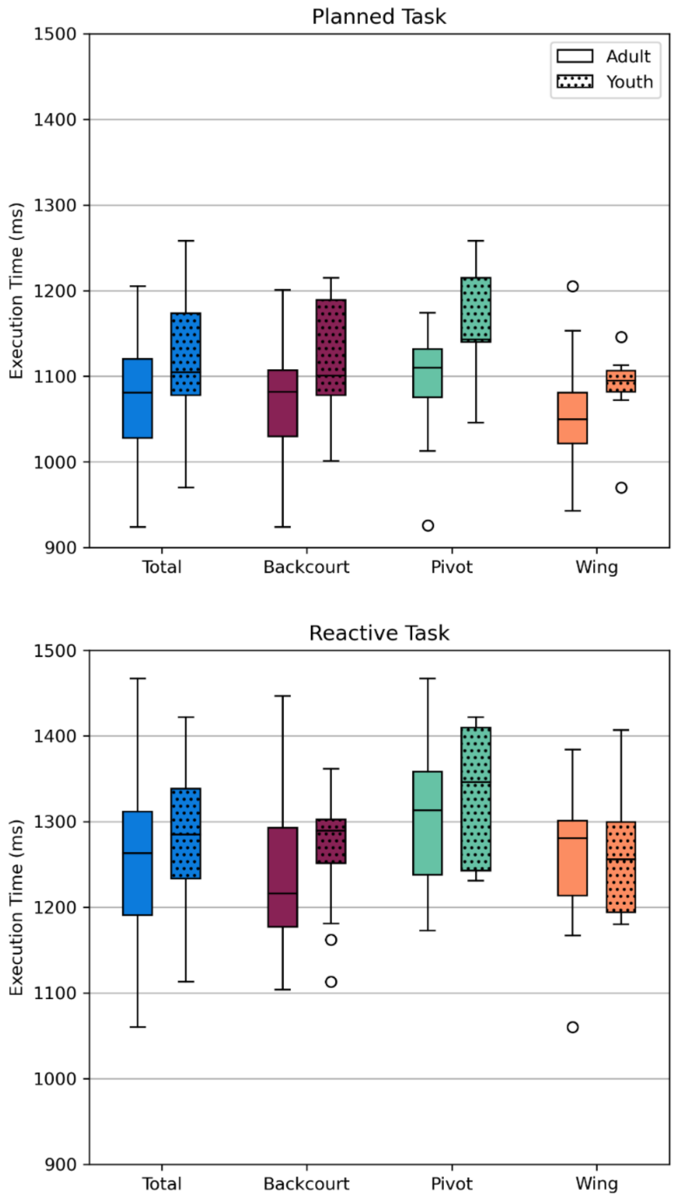

Figure 14. Execution time distributions for the planned and reactive tasks. Data is categorised per age group and playing position.

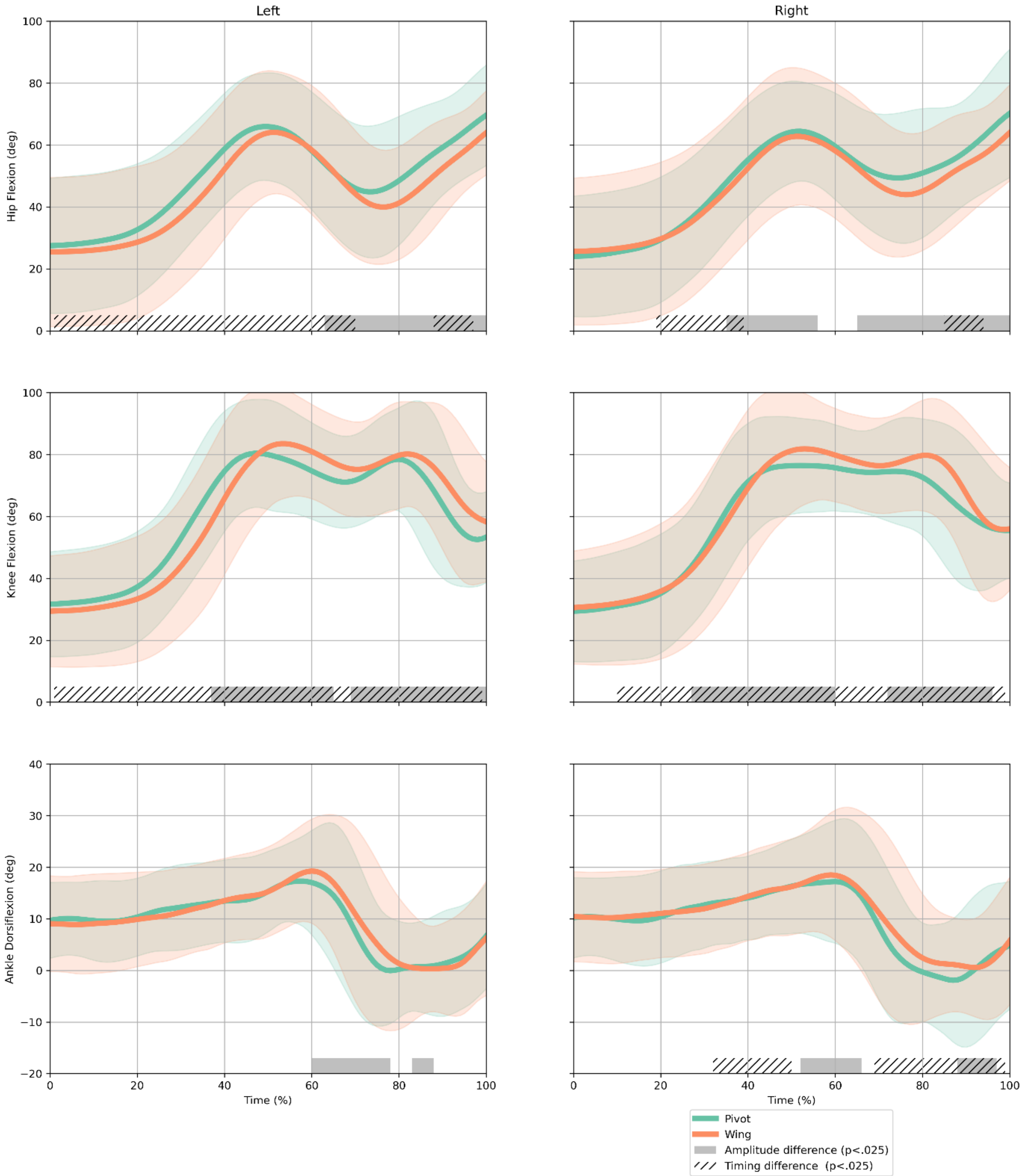

Figure 15. Kinematic comparison between wing and pivot using statistical nonparametric mapping. Data is pooled over conditions and age groups. Waveforms represent average hip/knee/ankle flexion for the ipsilateral leg in the movement to the left (light #1) and to the right (light #2).

4 Discussion

This dissertation has presented a body of scientific work that contributes to the goal of EDA-based injury risk screening for non-contact ACL injuries. Based on a theoretical perspective (study I) and with validated tools (study II), this thesis explored the mechanisms associated with non-contact ACL injuries in team ball sports athletes from an ecological dynamics approach. The various studies in this thesis investigated the complex relationships between cognitive functions, movement behaviour, and performance outcomes (study III) with particular attention to player-level findings (study V). It also presents a critical look at how cognitive functions are normally evaluated and generalised, highlighting the discrepancy in behavioural degrees-of-freedom between computer-based and sport-specific settings (study IV). The work in this thesis culminates in a mobile field-based investigation into the planned and reactive agility of elite handball players, serving as a proof-of-concept EDA-based screening protocol (study VI). Together, this dissertation represents several steps in the direction of applied kinematic research. Importantly, it proves that working methodically from an ecological dynamics approach yields insights that have potential for impact in practice, which is necessary in order to create support. In turn, this may contribute to future collaborations where time and resources are made available for more applied research. Exploring how the dynamics between player, task, and environment contribute to inciting events for biomechanical trauma (e.g., ligament rupture) offers valuable insights and research opportunities. A deeper understanding of these mechanisms could pave the way for targeted screening interventions to identify players at increased risk of sustaining a non-contact ACL injury.

4.1 Study Findings

Taken together, the findings of the studies in this thesis add to our understanding of the complex movement dynamics in team ball sports. Study I proposed a theory-based model with three principles for research that aims to adopt an ecological dynamics approach. The principles are: 1) preserving the athlete-environment relationship; 2) including player behaviour and playing situations in injury causation models; and 3) conducting non-reductionist analysis. This EDA model was used as a framework for the different studies in this dissertation. Study II conducted a concurrent validation of an IMU system compared to an OMB system for the recording of lower extremity kinematics during different team ball sports-related movements. This study found excellent agreement between the IMU and OMB systems for sagittal plane joint kinematics; variable agreement for the frontal and transverse planes; and relatively high deviations in absolute joint angles (i.e., vertical offsets). The findings of this study provided valuable technical knowledge and methodological expertise regarding the use of IMUs and thus served as a foundation for the subsequent studies.

Study III used an IMU system to record the movements of elite youth footballers performing a field-based running and passing drill. The EDA principles were followed by 1) conducting a football-specific drill on a football pitch, 2) introducing different constraints to a varying playing situation, and 3) analysing inter-joint coordination. This study showed that changing the constraints of a given task (i.e., adding defender dummies to a football drill) or the constraints of an individual (i.e., perceptual limitation through stroboscopic vision) affects the performance outcomes as well as the movement coordination that emerges. This finding provided the implication that the extent to which an athlete is able to cope in a constraint-rich environment and perform whilst maintaining control over their movements might be the key to better understanding what contributes to non-contact ACL injury mechanisms. This is in line with the ecological dynamics perspective, which describes "how performance emerges from constraints on performer-environment relationships" (Davids et al. 2015). The self-organization of movement, also called behavioural dynamics, is in large part governed by the perception-action coupling of an athlete (Warren 2006). To clarify, information about the constraints, which are often quickly changing (e.g., relative position of players on a field), must be perceived by the athlete and relevant details must be derived from them in order to produce appropriate action responses. This process of perception-action carries significant demands for the cognitive control of an athlete, also called executive functions, which include inhibition, working memory, and cognitive flexibility (Diamond 2013). Moreover, it has been hypothesised that working memory forms an interface between perception and action (Baumeister 2013). Working memory is a brain function that retains information temporarily and neuroscience literature has proposed that it interconnects the perception circuits in the parietal cortex with the action circuits in the frontal cortex (Baddeley 2012). Given the important role of executive functioning in the self-organization of movement, it would follow that by evaluating the executive functioning of athletes, it may provide insight into potential individual risk factors. Deficiencies or mistakes in executive functioning might be the underlying reason why some athletes produce suboptimal or risky movement patterns. For example, when insufficient attention is allocated to perception, or when a player has poor response inhibition, this may potentially result in the player failing to adjust their movements to unexpected changes in a playing situation, such as an opponent's sudden change-of-direction.

Traditionally, cognitive assessments have used computer-based tests for reliable and standardised evaluation (Voss et al. 2010). However, the ecological dynamics perspective recommends that behaviour is best studied when performer-environment relationships are preserved. In order to bridge this gap, study IV investigated how computer-based and novel sport-specific assessments of executive functions compare. Specifically, this study tested the construct validity between the two paradigms for working memory and inhibition and found only low to moderate construct validity. This finding implies that computer-based and sport-specific assessments may not be interchangeable, likely due to discrepancy in degrees-of-freedom that are involved. Study IV concludes by suggesting that research should develop more sport-specific cognitive assessments. Study V follows this suggestion and explores the effects of cognitive demands on performance in a sport-specific stop-signal task when compared to a choice-reaction task. The EDA principles were followed by 1) examining a gross-motor reaction task instead of a button-press task, 2) simulating unpredictable stop scenarios, and 3) including both group-level and player-level analysis. By dividing execution time (ET) into reaction time (RT) and movement time (MT) (Schmidt & Lee 2013), study V was able to specify the observed performance delay to an increase in reaction time. In other words, the presence of random stop-signals caused the players to initiate movement later. Interestingly, when the analysis was shifted from group-level to player-level, this increase in reaction time was accompanied by varying changes in movement time. Some players compensated for the longer RT by moving faster, resulting in a shorter MT, in an attempt to maintain overall ET. Other players suffered from an aggravating MT increase, adding to the already larger ET, the hesitant movement initiation apparently carrying over negatively to the speed of movement execution. These distinct performance profiles highlight the individual nature of behavioural and performance dynamics. This finding also reveals how a surplus in physical capacity can effectively be put to use when a player is subjected to increased cognitive demands. Furthermore, the findings of study V are in line with previous literature on agility which proposed that athletes can be fast or slow movers and similarly also fast or slow thinkers (Gabbett & Sheppard 2013). This classification yields four different player types: 1) fast mover & fast thinker, 2) fast mover & slow thinker, 3) slow mover & fast thinker, and 4) slow mover & slow thinker. Admittedly, such a classification is slightly rudimentary, since it ignores the average player who inhabits the middle ground of moving or thinking speed. Including the percentile ranking of an athlete's performance compared to peers is a potential improvement, because it equally informs all athletes of their relative performance. Nevertheless, the original four-part model might still be a useful tool in identifying those players who do fit into outlying performance profiles and perhaps it can thereby help the individualisation of training. Furthermore, it could be hypothesized that certain profiles may be associated with an increased risk of injury. For example, a fast moving & slow thinking player might have strong physical qualities, yet they could be sluggish to perceive and decide on a different movement strategy when the playing situation demands it. As a result, this player might not be able to avoid a hazardous action, such as injury-associated posture or contact with another player. Of course, these performance profiles are not expected to be rigid. Players are likely to change between profiles due to any combination of constraints, such as muscular fatigue or external distractions. By investigating these individual components of player performance, research may be able to contribute to our understanding of injury mechanisms.

Study VI took what was learned in the previous studies and applied it to a field-based project in elite handball. The EDA principles were followed by 1) conducting a multi-direction gross-motor reaction task on a handball court, 2) simulating planned and reactive movement scenarios, and 3) performing statistical nonparametric mapping on the joint kinematics. The study found significant increases in execution time when players performed a reactive agility task compared to a planned task. This finding represents the performance cost of additional cognitive demands. The study also found age- and playing position specific differences in execution time. Adult players outperformed the youth players in execution time, regardless of task condition. This finding highlights the discriminant validity of the agility task that was developed, since the adult players were expected to be superior (Wagner et al. 2022). Furthermore, backcourt and wing players outperformed pivots, regardless of task or age group. This finding expands on the discriminant validity of the test, since it is known that handball features playing position dependent physical demands, with backcourt and wing players covering more distance running (at high speed) than pivots. In addition to finding differences in execution time, study VI also identified kinematic differences. These findings offer new insights into the link between movement and performance dynamics. In particular, these findings reveal indications of different movement strategies being used between age groups and playing positions. Pivots moved with more hip flexion than backcourt and wing players, especially in the late phase of the movement (deceleration). Simultaneously, pivots moved with less peak knee flexion than backcourt and wing players overall. Comparing between the age groups revealed that youth players moved with less hip and knee flexion than the adults in the early phase of the movement (initiation), perhaps indicating a tendency for a different starting posture that is slightly more upright. Furthermore, youth moved with increased peak knee flexion in the late phase (deceleration), which may imply that there are differences in braking strategies. In conclusion, the findings of study VI offer implications for practice as well as research. The strong discriminant validity of the test proves its value and provides direction for future research into motor-cognitive abilities. The age- and playing position dependent performance and kinematics may inform individualised training or talent identification efforts.

4.2 Strengths and Limitations

Scientists who want to make the translation step from lab to field in order to improve generalisation of their findings are burdened with the challenge of designing a meaningful study that ensures some control over influencing variables, otherwise they risk losing all chance of interpretation (Parada 2018). Following the trade-off concept by Parada, where an increase in behavioural degrees-of-freedom coincides with a decrease in interpretability of findings, it is recommended that researchers make small incremental steps in the ecological validity of their experimental designs (study I). When moving research from the lab to the field, like many sport and behavioural scientists aspire to do, researchers are required to be professionally bilingual. People working in science and people working in practice may have a common goal that they want to work towards, such as improving performance metrics or reducing injury risk in athletes, however, the ideas through which to attain these goals are sometimes dissimilar. For example, a recent study on the adoption of ACL injury prevention programmes reported that 11% of coaches who adopted a programme did not follow the evidence-based recommendation for training frequency, which likely thwarted any benefit in terms of risk reduction (MacFarlane et al. 2024). In many instances, work priorities are not aligned either. This makes sense, since coaches have to worry about player lineups for the next match, as well as scheduling time for gym, warmup, recovery, etcetera. Whereas the scientist worries about the state that the player is in, during the snapshot when the player is available for assessment, by interpreting as much data as possible to distil what is relevant. This multidisciplinary way of working, however difficult, can be incredibly fruitful. It requires understanding from both sides. The coach must appreciate the value of data-driven implications (Petushek et al. 2021), while the scientist must appreciate the advisory role that they fill in the larger organisation. Future prevention programmes that are based on an ecological dynamics approach may become more complex in their design and set-up and may therefore require a higher level of expertise for interpretation. In order to facilitate implementation and adherence, this calls for increased collaboration between science and practice (Arundale et al. 2022).

During the years in which these studies were conducted, there has been significant technological advancement in terms of wearable sensors for motion capture purposes. IMUs are absolutely crucial for a sport scientist that wishes to quantify movement behaviour in the context of injury. The popular predecessor to the IMU, the optoelectronic marker-based (OMB) system, although reliable and precise, has several practical limitations to overcome. The setup of a calibrated volume surrounded by cameras is rarely feasible in sport practice and it imposes strict borders between which movements are recorded. The use of IMUs solves many of these issues with their independence of both cameras and a calibrated volume. Early on in development, IMUs were struggling with inaccuracy just like any other measurement device. Now that IMU systems are more mature, they feature smart filtering algorithms to compensate for phenomena such as soft tissue artefacts. More recently, a new contender has entered the field of motion capture, namely 'markerless' tracking like Theia3D which uses 2D video cameras to estimate 3D human poses with deep learning algorithms (Augustine et al. 2025). Although this eliminates some of the drawbacks of traditional OMB systems, for example, the time-consuming marker fixation, markerless tracking still inherently suffers from many of the same camera-related factors, for instance, camera calibration, sensitivity to light level, dependence on sufficient background contrast, and measurement error due to loose clothing (Augustine et al. 2025). The availability of these different measurement systems for motion capture, each with their strengths and weaknesses, facilitates research on different points on the spectrum "from lab to field" or "athlete-environment preservation". Whether it is an early lab-based study that requires heightened control over variables to explore the intricacies of a complex mechanism, or whether it is field-based experiment that must allow more behavioural degrees-of-freedom to improve generalisability, each will have a motion capture system that is suitable for the job.

Over the years, many researchers have made their case for movement variability (Davids et al. 2006). Traditionally, variability was considered as noise that obscures the true signal (Bartlett et al. 2007). However, many researchers now consider that variability in movement behaviour can serve as a valuable descriptor of the human motor system (Bartlett et al. 2007). From this perspective, variability may be considered as a functional attribute that provides flexibility through a multitude of movement solutions. For example, imagine adjusting your stride length to avoid stepping in a puddle. You intend to step over the puddle. In order to accomplish this task, you might employ more plantarflexion of your stance leg prior to toe-off or more hip flexion of your swinging leg. Simultaneously, you might make some postural adaptations such as trunk lean or shoulder abduction to maintain balance. These types of movement variability are clearly beneficial to task performance. Nevertheless, the human motor system possesses more degrees-of-freedom than it needs to fulfil any given task (Bernstein 1967). For instance, a large hip abduction motion of the swinging leg does not contribute much to propulsion or balance in walking. This type of movement variability is therefore unlikely to help you step over the puddle and thus cannot be considered as beneficial to task performance. In conclusion, variability can neither be labelled as entirely functional nor as complete noise. Instead, its value must be derived from its context-specific effects on task performance, while taking into account the capabilities of the individual. The direct assessment of movement variability was limited in the studies covered by this dissertation. Team ball sport movements are complex collections of variables that are difficult to capture in one discrete measure of variability. Cyclic movements like running or swimming are suitable for nonlinear descriptors of variability such as entropy measures or Lyapunov exponent (Silva et al. 2022). However, acyclic movements like a sidestep cut, which are prevalent in team ball sports, often cannot be analysed using these methods because a non-straight trajectory confounds the periodicity of the data (Morrison et al. 2019, Moraiti et al. 2007). In order to deal with the complexity of variability in such team ball sport movements, recent literature has proposed a categorisation into strategic variability and execution variability (Cowin et al. 2022). Strategic variability refers to the different movement solutions used to complete a task. Execution variability refers to the minor adjustments of the body between repetitions of the same movement strategy. Recent research has also developed a strategy quantification method for team ball sport movements using different variability attributes, such as the number of foot contacts, stride length variance, and cumulative change in heading angle (Eke et al. 2017). These developments are expected to contribute to our understanding of self-organized movement and adaptations to constraints in team ball sport players. In particular, these metrics of movement variability may help to identify in which instances variability is functional and in which it is detrimental or even harmful to the athlete.

4.3 Implications

Based on the results of the studies presented in this dissertation, several ideas have formed with regards to an outlook on both science and practice. Sport science should continue to explore the mechanisms by which movements are self-organized, including for those movements which are associated with non-contact ACL injuries. The neurocognitive dynamics of a player should be considered as an integral part of the mechanism behind non-contact ACL injury. Whether a playing situation presents an inciting event for injury is highly individual. Understanding this disposition and how that culminates in quantifiable movement adaptations is key to identifying injury risk. Fortunately, the last few years have seen substantial developments in this field. For instance, the *sequence of prevention* has been revisited to adapt step 1 so that it considers the (behavioural) complexity of injury phenomena (Bolling et al. 2018). Moreover, recent literature has revealed insightful new findings related to behaviour, neurocognition, and playing style in team sport athletes that contribute to risk of injury (Gokeler et al. 2024, Schultz et al. 2021). The field of sport science continues to be tasked with finding a compromise between 1) obtaining statistical power through conventional group-level analysis and 2) maintaining relevance and sensitivity of findings to the individuality of athletes by developing novel player-level analysis methods. Innovations in applied machine learning (ML) hold promise for future exploration of the complex dynamics between player, task, and environment (Benjaminse et al. 2024, Van Eetvelde et al. 2021). Furthermore, ML may present the key to figuring out how to deal with the complexity and high dimensionality of these dynamics. It will likely require multidisciplinary work to develop ML models that are computationally effective as well as beneficial in their application to sports.

Sport practice should continue collaborating with researchers. The field of elite sports is increasingly tasked with incorporating data-driven decision-making (Hammes et al. 2022), which should involve the employment of dedicated personnel like embedded sport scientists or data scientists. It is in the interest of everyone (player, coach, trainer, physiotherapist, teammates, etc.) to be well-informed about not only the performance of a player, but also their movements, stress level, and recovery status through frequent evaluations. For example, if a player with poor recovery status (i.e., physical and psychological readiness) is able to maintain performance at the cost of movement quality, they might be prone to overexerting themselves which could result in (re)injury (Kaplan & Witvrouw 2019). The burden of injury extends to the absence of a player in a team (i.e., time loss), which may hurt the odds of the team winning the next match. Rather than risking the injury, data-driven practitioners may deliberate on benching the player instead, giving them more recovery time. Obviously, incorporating science into practice is no small task and such innovations are perhaps best implemented in a way that compliments already scheduled training sessions or physiotherapy appointments in order to make it feasible.

5 Conclusion

In conclusion, this thesis took an ecological dynamics approach to studying team ball sports movements in the context of non-contact ACL injury risk. The studies in this thesis investigated mechanisms and relationships between performance outcomes, various constraints, and movement behaviour in team ball sport players. The findings revealed highly individual adaptations to constraints, as well as complex relationships between performance measures and movement strategies. This aligns with the ecological dynamics perspective, which emphasizes studying movement at the athlete-environment level rather than relying on generalized group-level analyses or "one size fits all"-methodology like prescribing neuromuscular training for an entire athlete population to prevent injuries. By gaining insight into what contributes to the individual self-organization of movements in team ball sports, it improves our understanding of which combination of constraints (i.e., task, environment, individual) are associated with the inciting events for non-contact ACL injury. Screening should incorporate sport-specific motor tasks with varying neurocognitive load to better assess an athlete's ability to maintain performance and movement integrity under different demanding conditions. This approach allows for a more comprehensive evaluation of an individual's strengths, weaknesses, and potential predispositions to injury, which may ultimately contribute to more tailored and effective prevention efforts.

Scientific Dissemination

Peer-reviewed publications

- Bolt, R., Heuvelmans, P., Benjaminse, A., Robinson, M. A., & Gokeler, A. (2021). An ecological dynamics approach to ACL injury risk research: a current opinion. Sports biomechanics, 1–14. Advance online publication. https://doi.org/10.1080/14763141.2021.1960419
- Büchel, D., Gokeler, A., Heuvelmans, P., & Baumeister, J. (2022). Increased Cognitive Demands Affect Agility Performance in Female Athletes - Implications for Testing and Training of Agility in Team Ball Sports. Perceptual and motor skills, 129(4), 1074–1088. https://doi.org/10.1177/00315125221108698
- Heuvelmans, P., Benjaminse, A., Bolt, R., Baumeister, J., Otten, E., & Gokeler, A. (2022). Concurrent validation of the Noraxon MyoMotion wearable inertial sensors in change-of-direction and jump-landing tasks. Sports biomechanics, 1–16. Advance online publication. https://doi.org/10.1080/14763141.2022.2093264
- Gokeler, A., Grassi, A., Hoogeslag, R., van Houten, A., Lehman, T., Bolling, C., Buckthorpe, M., Norte, G., Benjaminse, A., Heuvelmans, P., Di Paolo, S., Tak, I., & Villa, F. D. (2022). Return to sports after ACL injury 5 years from now: 10 things we must do. Journal of experimental orthopaedics, 9(1), 73. https://doi.org/10.1186/s40634-022-00514-7
- Nijmeijer, E. M., Heuvelmans, P., Bolt, R., Gokeler, A., Otten, E., & Benjaminse, A. (2023). Concurrent validation of the Xsens IMU system of lower-body kinematics in jump-landing and change-of-direction tasks. Journal of biomechanics, 154, 111637. https://doi.org/10.1016/j.jbiomech.2023.111637
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- Gokeler, A., Zandbergen, M. A., Hoogeslag, R. A. G., van Houten, A. H., Nijmeijer, E. M., & Heuvelmans, P. (2024) Neurocognitive Demands Shortens Jump Distance

and Reduce Coordination Variability of the Injured Leg in Athletes After ACL-Reconstruction. Knee surgery, sports traumatology, arthroscopy : official journal of the ESSKA, 10.1002/ksa.12439. https://doi.org/10.1002/ksa.12439

- Gondwe, B., Heuvelmans, P., Benjaminse, A., Büchel, D., Baumeister, J., & Gokeler, A. (2025). Unveiling the Distinctions: Computer Versus Sport-Specific Neurocognitive Tests. *Journal of Sport Rehabilitation*, 1–7. https://doi.org/10.1123/jsr.2024-0304
- Heuvelmans P., Gondwe B., Benjaminse A., Nijmeijer E., Baumeister J. & Gokeler A. (2025) Stop-Signal Task on a Training Platform Induces Player-Level Adaptations in Team Sport Athletes. Submitted at *Perceptual and Motor Skills.*
- Heuvelmans, P., Gokeler, A., Benjaminse, A., Baumeister, J., & Büchel, D. (2025) Agility in Handball: Position- and Age-Specific Insights in Performance and Kinematics using Proximity and Wearable Inertial Sensors. Submitted at *Sensors*.

Book chapters

- Gondwe, B., Benjaminse, A., Heuvelmans, P., Nijmeijer, E. M., Büchel, D., Tak, I., & Gokeler, A. (2024). Neurocognition and Sport: An Overview of Its Application to Sports Injury Prevention and Rehabilitation. In M. N. Doral & J. Karlsson (Eds.), Sports Injuries: Prevention, Diagnosis, Treatment and Rehabilitation (pp. 1–12). Springer Berlin Heidelberg. https://doi.org/10.1007/978-3-642-36801-1_349-1

Presentations

- Oral presentation at the "Sportmedisch Wetenschappelijk Jaarcongres", Ermelo, Netherlands (Jun 2022) titled: "5 Ws to optimally apply new sensor technology in ACL rehabilitation".
- Oral presentation and motion capture workshop for the Sports Medicine Course at University Krems, Austria (Sept 2022) titled: "Return-to-Sport: On-Field Rehabilitation".
- Motion capture workshop at Aston Villa Football Club, Birmingham, United Kingdom (Apr 2024) titled: "Prevention of cruciate ligament injury".
- Guest lecture at Rizzoli Orthopaedic Institute and Isokinetic Rehabilitation Centre, Bologna, Italy (Jan 2025) titled: "Return-to-Play in Professional Handball: Medically cleared but are baseline data met?".

- Oral presentation at the German Exercise Science and Training Conference (GEST), Saarbrücken, Germany (Feb 2025) titled: “Comparing Planned and Reactive Agility in Elite Handball Players: Temporal and Kinematic Performance”.

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Appendix

A – Publications and manuscripts of the included studies

Study I

SPORTS BIOMECHANICS
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An ecological dynamics approach to ACL injury risk research: a current opinion

Ruben Bolt [a], Pieter Heuvelmans [a], Anne Benjaminse [a,b], Mark A. Robinson [c] and Alli Gokeler [d,e,f]

[a]Department of Human Movement Sciences, University of Groningen, University Medical Center Groningen, Groningen, The Netherlands; [b]School of Sport Studies, Hanze University Groningen, Groningen, The Netherlands; [c]Research Institute for Sport and Exercise Sciences, Faculty of Science, Liverpool John Moores University, Liverpool, UK; [d]Exercise Science and Neuroscience Unit, Department Exercise & Health, Paderborn University, Paderborn, Germany; [e]Amsterdam Collaboration for Health and Safety in Sports, Department of Public and Occupational Health, Amsterdam Movement Sciences, VU University Medical Center, Amsterdam, The Netherlands; [f]Department of Sports Medicine, OCON Centre of Orthopaedic Surgery and Sports Medicine, Hengelo, The Netherlands

ABSTRACT
Research of non-contact anterior cruciate ligament (ACL) inj1ury risk aims to identify modifiable risk factors that are linked to the mechanisms of injury. Information from these studies is then used in the development of injury prevention programmes. However, ACL injury risk research often leans towards methods with three limitations: 1) a poor preservation of the athlete-environment relationship that limits the generalisability of results, 2) the use of a strictly biomechanical approach to injury causation that is incomplete for the description of injury mechanisms, 3) and a reductionist analysis that neglects profound information regarding human movement. This current opinion proposes three principles from an ecological dynamics perspective that address these limitations. First, it is argued that, to improve the generalisability of findings, research requires a well-preserved athlete-environment relationship. Second, the merit of including behaviour and the playing situation in the model of injury causation is presented. Third, this paper advocates that research benefits from conducting non-reductionist analysis (i.e., more holistic) that provides profound information regarding human movement. Together, these principles facilitate an ecological dynamics approach to injury risk research that helps to expand our understanding of injury mechanisms and thus contributes to the development of preventative measures.

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Ecological dynamics; ACL; injury risk research; non-reductionist; self-organisation

Introduction

Non-contact anterior cruciate ligament (ACL) ruptures are injuries that typically occur during dynamic movements such as rapid deceleration or change of direction (Cochrane et al., 2007). These injuries involve significant financial costs for society, large personal

CONTACT Alli Gokeler alli.gokeler@uni-paderborn.de
Bolt and Heuvelmans wrote the manuscript. Benjaminse, Gokeler, and Robinson provided comments and edits for the manuscript.

burden due to the great number of days of absence from training and match play (Ardern et al., 2011; Stewart et al., 2017), and a high risk of post-traumatic osteoarthritis (Shelbourne et al., 2017). Due to these long-lasting consequences, the prevention of ACL injuries should have top priority (Hewett et al., 2016). Over the past 20 years, researchers have identified modifiable (biomechanical and neuromuscular) risk factors related to the mechanisms of ACL injury in team sports (Hewett et al., 2005; Krosshaug et al., 2016; Leppänen et al., 2020; Zebis et al., 2009). These risk factors have provided information for the development of ACL injury prevention measures (Hewett et al., 2016), through the 'Sequence of Prevention' model (Van Mechelen et al., 1992): i.e., 1) establishing the extent of the sports injury problem (incidence & severity), 2) establishing aetiology and mechanism of injuries, 3) introducing preventive measures, and 4) assessing their effectiveness by repeating step 1.

Establishing the modifiable risk factors and mechanisms of injury through injury risk research is an essential step in the 'Sequence of Prevention'(Van Mechelen et al., 1992). These lab-based studies typically aim to mimic movements that characterise injury risk scenarios such as change-of-directions or jump landings and assess the biomechanics associated with these movement tasks (Shultz et al., 2015). Considering the importance of these injury risk studies, we have the following concerns regarding their methods. First, injury risk research typically takes place in a laboratory setting that fails to preserve the athlete-environment relationship. As a result, the generalisability of findings may be limited. Second, injury risk research is often conducted from a strictly biomechanical approach. This is representative of adopting a 'narrow' model of injury causation, as this approach may overlook the effects of other variables, such as player behaviour or the surrounding environment. Third, injury risk studies that analyse single-joint biomechanics using linear statistical measures are reductionist and neglect information about the adaptability and complexity of human movement. Together, these aspects of injury risk research methods limit the knowledge gained from these studies and thus narrow our understanding of injury risk (Figure 1a).

To address these limitations, we propose an approach from an 'ecological dynamics' perspective that considers the human body as a complex adaptive system that interacts with its environment, which is best studied at the athlete-environment level of analysis (Renshaw et al., 2019). Although this ecological dynamics perspective is already prominent in the fields of sports performance (Davids et al., 2015; Seifert et al., 2013; Woods et al., 2019) and sport psychology (Araújo et al., 2019; Otte et al., 2020; Renshaw et al., 2019), its implementation in injury risk research is limited. While this paper specifically discusses non-contact ACL injury risk research, this approach is also applicable to other domains. This article consists of three parts. First, we describe how movements emerge through self-organisation and underline the importance of 'context' in studying movement behaviour and its relation to injury situations. Second, we discuss three principles that enhance ACL injury risk research (Figure 1b): preserving the athlete-environment relationship, including behaviour and the playing situation in the injury causation model, and conducting non-reductionist (i.e., more holistic) analysis. Finally, we conclude with an example of a study design that adheres to the proposed principles. By providing these principles, we hope to offer researchers an approach that helps expand the understanding

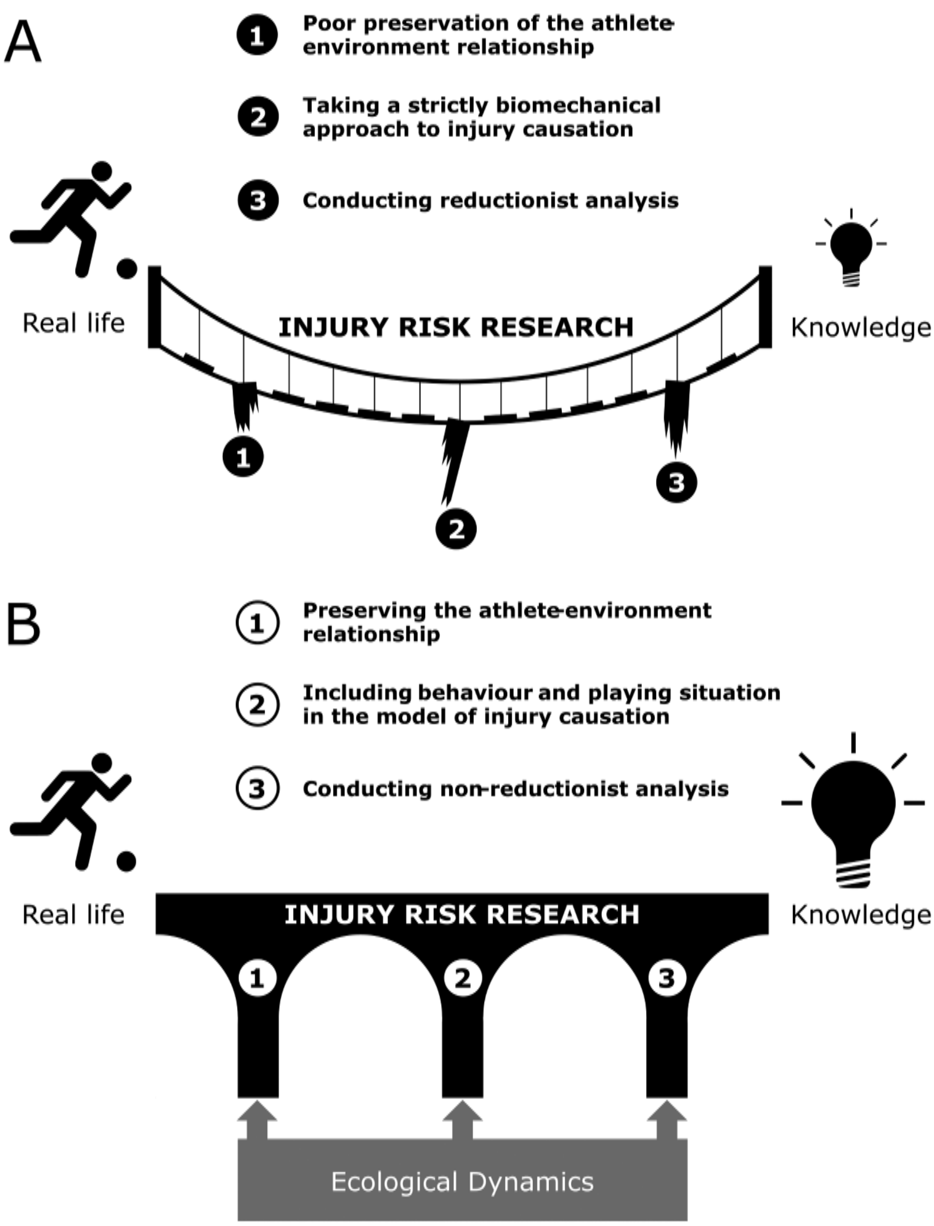

Figure 1. Schematic representation of injury risk research as the bridge between *real life* and *knowledge*. (a) Limitations of current injury risk research methods are pitfalls that limit the knowledge obtained from these studies. (b) Principles for an ecological dynamics approach to injury risk research. These principles provide a foundation for research that is more generalisable and less reductionist, expanding the knowledge that is obtained.

of injury mechanisms and thus contributes to the development of effective preventive measures.

'Context' and self-organised movements

Human movement can be viewed as the emergent result of the interaction between the athlete and its surrounding context (Newell et al., 1989). The athlete performs in a context that is shaped by three types of constraints; the individual constraints, the environmental constraints, and the task constraints (Figure 2). Individual-related constraints, for

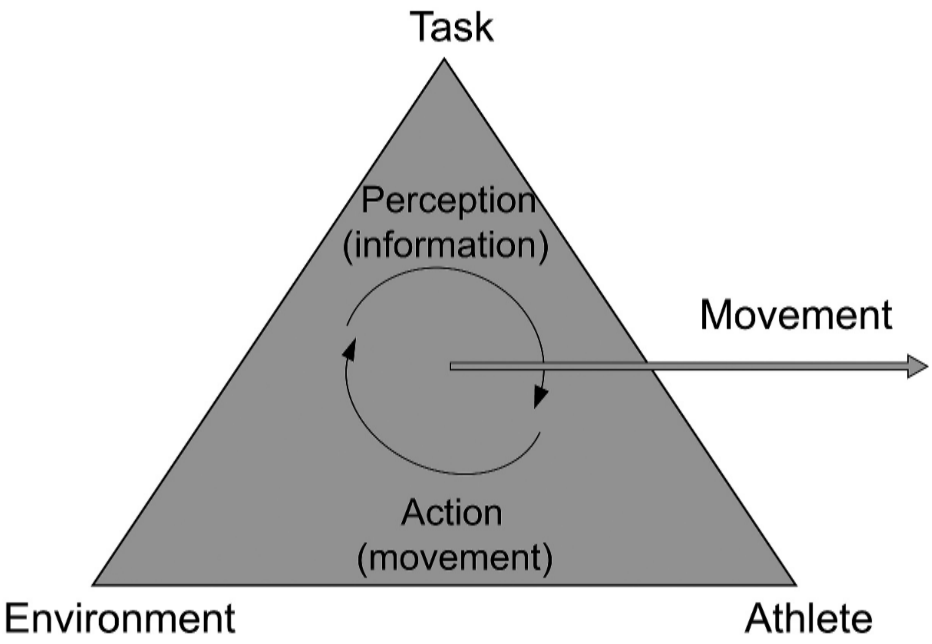

Figure 2. Movement is the emergent result of the athlete perceiving and acting within a context that is shaped by its constraints (Newell et al., 1989). An adapted figure from Davids et al. (Davids et al., 2003).

example, may concern the athlete's characteristics such as height, weight, limb length, fatigue, or anxiety (Renshaw et al., 2010). Environmental constraints may include features like the type of terrain, light condition, weather, or boundaries of the field. Task constraints may include the goal of the task and any rules or objects that specify or constrain the athlete's response dynamics, for instance, the actions of other players (Renshaw et al., 2010). Together, these constraints shape the context in which the athlete perceives and acts. Movement in sport is therefore not produced by an isolated athlete, but emerges from a dynamically varying coupling between the athlete's characteristics, the stimulus-rich environment, and the desired actions (i.e., tasks) (Araújo & Davids, 2011).

Adopting this view of movement behaviour has two important consequences for studying movement. First, most constraints are changeable and in fact may change rapidly (e.g., the relative position of players, fatigue levels, ball possession). Second, the relationship between the produced movement and the underlying constraints is nonlinear. To clarify, small changes to individual, task or environmental constraints can cause dramatic changes in movement patterns (Renshaw et al., 2010). Additionally, changes in different types of constraints can result in the exact same effect on the movement pattern (Schmidt et al., 1990). Recognising the changeable nature of constraints and the nonlinear relationship between constraints and movement is essential in studying movement behaviour.

In the process of self-organised movements, perception and action are coupled and cannot be studied in isolation. Expert athletes are not solely proficient movers, but excel in perceiving information from the environment and execute actions accordingly (Araújo et al., 2019; Lee et al., 2017, 2013). This direct connection between movement and the environment warrants research at the athlete-environment level. Therefore, if experimental studies intend to investigate game-like movement behaviour of athletes, aiming to preserve the athlete-environment coupling by adding game-specific stimuli is essential to elicit generalisable movement patterns (McGuckian, Cole, Pepping et al., 2018).

Principles for an ecological dynamics approach

Preserving the athlete-environment relationship

Athletes in team sports have to quickly perceive not only their own action opportunities but also those of opponents and teammates, while performing a movement. These continuous actions are performed under time pressure as movement possibilities emerge and disappear. A non-contact injury is therefore the result of a series of self-organised movements that emerge from the interaction with quickly changing constraints. Video analysis has shown that non-contact ACL injuries in team sports typically occur when the athlete is in close proximity to an opponent, while the athlete or the opponent is in possession of the ball (Boden et al., 2009; Brophy et al., 2015; Olsen et al., 2004). To acquire generalisable information about risk factors and injury mechanisms in these scenarios, experimental research should strive to present athletes with game-like variables so that the elicited movement is more reflective of the movements in injury scenarios.

Traditionally, the laboratory-based injury risk studies inherently provide athletes with limited room for self-organisation of their movements. Athletes are usually instructed to move along a predefined trajectory at a certain speed or to perform a jump in a marked area. Generally, game-like variables, such as interactions between participants or between the athletes and a ball, are omitted to preserve the standardisation and the repeatability of the protocol. Instead, participants are often instructed to respond to a simple visual cue that is atypical of the complex visual stimuli in game situations (e.g., an LED lighting up or an arrow being displayed) (Besier et al., 2001). Furthermore, trials wherein the participant fails to successfully complete the prescribed task are typically discarded. As a consequence, the movement tasks studied in the lab are different from the movement behaviour that would emerge from scenarios on the pitch (McGuckian, Cole, Pepping et al., 2018). The poor generalisability of these studies limits a critical step of the 'Sequence of Prevention' model; to identify risk factors and injury mechanisms (Van Mechelen et al., 1992).

In the last decade, researchers have made efforts to include game-like variables into their experiments. For instance, some studies have included sport-specific dual-tasks like dribbling, intercepting, or passing a ball during a change-of-direction manoeuvre (Almonroeder et al., 2019; Chan et al., 2009; Fedie et al., 2010; Monfort et al., 2019). Other studies had the athlete respond to an opponent or a video projection of an opponent in a simulated game scenario (Fujii et al., 2014, 2015; Lee et al., 2019; Spiteri et al., 2014). In addition to this, rather than discarding unsuccessful trials, some studies have investigated the underlying coordination of unsuccessful task performance (DiCesare et al., 2020) or used the number of unsuccessful trials as a performance measure (Lee et al., 2017). These improvements in methods are commendable and exemplary steps towards the first principle: preserving the athlete-environment relationship. However, researchers should remain careful when generalising findings from these studies. Studies should first specify the context towards which they intend to generalise their findings, and then explain how that context is represented in their experimental designs (McGuckian, Cole, Jordet et al., 2018).

Researchers that wish to adhere to this principle should consider designing experiments which maintain the athlete-environment coupling by including elements of the sport that are relevant to the game scenario of interest; such as the ball, other players, and objectives that are related to real game scenarios (e.g., evading, intercepting). Of course, such experiments are best performed on the field. Developments in wearable inertial sensor technology are now facilitating performance evaluation on the field rather than in the laboratory (Camomilla et al., 2018). Nevertheless, when investigating dynamic movements (e.g., jumping), the validity of lower extremity joint kinematics in the frontal and transverse planes is currently only deemed 'fair-to-good' (i.e., on a scale of 'poor; 'fair-to-good'; 'excellent') and thus warrants further developments (Al-Amri et al., 2018).

Efforts to improve the athlete-environment relationship will likely increase complexity of the dataset due to an increase in the number of uncontrolled variables. Researchers are therefore challenged with finding the balance between the preservation of the athlete-environment coupling and the interpretation of the dataset. For instance, navigating around training dummies introduces more coordinative complexity when compared to pre-planned sidestep cutting. Likewise, replacing training dummies with real opponents adds additional coordinative complexity, as well as variables related to affordance perception (Araújo et al., 2019). We advise to take small steps on this spectrum of athlete-environment preservation, so that it aids the interpretation of the increasingly complex datasets.

Including behaviour and the playing situation in the injury causation model

It has long been popular to study ACL injury risk using a biomechanical approach (Fung, 1993; Whiting & Zernicke, 1998). A goal of this approach is to identify modifiable risk factors that can provide information for prevention strategies (Hewett et al., 2016). The focus typically lies on describing biomechanical characteristics at a specific foot contact during a change-of-direction or landing from a jumping movement (Nedergaard et al., 2020; Peebles et al., 2020). The movement tasks that are investigated are designed to mimic the movements during which ACL injuries occur. This approach is appropriate for research regarding the internal and external joint loads of such movement tasks, and it may serve as a 'stepping stone' to facilitate the interpretation of more complex models. However, this approach is incomplete for a comprehensive understanding of actual injury mechanisms (Nilstad et al., 2021).

ACL injury risk research demands an approach that is based on a more comprehensive injury causation model. In 2005, Bahr & Krosshaug (2005) proposed a conceptual model describing the factors that contribute to the inciting event of an injury. According to this model, the description of an inciting event should include information not only about the biomechanical characteristics, but also about the playing situation and the behaviour of the athlete and other players. Descriptive video analyses have shown that athlete behaviour and playing situations are highly sport-specific (Carlson et al., 2016; Della Villa et al., 2020). This highlights the importance of athlete behaviour and playing situations in the inciting event of injury and thus supports the inclusion of these factors in the injury causation model that researchers adopt.

To determine the effects of player behaviour and playing situations on injury risk, we suggest designing experiments that preserve the athlete-environment relationship while considering factors such as perceptual skills and decision making of the athletes (e.g Hughes & Dai, 2021) For instance, by studying the visual exploratory behaviour of athletes, it might be possible to link visual exploratory behaviour prior to an action with the biomechanical characteristics during the action (Wilkerson et al., 2017). Taken together, adopting this comprehensive injury causation model likely expands our understanding of injury risk and thus may inform new prevention strategies.

Comprehensive movement analysis requires non-reductionist methods

A movement pattern is a series of movements over time. The reduction of this time series during analysis needs to retain the information of interest regarding the research questions. In injury risk studies, researchers typically analyse the kinematics of movements using linear descriptives such as means, ranges and standard deviations. The results are often joint-specific snapshots of the mechanical properties during short time windows, e.g., peak knee valgus moment during weight acceptance (Shultz et al., 2015). Researchers then compare the kinematics or kinetics to examine differences between groups, interventions, conditions, or exercises. In this section, we will describe how this 'reductionist analysis' often reduces the data to such an extent that it discards important information regarding injury risk. We then discuss how the use of linear descriptives overlooks relevant information and propose a few non-reductionist (i.e., more holistic) methods that provide profound information that helps our understanding of injury risk mechanisms.

The reduction of a series of movements to a short time window neglects information regarding preceding movement behaviour. By doing so, information regarding movement strategies that constitute safe biomechanical characteristics is neglected. Alternatively, safe biomechanics may have involved unsafe preceding movement behaviour. For example, the penultimate step of a change-of-direction has shown to provide important information for the description of the movement behaviour prior to an injury (Jones et al., 2016). Including the previous steps into the window of analysis provides information regarding movement strategies that facilitate the biomechanics at final contact. By expanding the measurement window, the information that constitutes the variable of interest is retained. This allows for the extraction of information regarding safe movement strategies which is essential for informing prevention programmes. An example of a linear analysis method that is appropriate for analysing time series is statistical parametric mapping (SPM) (Pataky et al., 2015).

Experimental studies usually collect their data through multiple trials of a movement task. As movement patterns differ between trials (Stergiou & Decker, 2011), within-person movement variability is ever present in the data. The kinematic study of movements therefore inevitably involves movement variability. Traditionally, variability is considered noise and quantified as the deviation from the mean (Stergiou & Decker, 2011). There are a few important limitations in the analysis of movement variability using linear descriptives. First, the use of linear descriptives assumes that lower variability equals a more stable system with less noise. However, there are examples where movements with high variability are more deterministic (i.e., predictable variability), which shows greater stability in a movement (Stergiou & Decker, 2011; Strongman & Morrison, 2020). Variability therefore requires a measure other than the standard deviation to describe the stability of movement patterns. Second, linear descriptives reduce a time series to a single description, discarding any information regarding the temporal structure of variability (Stergiou & Decker, 2011). Third, the comparison of effects between groups can be inaccurate, as within-person variability may be higher than between-group variability (Fisher et al., 2018; Glazier & Mehdizadeh, 2019). Fourth, when assessing the effect of a constraint on a movement task, the effect can differ between individuals, which violates the assumption of homogeneity of linear testing models (Glazier & Mehdizadeh, 2019).

Human movement is inherently variable and this plays a vital role in the adaptability and coordination of the movement system (Bartlett et al., 2007). There are a few analysis methods that provide profound information that linear analysis methods do not provide. First, the uncontrolled manifold (UCM) hypothesis relates variability towards a performance variable that the movement system aims to control (Latash et al., 2002); variability is divided into variability that affects the performance variable and variability that does not. This way, UCM-based analysis does not solely quantify variability, but offers the possibility to relate it to a performance measure of movement (Latash et al., 2002). Second, the Lyapunov exponent gives a description of the stability of the system in repeating movements, offering the possibility to measure stability in a variable movement pattern (Stergiou & Decker, 2011). For example, a decrease in functional responsiveness (i.e., the response to a perturbation) has been shown in the ACL-deficient knee of athletes using Lyapunov exponents (Moraiti et al., 2007). Third, entropy analysis methods such as the approximate (Cavanaugh et al., 2006), multiscale (Moras et al., 2018), or sample entropy (Morrison et al., 2019), allow for the description of the rigidness of the system (Costa et al., 2005; Stergiou & Decker, 2011). By comparing the rigidness of a system between conditions, the effect of the condition can be described while within-movement variability is not neglected. For example, increased variability has been revealed in the acceleration of rugby players in a ball situation compared to a no-ball situation (Moras et al., 2018).

The use of non-reductionist analysis methods such as the UCM, Lyapunov exponent, and entropy analysis provides profound information regarding the coordination of the motor system and its response dynamics that linear measures do not provide. For example, approximate entropy analysis found significant differences in postural control between previously concussed participants and healthy controls, while the initial analysis using linear statistics deemed participants to be recovered of their concussion (Cavanaugh et al., 2006). However, despite their value, there are limitations to the use of these methods. For instance, the sample entropy analysis of biomechanics in cyclical movements is sensitive to changes in the trajectory of the movement (Morrison et al., 2019). Likewise, the calculation of the Lyapunov exponent requires repeated movements within a trial. To add, most non-reductionist methods require a larger sample size to correctly analyse variability (e.g., Robinson et al., 2021; Rosenblatt & Hurt, 2019). Nevertheless, expanding the toolkit used in injury risk research with non-reductionist methods in appropriate situations will allow researchers to extract information which linear measures otherwise neglect. As a result, it will improve the understanding of the relationship between the coordination of the motor system, the role of movement variability, constraints and injury risk.

A study design that adheres to these three principles

To exemplify the use of these principles, let us imagine a study that aims to examine the effect of fatigue on the kinematics of sidestep cutting in a ball vs. no ball condition, aimed towards football research. The *athlete-environment coupling* would be preserved by capturing kinematic data on the football pitch using inertial sensors. Participants would perform sidestep cuts around training-dummies, allowing for the movement to self-organise closer to how it would in real matches. The real-world constraints would be mimicked by inducing sport specific fatigue through a football match simulation (Azidin et al., 2015). The study would *include behaviour and the playing situation to the injury causation model* by investigating a potential confounding or mediating effect of visual exploratory behaviour by testing conditions with and without ball possession. Furthermore, the study would comply with the principle of *non-reductionist analysis* by complementing linear descriptives with an UCM analysis. Using the UCM analysis, changes in the variability of joint-angles can be related to a control strategy such as the stability of the centre of mass of the athlete (Papi et al., 2015). This analysis may identify mechanisms between fatigue and unstable movements. Such mechanisms may lead to the identification of novel risk factors, which can then be used to identify players that are at increased risk of fatigue-induced injury. The results of the study would be discussed in the context of the experiment and related to the context of the performance environment (Davids et al., 2015). As changes in behaviour are non-linearly related to movements (see Section 2), an explicit description of the context of the experiment would be required, allowing for a better comparison of effects between studies and providing suggestions for future research.

Conclusion

This paper presents an ecological dynamics approach to injury risk research through three principles. It is important to realise that the implementation of only one of these three principles will not yield the desired effect. For example, maintaining the athlete-environment coupling whilst using only linear measures will still neglect relevant information. Using non-reductionist (i.e., more holistic) methods in a non-representative lab setting does not provide profound information regarding the performance context, limiting the generalisability of the results. Similarly, limiting the research scope with a strictly biomechanical approach to injury causation prevents the possibility to span results across relevant fields. Thus, the implementation of this ecological dynamics approach warrants a simultaneous consid1eration of all three principles.

Undoubtedly, conducting research according to these theoretical principles poses practical challenges that warrants attention. Firstly, efforts to preserve the athlete-environment relationship may increase the complexity of datasets. Researchers should therefore take small steps in preserving the athlete-environment relationship in order to aid the interpretation of these increasingly complex datasets. Secondly, when including playing situations and behaviour in the injury causation model, it may help to form multidisciplinary research groups (e.g., biomechanists, sport psychologists, coaches/trainers) and learn from each other's perspectives. Thirdly, to correctly implement non-reductionist analyses, researchers should adjust their study designs so that they meet the requirements of the analysis methods (e.g., sufficient sample size, appropriate measurement window). By collaborating with statisticians, mathematicians, or other experts, researchers can explore the wealth of available methods to find appropriate analyses for their research questions. We believe that studies using this approach will be more generalisable and less reductionist. This results in improved understanding about risk factors and injury mechanisms, thereby contributing to the sequence of prevention.

Disclosure statement

No potential conflict of interest was reported by the author(s).

ORCID

Ruben Bolt http://orcid.org/0000-0002-0843-5063
Mark A. Robinson http://orcid.org/0000-0002-5627-492X

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Study II

SPORTS BIOMECHANICS
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Concurrent validation of the Noraxon MyoMotion wearable inertial sensors in change-of-direction and jump-landing tasks

Pieter Heuvelmans [a], Anne Benjaminse [b,c], Ruben Bolt [b], Jochen Baumeister [a], Egbert Otten [b] and Alli Gokeler [a]

[a]Exercise Science and Neuroscience Unit, Department of Exercise & Health, Paderborn University, Paderborn, Germany; [b]Department of Human Movement Sciences, Faculty of Medical Sciences, University of Groningen, Groningen, the Netherlands; [c]School of Sport Studies, Hanze University Groningen, Groningen, the Netherlands

ABSTRACT
Wearable inertial sensors (WIS) facilitate the preservation of the athlete-environment relationship by allowing measurement outside the laboratory. WIS systems should be validated for team sports movements before they are used in sports performance and injury prevention research. The aim of the present study was to investigate the concurrent validity of a wearable inertial sensor system in quantifying joint kinematics during team sport movements. Ten recreationally active participants performed change-of-direction (single-leg deceleration and sidestep cut) and jump-landing (single-leg hop, single-leg crossover hop, and double-leg vertical jump) tasks while motion was recorded by nine inertial sensors (Noraxon MyoMotion, Noraxon USA Inc.) and eight motion capture cameras (Vicon Motion Systems Ltd). Validity of lower-extremity joint kinematics was assessed using measures of agreement (cross-correlation: XCORR) and error (root mean square deviation; and amplitude difference). Excellent agreement (XCORR >0.88) was found for sagittal plane kinematics in all joints and tasks. Highly variable agreement was found for frontal and transverse plane kinematics at the hip and ankle. Errors were relatively high in all planes. In conclusion, the WIS system provides valid estimates of sagittal plane joint kinematics in team sport movements. However, researchers should correct for offsets when comparing absolute joint angles between systems.

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Introduction

Rapid changes-of-direction and jumping are typical movements in team ball sports. They are used to differentiate between performance levels and may be useful when profiling or selecting young players (Pojskic et al., 2018; Sattler et al., 2015). By investigating the biomechanics of such dynamic team sport movements, researchers intend to better understand successful performance. This knowledge could help the development of new training programmes. Furthermore, an improved understanding of successful

CONTACT Pieter Heuvelmans pieter.heuvelmans@upb.de

performance can potentially also help us prevent injuries related to unsuccessful performance. Many studies on dynamic team sport movements have been conducted in a laboratory setting using an optoelectronic marker-based (OMB) system (van der Kruk & Reijne, 2018). More recently, wearable inertial sensors (WIS) have become popular for human movement analysis outside the laboratory setting (Iosa et al., 2016). The application of WIS in sports is wide; including team sports (e.g., football, rugby, basketball), individual sports (e.g., tennis, golf, weightlifting), and cyclic sports (e.g., running, swimming, rowing) (Camomilla et al., 2018). WIS systems allow study designs that are more ecologically valid as the preservation of the athlete-environment relationship is maintained (Bolt et al., 2021). Furthermore, WIS systems represent a low-cost, easy-to-use alternative to OMB systems (Iosa et al., 2016). Although the concurrent validity of WIS systems has shown to be acceptable-to-excellent in gait analysis (Berner et al., 2020), previous research has indicated low accuracy in more complex dynamic movements (Godwin et al., 2009; Iosa et al., 2016; Poitras et al., 2019). Motion capture of dynamic movements using WIS is more challenging than for slower movements like gait because it requires higher sample frequencies, especially when studying moments of impact (e.g., jump-landing or the plant foot in a change-of-direction), and it can negatively affect sensor fixation or orientation estimation due to the higher linear accelerations (van der Kruk & Reijne, 2018). It is important that the concurrent validity of WIS systems is always investigated per system and under the conditions of interest to determine their accuracy (Lindemann et al., 2014). To the best knowledge of the authors, the Noraxon MyoMotion WIS system has not been validated for change-of-direction and jump-landing tasks. The aim of this study was to investigate the concurrent validity of the Noraxon MyoMotion WIS system (Noraxon USA, Inc., Scottsdale, AZ, USA) in quantifying lower extremity joint kinematics in change-of-direction and jump-landing tasks when compared to a Vicon OMB system (Vicon Motion Systems Ltd, Oxford, UK). It is hypothesised that the two systems will present high agreement for joint motion in the sagittal plane.

Materials and methods

Participants

Five female (age: 21.4 ± 1.8 yrs, height: 176.3 ± 7.5 cm, mass: 66.8 ± 7.8 kg) and five male (age: 22.2 ± 1.6 yrs, height: 182.8 ± 6.9 cm, mass: 75.4 ± 11.1 kg) participants were included. Inclusion criteria were; between 18–25 years old, recreationally active in sports (i.e., two to three times per week in moderate to high intensity activity), free from lower extremity injury, and free from any pain that would impair their ability to run or jump. Procedures were approved by the institutional Medical Ethics Committee (IRB nr. 2018/249). Participants signed an informed consent form prior to inclusion in the study.

Instruments and procedures

Participants wore tight-fitting sportswear to minimise movement artefacts and their preferred indoor sports shoes. Long hair was tied in a knot to prevent occlusion of the reflective markers. Participants were fitted with nine Noraxon MyoMotion inertial sensors (Noraxon MyoMotion Research PRO, Noraxon USA, Inc., Scottsdale, AZ, USA) according to the guidelines of the manufacturer at C7, L1/T12, sacrum, thighs, shanks, and feet (Figure 1). A total of twenty-one reflective markers were placed according to the Vicon Plug-in Gait model (Vicon Plug-in Gait Reference Guide, Vicon Motion Systems Ltd, Oxford, UK) (Figure 1). High test and retest repeatability and good measurement accuracy of the Vicon Plug-in Gait model have been reported previously (Kadaba et al., 1989; McGinley et al., 2009). To scale the Noraxon MyoMotion model to each participant, anthropometric measures were collected: body height, body mass, torso length (from C7 to posterior superior iliac spine), pelvis width (measured at the iliac crest), thigh length (from the proximal process of the greater trochanter to the centre of the lateral femoral epicondyle), shank length (from the centre of the lateral femoral epicondyle to the centre of the lateral malleolus), and foot length (from the calcaneal tuberosity to the distal end of the hallux). Anthropometric measurements were performed to scale the Vicon model to each participant: body height and mass, leg length (from anterior superior iliac spine to the centre of the medial malleolus), knee width (medio-lateral width at the joint line), and ankle width (medio-lateral width at the malleoli). For concurrent validation purposes, WIS kinematic data (200 Hz) were compared with simultaneous data collected by a 200 Hz 8-camera Vicon motion analysis system (Vicon Motion Systems Ltd, Oxford, UK). The systems recorded synchronously via sync pulse using a Noraxon MyoSync synchronisation system (model 262, Noraxon USA, Inc., Scottsdale, AZ, USA). Static calibrations were performed for both systems according to manufacturer specifications.

The participants were asked to identify their dominant lower extremity, defined as the preferred leg for jumping and landing. The change-of-direction and jump-landing tasks were personalised based on body height and leg dominance using tape markings on the floor and cones (Figure 2). All tasks utilised taped rectangular targets on the

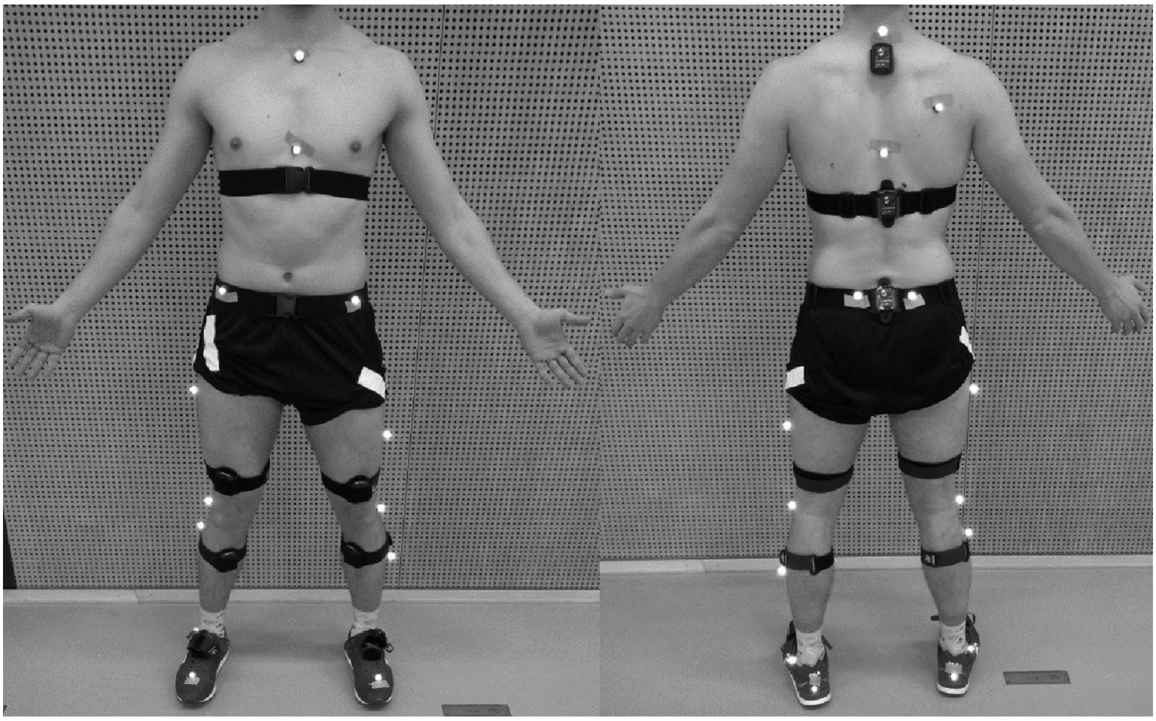

Figure 1. Placements of reflective markers and wearable inertial sensors.

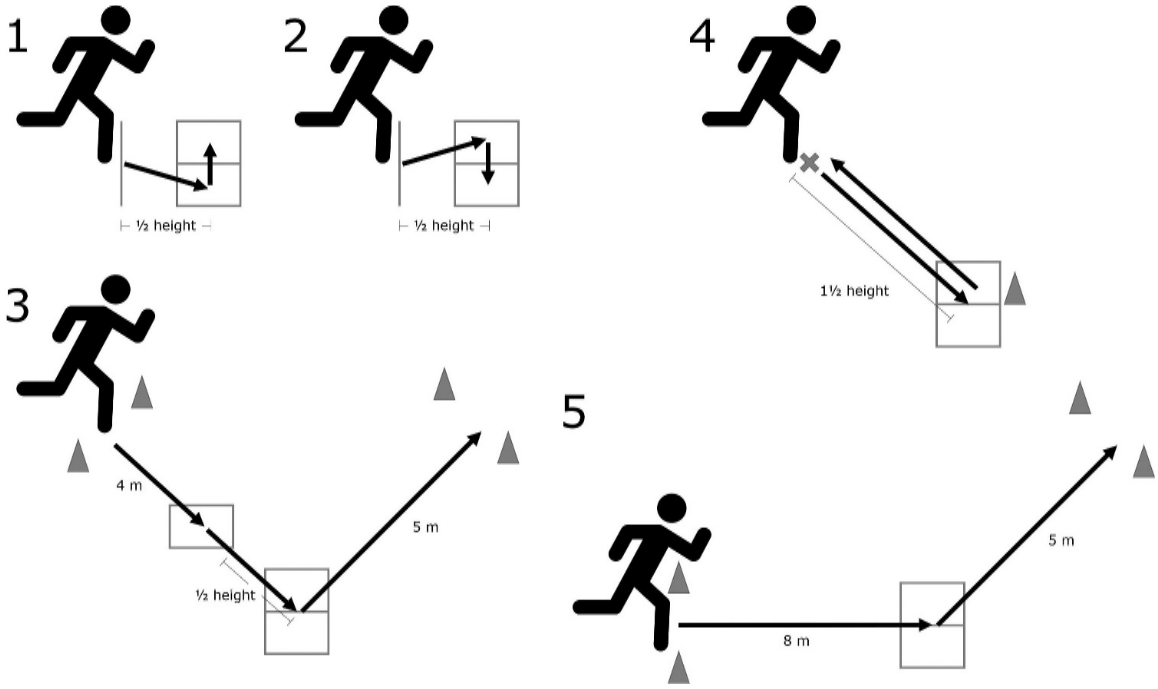

Figure 2. Change-Of-Direction and jump-landing tasks (right-leg dominance depicted): (1) Single-leg hop: Participants performed a single-leg hop to the ipsilateral target with their dominant leg, immediately followed by a single-leg hop to the contralateral target. (2) Single-leg crossover hop: Participants performed a single-leg hop to the contralateral target with their dominant leg, immediately followed by a single-leg hop to the ipsilateral target. (3) Double-leg vertical jump: Participants ran towards the targets at a 45-degree angle. After pushing off with their non-dominant leg, participants performed a double-leg landing on the targets, immediately followed by a double-leg vertical jump. After the second landing, the participants shuffled in a perpendicular direction, contralateral to their dominant leg. (4) Single-leg deceleration: Participants performed quick steps towards the targets at a 45-degree angle. Upon landing on the target with their dominant leg, the participants performed a single-leg deceleration and push-off to return to their starting position. (5) Sidestep cut: Participants ran at a moderate speed 5 meters towards the targets and performed a 45-degree sidestep cut with their dominant leg on the target and continued running for 5 metres.

floor (40 by 60 cm) to indicate take-off and landing sites. The single-leg hop and single-leg crossover hop were individualised by taking ½ body height for the hopping distance, indicated by a tape line on the floor. The tape markings for double-leg vertical jump consisted of three rectangular targets, with the take-off target at ½ body height distance from the centre of the two landing targets. For the single-leg deceleration task, distance from the starting position (taped 'X' on the floor) to the change-of-direction (rectangular target in front of a cone) was individualised to 1½ body height. The start and finish of the double-leg vertical jump and side-step cut were demarcated by 1-metre wide cone gates. Participants were coached to use a submaximal approach speed for the double-leg vertical jump and side-step cut. For the purpose of analysis, all motor tasks were collected for the dominant leg. The researcher explained and demonstrated the tasks and the participants performed practice trials. After familiarisation with the tasks, the participants were instructed to perform five trials of each task, in the order that they preferred. Each trial was followed by a 30s rest period. Trials were discarded if the participants lost balance; if a foot partially or completely missed the targets; or if they touched a target with the incorrect foot. Participants were measured on two occasions with a 5–7 day interval.

Data processing

Kinematic data were recorded for the full duration of each motor task (Figure 2). Raw data were digitised in Vicon Nexus (version 2.7.1, Vicon Motion Systems Ltd, Oxford, UK) and MyoResearch 3 (MR3, version 3.14.52, Noraxon USA, Inc., Scottsdale, AZ, USA). Before exporting the data, OMB trajectory data were smoothed using a Woltring filter (Woltring, 1995) and WIS data were processed with the manufacturer's proprietary sensor fusion algorithm and Kalman filtering. Further data processing and waveform analyses were conducted with a customised software using MATLAB 9.6 (The MathWorks Inc., Natick, MA). Noraxon quaternion output was transferred to Euler angles in degrees through a rotation matrix. The Vicon Euler angle order of YXZ for hip and ankle joints and their signs were taken as the convention. Outlying data were regarded as part of the observations and therefore were only excluded if no comparison could be made between systems due to technical issues.

Statistical analysis

Concurrent validity was assessed using cross-correlation (XCORR), root mean square deviation (RMSD), and amplitude difference (ΔAMP) between lower extremity joint kinematics recorded by the WIS and OMB systems. XCORR is a measure of agreement between two time series (Islam et al., 2020). Level of agreement was interpreted as 'poor' if XCORR <0.40, 'fair' if XCORR 0.40–0.75, and 'excellent' if XCORR >0.75 (Kadaba et al., 1989), as used in a recent study with a similar design albeit for different correlation measures (Di Paolo et al., 2021). RMSD is a measure of error and was calculated by taking the square root of the average of squared deviations (Robinson et al., 2014). ΔAMP is also a measure of error and was calculated by taking the maximum difference in amplitude between waveforms. When compared to taking the absolute difference in range of motion, ΔAMP is better suited to describe error between waveforms because it quantifies noise rather than implying that it is part of the physiological range of motion of a joint. ΔAMP was defined as WIS minus OMB data. Level of error was interpreted as 'low' if the measure of error ≤5° (Di Paolo et al., 2021). Due to the tasks being focused on the dominant leg, only the joint kinematics of the dominant leg are reported.

Results

A total of 491 trials (98%) were included and used for comparison between the two systems. Nine trials (2 for single-leg crossover hop, 6 for single-leg deceleration, and 1 for sidestep cut) were excluded from further analysis due to failure of one of the systems to record the full trial.

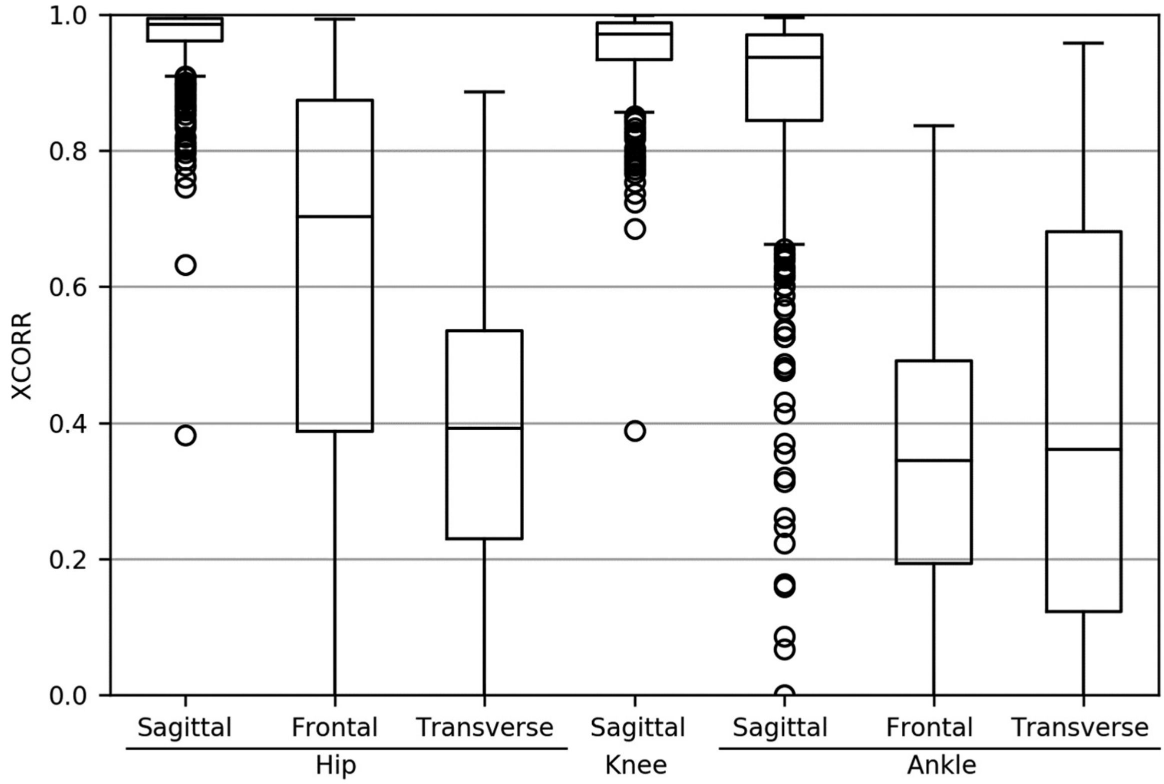

Figure 3. Cross-Correlations (XCORR) between the two motion capture systems.

Agreement

Sagittal plane joint angles demonstrated excellent XCORR for the hip (median: 0.99, interquartile range (IQR): 0.03), knee (median: 0.97, IQR: 0.05), and ankle (median: 0.94, IQR: 0.13) (Figure 3). Frontal plane joint angles presented fair XCORR at the hip (median: 0.70, IQR: 0.49), but poor for the ankle (median: 0.34, IQR: 0.30). Transverse plane hip (median: 0.39, IQR: 0.31) and ankle (median: 0.36, IQR: 0.56) angles displayed poor XCORR.

Errors

Knee sagittal plane angles had the highest RMSD (median: 16.33°, IQR: 10.97°), followed by hip (median: 14.67°, IQR: 8.80°) and ankle transverse plane angles (median: 13.26°, IQR: 8.87°) (Figure 4). Ankle sagittal (median: 7.55°, IQR: 6.87°) and frontal plane (median: 7.38°, IQR: 3.54°) angles showed the lowest RMSD. Ankle frontal plane angles demonstrated the highest ΔAMP (median: 18.06°, IQR: 10.11°), followed by hip transverse angles (median: 5.49°, IQR: 13.02°) and knee sagittal angles (median: -3.09°, IQR: 9.64°) (Figure 5).

Motor tasks

Jump-landing tasks (single-leg hop, single-leg crossover hop, and double-leg vertical jump) and change-of-direction tasks (single-leg deceleration and sidestep cut) all displayed excellent XCORR for sagittal plane joint angles (Table 1). Double-leg vertical jump and single-leg deceleration demonstrated excellent XCORR for hip frontal

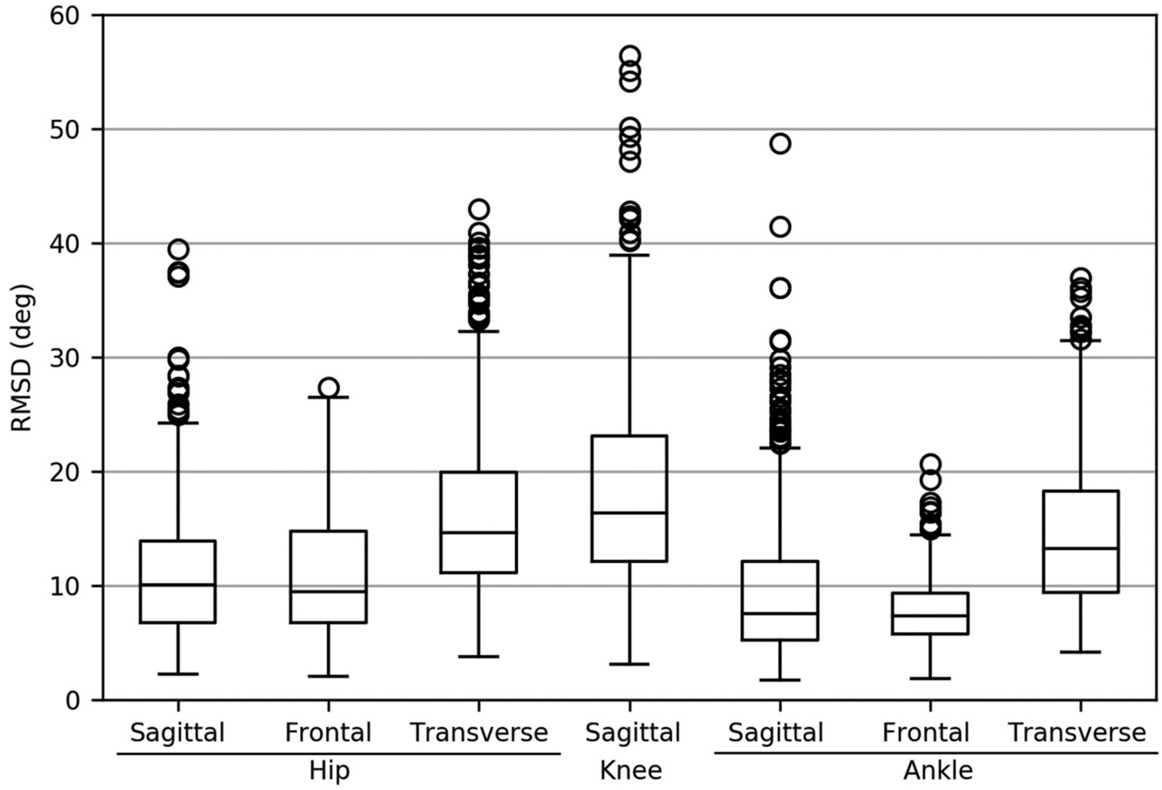

Figure 4. Root mean square deviations (RMSD) between the two motion capture systems.

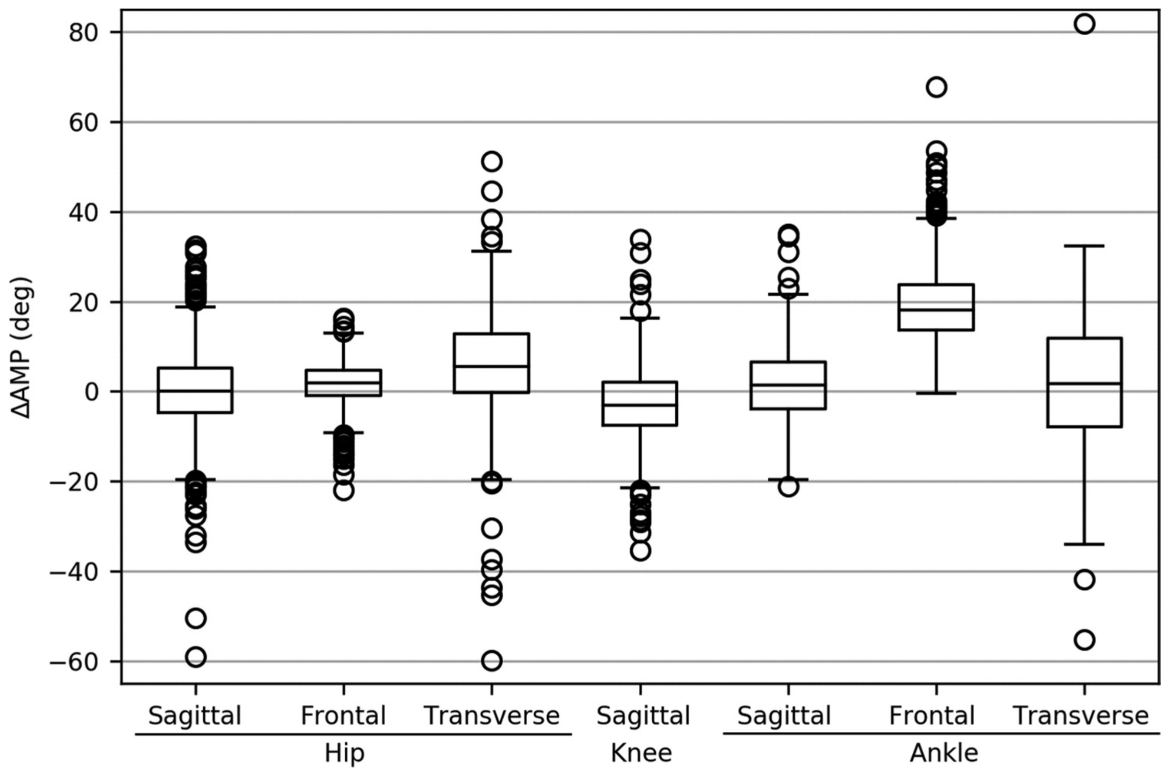

Figure 5. Amplitude differences (ΔAMP) between the two motion capture systems.

Table 1. Measures of agreement (XCORR) and error (RMSD, ΔAMP) between the two motion capture systems for the five motor tasks, median (interquartile range).

	Hip			Knee	Ankle		
	Sagittal	Frontal	Transverse	Sagittal	Sagittal	Frontal	Transverse
XCORR							
single-leg hop	0.97 (0.06)	0.62 (0.52)	0.37 (0.27)	0.97 (0.05)	0.94 (0.11)	0.31 (0.29)	0.60 (0.35)
single-leg crossover hop	0.97 (0.06)	0.59 (0.50)	0.40 (0.26)	0.95 (0.05)	0.93 (0.14)	0.31 (0.25)	0.73 (0.36)
double-leg vertical jump	0.99 (0.01)	0.77 (0.37)	0.34 (0.22)	0.98 (0.03)	0.96 (0.05)	0.39 (0.26)	0.26 (0.36)
single-leg deceleration	1.00 (0.01)	0.85 (0.25)	0.27 (0.44)	0.99 (0.02)	0.94 (0.12)	0.34 (0.33)	0.17 (0.27)
sidestep cut	0.98 (0.04)	0.66 (0.67)	0.51 (0.31)	0.94 (0.09)	0.88 (0.14)	0.37 (0.37)	0.21 (0.46)
RMSD							
single-leg hop	11.31° (5.88°)	7.80° (5.69°)	12.31° (6.91°)	14.77° (9.13°)	8.91° (9.23°)	6.22° (2.46°)	9.20° (7.30°)
single-leg crossover hop	11.99° (6.38°)	8.11° (6.25°)	11.60° (6.82°)	16.16° (8.23°)	12.13° (11.09°)	7.58° (3.81°)	9.85° (6.08°)
double-leg vertical jump	7.67° (7.12°)	9.42° (7.09°)	17.00° (7.13°)	15.57° (8.04°)	6.33° (4.37°)	8.26° (4.07°)	13.52° (7.40°)
single-leg deceleration	9.41° (5.37°)	14.43° (11.71°)	17.25° (16.42°)	15.74° (8.00°)	5.49° (2.89°)	7.47° (2.85°)	15.73° (7.50°)
sidestep cut	10.76° (9.82°)	11.15° (8.43°)	16.80° (12.77°)	25.89° (16.50°)	8.12° (5.11°)	7.72° (2.79°)	15.91° (9.31°)
ΔAMP							
single-leg hop	-1.58° (9.22°)	1.90° (3.75°)	4.01° (9.73°)	0.01° (9.50°)	-17.83° (7.31°)	-23.72° (8.90°)	1.02° (9.09°)
single-leg crossover hop	-2.41° (7.44°)	2.12° (3.89°)	2.11° (8.02°)	-2.40° (7.38°)	-16.74° (7.37°)	-24.11° (12.71°)	1.11° (11.50°)
double-leg vertical jump	5.14° (7.72°)	2.67° (4.78°)	10.09° (12.09°)	-2.36° (9.13°)	-26.86° (13.36°)	-29.92° (10.07°)	2.90° (11.10°)
single-leg deceleration	-1.58° (11.66°)	-0.76° (5.61°)	3.26° (13.69°)	-4.26° (9.70°)	-29.27° (9.76°)	-30.49° (10.74°)	0.53° (12.23°)
sidestep cut	1.10° (11.26°)	3.20° (6.58°)	13.39° (18.25°)	-4.34° (11.74°)	-0.56° (12.23°)	-24.62° (8.31°)	1.22° (10.55°)

XCORR = cross-correlation; RMSD = root mean square deviation; ΔAMP = amplitude difference.

plane angles, but poor XCORR for hip transverse plane angles. All motor tasks presented poor XCORR for ankle frontal plane angles. Single-leg hop and single-leg crossover hop both displayed fair XCORR for ankle transverse plane angles, while the other motor tasks showed poor XCORR. Sidestep cut featured the highest RMSD of the five motor tasks, with a median of 25.89° (IQR: 16.50°) for knee sagittal plane angles. The other RMSDs ranged from 5.49° (IQR: 2.89°) to 17.25° (IQR: 16.42°) across motor tasks and joint angles. All motor tasks demonstrated high ΔAMP for ankle sagittal and frontal plane angles, ranging from -16.74° (IQR: 7.37°) to -30.49° (IQR: 10.74°). The other ΔAMPs ranged from -4.34° (IQR: 11.74°) to 13.39° (IQR: 18.25°) across motor tasks and joint angles.

Discussion and implications

Agreement

In change-of-direction and jump-landing tasks, sagittal plane lower extremity joint angles showed excellent agreement between the WIS and OMB systems. This finding is in line with previous comparisons between WIS and OMB systems for complex movements (Di Paolo et al., 2021; Poitras et al., 2019). Frontal and transverse plane hip and ankle joint angles, however, displayed highly variable agreement, ranging from poor to excellent agreement for each of the five different motor tasks. Because the range of motion is inherently smaller in the frontal and transverse planes, the influence of noise is relatively large when compared to movement in the sagittal plane. Noise in motion capture is multifactorial, but it often relates to incorrect estimations of segmental orientations which causes so-called ‘cross-talk’ between different planes of joint motion: motion in one plane is incorrectly registered as motion in another (Mok et al., 2015). While previous studies have investigated movements like squats or gait (Berner et al., 2020; Teufl et al., 2019), all motor tasks in the current study featured complex dynamic movements, with simultaneous motion in multiple planes, which have been found to affect WIS accuracy due to higher linear accelerations (Poitras et al., 2019; van der Kruk & Reijne, 2018). Similarly, the accuracy of the OMB system may have been affected by task complexity and soft tissue artefacts due to the limited number of segmental markers used in the Vicon Plug-in Gait model. Between-system agreement in the frontal and transverse plane will likely benefit from innovations in both WIS hardware and software. Hardware could be improved by increasing the internal sampling frequency and by optimising the sensor fixation methods to limit impact-related noise. Software could be improved by novel sensor fusion algorithms and filtering methods that are designed to deal with the higher levels of noise associated with more dynamic movements.

Errors

All change-of-direction and jump-landing tasks were characterised by offset errors regardless of waveform agreement, with RMSD ranging between 5.49° and 25.89° across the joint planes (Table 1). This confirms previous reports of WIS over- or underestimating joint angles (Teufl et al., 2019). A probable source for this error is a between-system discrepancy in setting the 0°-point for joints through calibration. Researchers should therefore be careful when using absolute angles and it suggests that offset correction methods are required when comparing findings between studies that have used WIS or OMB systems.

Knee sagittal plane angles displayed low amplitude differences (ΔAMP: -4.34°–0.01°), while the offset errors were relatively high (RMSD: 14.77°–25.89°), especially in sidestep cut (RMSD: 25.89°). This paradoxical observation is explained by the fact that amplitude differences are affected by direction (i.e., WIS minus OMB) while RMSD is directionless. This finding, hence, indicates that the variation in amplitude differences lies around 0°, but that the magnitude of offset error is relatively large.

Ankle sagittal and frontal plane angles demonstrated large amplitude differences (ΔAMP >16°) across all motor tasks, while the offset errors were relatively moderate (RMSD: 5.49°–12.13°). These error measures are greater than previously reported for bilateral squats (SQ), single-leg squats (SLS), and countermovement jumps (CMJ) (Teufl et al., 2019). This difference can likely be explained by the highly dynamic movements investigated in the current study. In line with this argument, Teufl and colleagues reported that the more dynamic task, CMJ, demonstrated greater errors than SQ and SLS in their study (Teufl et al., 2019). A simultaneous low RMSD with high ΔAMP indicates that the waveforms have low deviation for the majority of the time but show short bursts of large deviation. This is possibly due to impact artefacts on the WIS at the moment of initial contact causing sudden spikes in the recorded joint angles, or due to insufficient reflective markers for the OMB system causing a temporary obstruction of the segmental orientation of the foot. This source of error could likely be reduced by stricter fixation methods for the foot inertial sensor or additional reflective markers on the foot segment.

Limitations

A limitation of this study is the lack of frontal and transverse plane knee kinematics, since —at the time of data acquisition—the default kinematic modelling settings for the Noraxon MyoMotion WIS system interpreted the knee joint as 1 degree-of-freedom. However, these modelling settings are not appropriate for research investigating anterior cruciate ligament (ACL) injury, which has been linked to changes-of-direction and jump-landings (Boden et al., 2000; Olsen et al., 2004); since this type of injury typically occurs with a combination of knee abduction and external rotation of the tibia (Della Villa et al., 2020). Future investigations should therefore utilise kinematic modelling settings that interpret the knee joint as 3 degrees-of-freedom, to investigate the concurrent validity of frontal and transverse knee joint angles in complex dynamic movements. Furthermore, the OMB model used in this study features a limited number of reflective markers, which may have introduced measurement error. Further developments in WIS systems should be validated against OMB models with a greater number of reflective markers to minimise measurement error.

Conclusions

Taken together, this study shows that the Noraxon MyoMotion WIS system can provide valid estimates of lower extremity sagittal joint kinematics during change-of-direction and jump-landing tasks, when compared to a Vicon OMB system. However, a word of caution when comparing absolute angles without correcting for offsets. Moreover, the results of this study also indicate that caution should be taken when interpreting lower extremity frontal and transverse plane kinematics of complex dynamic movements as between-system agreement is highly variable.

Acknowledgments

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Author contributions

Conceptualization, P.H., A.B., R.B. and A.G.; methodology P.H., A.B., R.B. and A.G.; software, E. O.; validation, P.H., A.B., R.B. and A.G.; formal analysis, P.H., R.B. and E.O.; investigation, P.H., A. B., R.B. and A.G.; resources, A.B., J.B. and A.G.; data curation, P.H., R.B. and E.O.; writing—original draft preparation, P.H.; writing—review and editing, A.B., R.B., J.B., E.O. and A.G.; visualisation, P.H., A.B., R.B. and A.G.; supervision, A.B., J.B. and A.G.; project administration, A.B., J.B. and A.G. All authors have read and agreed to the published version of the manuscript.

Data availability statement

The data presented in this study are available on reasonable request. The data are not publicly available due to privacy restrictions.

Disclosure statement

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ORCID

Pieter Heuvelmans http://orcid.org/0000-0002-9957-7963
Jochen Baumeister http://orcid.org/0000-0003-2683-5826
Egbert Otten http://orcid.org/0000-0003-4719-2241

Informed consent statement

Informed consent was obtained from all subjects involved in the study.

Institutional review board statement

Procedures were approved by the institutional Medical Ethics Committee (IRB nr. 2018/249).

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Appendix

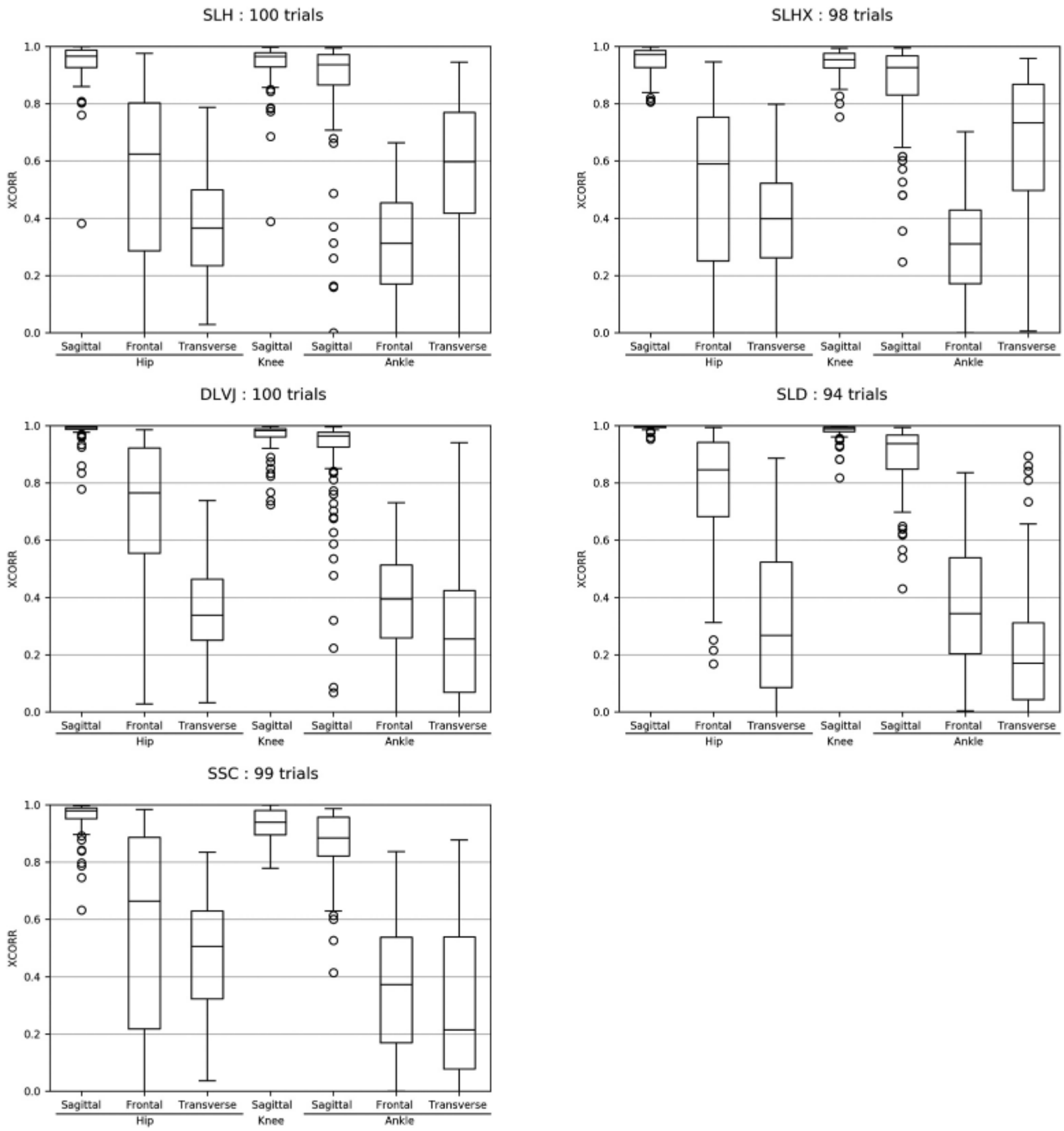

Figure A1. Cross-correlations (XCORR) per motor task. SLH = single-leg hop; SLHX = single-leg crossover hop; DLVJ = double-leg vertical jump; SLD = single-leg deceleration; SSC = sidestep cut.

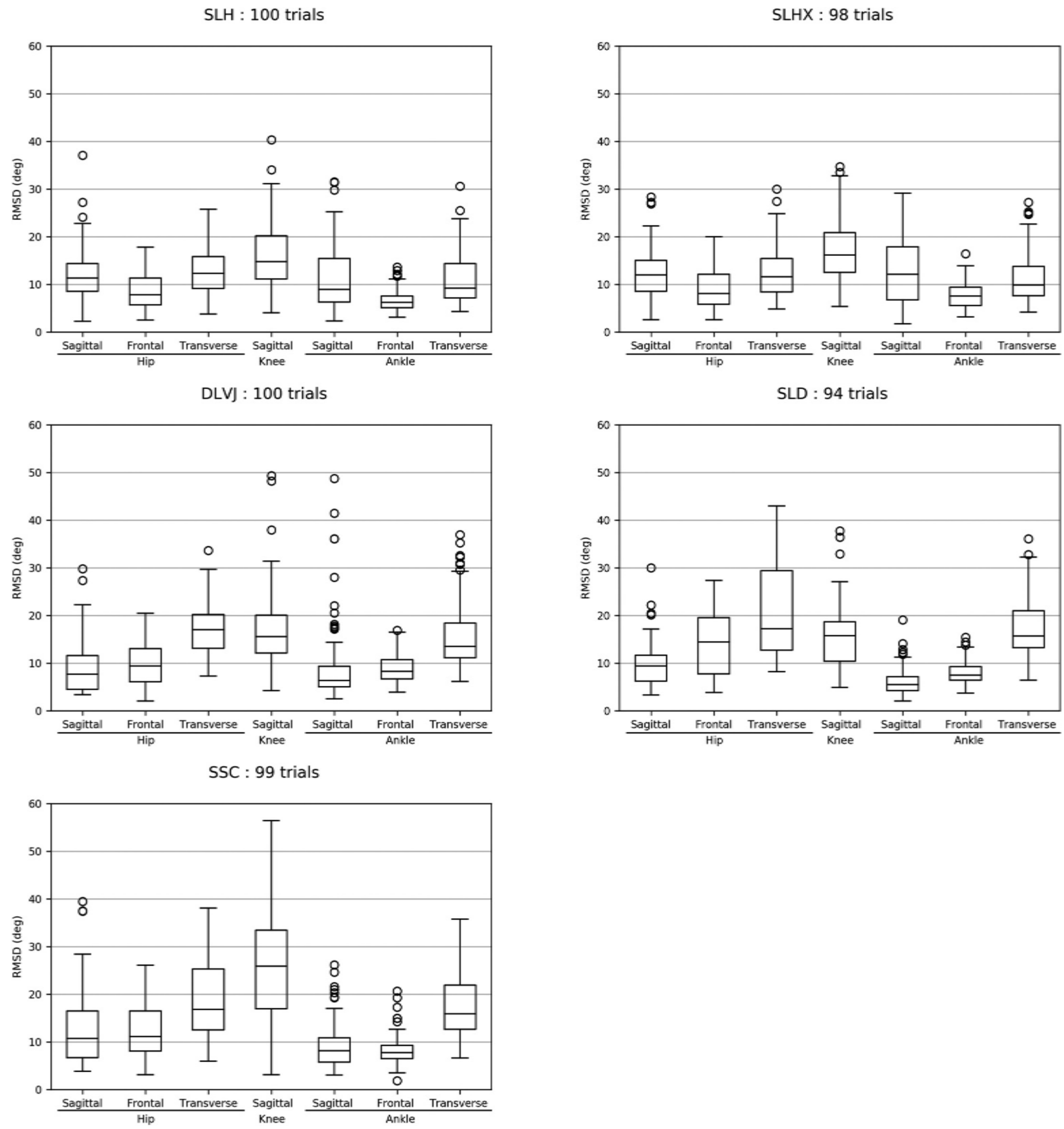

Figure A2. Root mean square deviations (RMSD) per motor task. SLH = single-leg hop; SLHX = single-leg crossover hop; DLVJ = double-leg vertical jump; SLD = single-leg deceleration; SSC = sidestep cut.

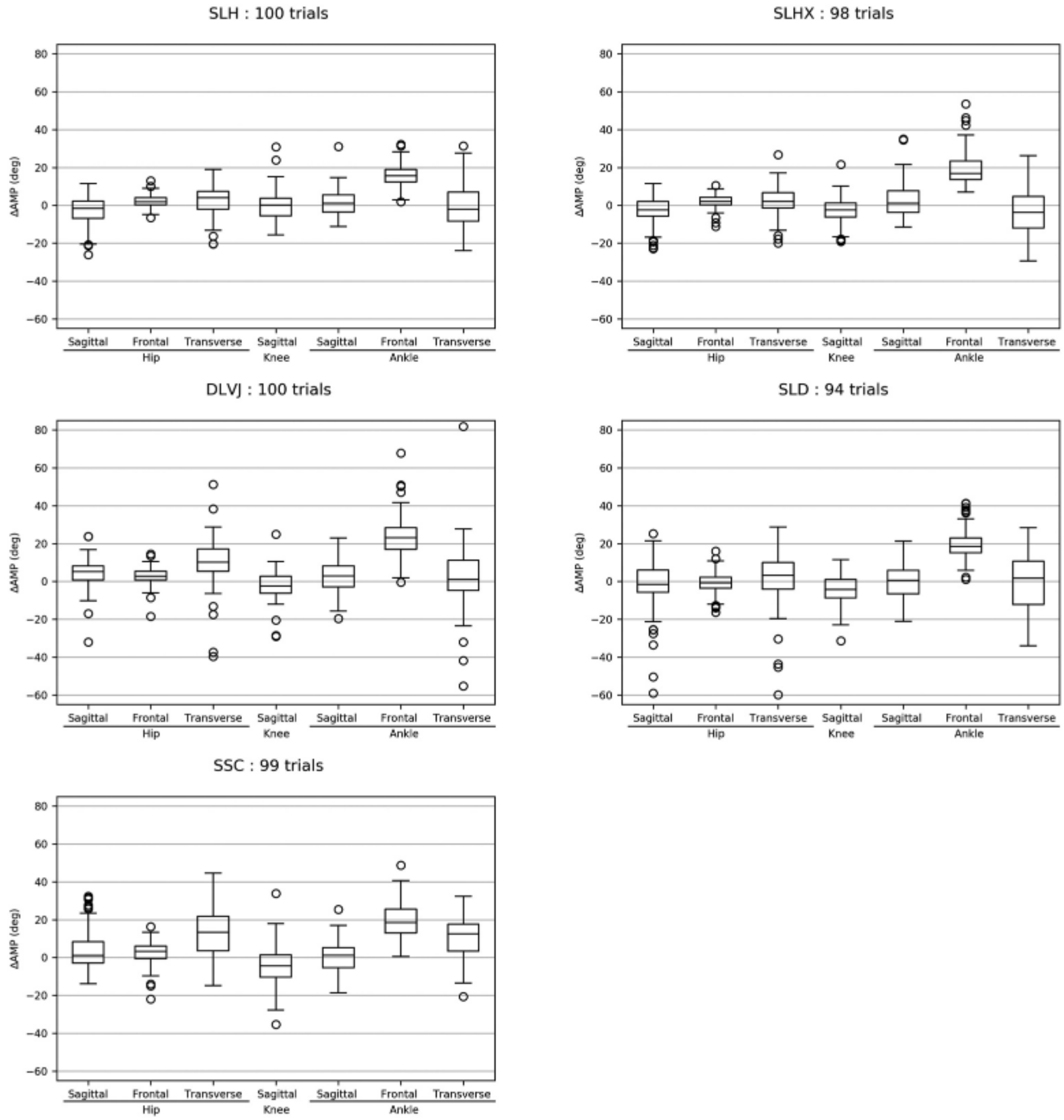

Figure A3. Amplitude differences (ΔAMP) per motor task. SLH = single-leg hop; SLHX = single-leg crossover hop; DLVJ = double-leg vertical jump; SLD = single-leg deceleration; SSC = sidestep cut.

Study III

Original Manuscript

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Relationships Between Task Constraints, Visual Constraints, Joint Coordination and Football-Specific Performance in Talented Youth Athletes: An Ecological Dynamics Approach

Pieter Heuvelmans[1], Stefano Di Paolo[2], Anne Benjaminse[3,4], Laura Bragonzoni[2], and Alli Gokeler[1]

Abstract

Individual performance in team sports is a multifactorial reflection of how well a player can cope and accomplish tasks in varied playing situations. Thus, performance analysis should not only focus on outcomes, but also on underlying mechanisms of those outcomes. We adopted principles of the ecological dynamics approach (EDA) to investigate the effect of introducing constraints on players' joint coordination responses for a football-specific performance drill outcome. Seventeen talented youth football (soccer) players performed a football-specific drill under different conditions: basic constraints, additional defender dummies, stroboscopic glasses, and a combination

[1]Exercise Science and Neuroscience Unit, Department of Exercise & Health, Faculty of Science, Paderborn University, Paderborn, Germany
[2]Department for Life Quality Studies, University of Bologna, Bologna, Italy
[3]Department of Human Movement Sciences, Faculty of Medical Sciences, University of Groningen, Groningen, the Netherlands
[4]School of Sport Studies, Hanze University Groningen, Groningen, the Netherlands

Corresponding Author:
Pieter Heuvelmans, Exercise Science and Neuroscience Unit, Department of Exercise & Health, Faculty of Science, Paderborn University, Warburger Str 100, 33098 Paderborn, Germany.
Email: pieter.heuvelmans@upb.de

of the latter two constraints. We recorded these players' execution time, passing accuracy, and lower extremity joint kinematics. We calculated joint coordination for hip-knee, knee-ankle, and trunk-hip couplings. The added constraints negatively affected execution time and passing accuracy, and caused changes in joint coordination. Furthermore, we identified a relationship between execution time and joint coordination. This study serves as an example how the EDA can be adopted to investigate mechanisms that underlie individual performance in team sports.

Keywords

ecological dynamics, football, constraints, joint coordination, performance

Introduction

Performance in team sports derives in part from a combination of physical and perceptual-cognitive factors governing an athlete's ability to meet their goals in open-skill play (Davids et al., 2003, 2008). Varied playing situations arise from task, environment, and athlete-related constraints (Renshaw et al., 2010). Task constraints may include the athlete's objective and any rules or objects that specify or constrain the athlete's response dynamics, such as opponents blocking a desired passing direction. Environmental constraints may include features like the type of terrain and weather conditions. Athlete-related constraints may involve the individual's own physical and mental characteristics (e.g., height, weight, limb length, and level of attention, motivation, or anxiety). These constraints serve as boundaries that shape an athlete's self-organizing movement patterns (Renshaw et al., 2010). The effects of many constraints are mediated by the athlete's ability to perceive them. For instance, while it has been demonstrated that visual–perceptual abilities are enhanced in more skilled versus less skilled athletes (Mann et al., 2007; Voss et al., 2010), stroboscopic vision has been shown to reduce sport performance, especially in skilled athletes (Beavan et al., 2021). These interaction effects highlight the importance of visual perception on sport performance.

One criticism of conventional methods of performance analysis is their focus on outcomes rather than underlying processes that produce those outcomes (Torrents & Balagué, 2006). In EDA, the focus is on understanding *how* players and teams regulate their sport performance (Seifert et al., 2017). The EDA integrates theories from the constraints-led approach, ecological psychology, and complex systems approach in neurobiology (Seifert et al., 2017). Hence, the EDA views players and teams as complex adaptive systems and recognizes that the relationship between movement coordination and performance may be non-linear and non-proportional (Seifert et al., 2017). To clarify, since every athlete has individual movement solutions intended to satisfy the constraints imposed on them (Renshaw et al., 2010), coordination between different joints or body segments may vary even when performing the same task

(Weir et al., 2019). To best understand these complex interactions underlying sports performance, we must investigate how movements are coordinated and controlled within dynamic environments.

Studies that adopt the EDA preserve the athlete-environment relationship (Bolt et al., 2021). In the field, athletes are free from laboratory restrictions and can make sport-specific movements that should be the subject of study in performance analysis. Measuring "on the pitch," however, complicates data interpretation with increased numbers of uncontrolled variables (Parada, 2018). Researchers should, therefore, be mindful of the steps that they take to preserve the athlete-environment interaction; they must take incremental steps, investigating only a small number of uncontrolled variables at once to facilitate interpretation of the data (Bolt et al., 2021). By applying the principles of the EDA on a football pitch, we hoped to examine how player movements are coordinated and how this performance is affected by additional constraints. Our aim in this study was to investigate the effect of additional task and athlete-constraints on the performance and joint coordination of talented youth football players during this single football-specific drill. Our secondary aim was to present a novel EDA-based method for investigating the mechanisms that underlie this performance. We hypothesised that players would demonstrate non-linear adaptations to the complexity of various constraints, and that subsequent joint coordination responses would explain differences in player performances.

Method

Participants

Seventeen talented male youth football (soccer) players (*M* age = 13.9. *SD* = .3 years; *M* height = 1.64, *SD* = .09 m; *M* weight = 50.9, *SD* = 7.4 kg) were recruited from the talent development program of the youth academy of a professional football club. All players were free from any neurological disease and/or visual impairment at the time of testing, and they had no history of serious lower extremity injury or surgery within the previous year, based on medical screening at the start of the season by medical staff of the youth academy. The players were all field players, at the competitive phase of the season (i.e., month of April) when their performance was most representative of their optimal abilities, and all players had trained 4–5 times per week. Prior to participants' enrollment, we explained to them the purpose of the study and obtained both their informed written assent and the informed consent of their parents. The study and its procedures were approved by the ethics committee of Paderborn University, Paderborn, Germany.

Procedures

Players wore their own football shoes, and tests were performed in daylight on an artificial turf football pitch. We used the Microgate Witty SEM system (Microgate Srl, Italy) to indicate the player's running direction at the beginning of the course by means of an LED indicator (Figure 1). We used a SmartGoals System (SmartGoals B.V., the Netherlands) to display the target goal. We used Senaptec Strobe glasses (SENAPTEC Inc., USA) to apply a perceptual constraint to the player. The lenses flickered between clear and opaque at 3 Hz. 3D lower extremity, and we collected trunk kinematics during each trial by means of wearable inertial sensors. Players wore a MVN Lycra suit (Xsens Technologies, the Netherlands) that holds 17 inertial sensors with an internal sample rate of 1000 Hz. The overall system output frequency is 240 Hz. We gathered

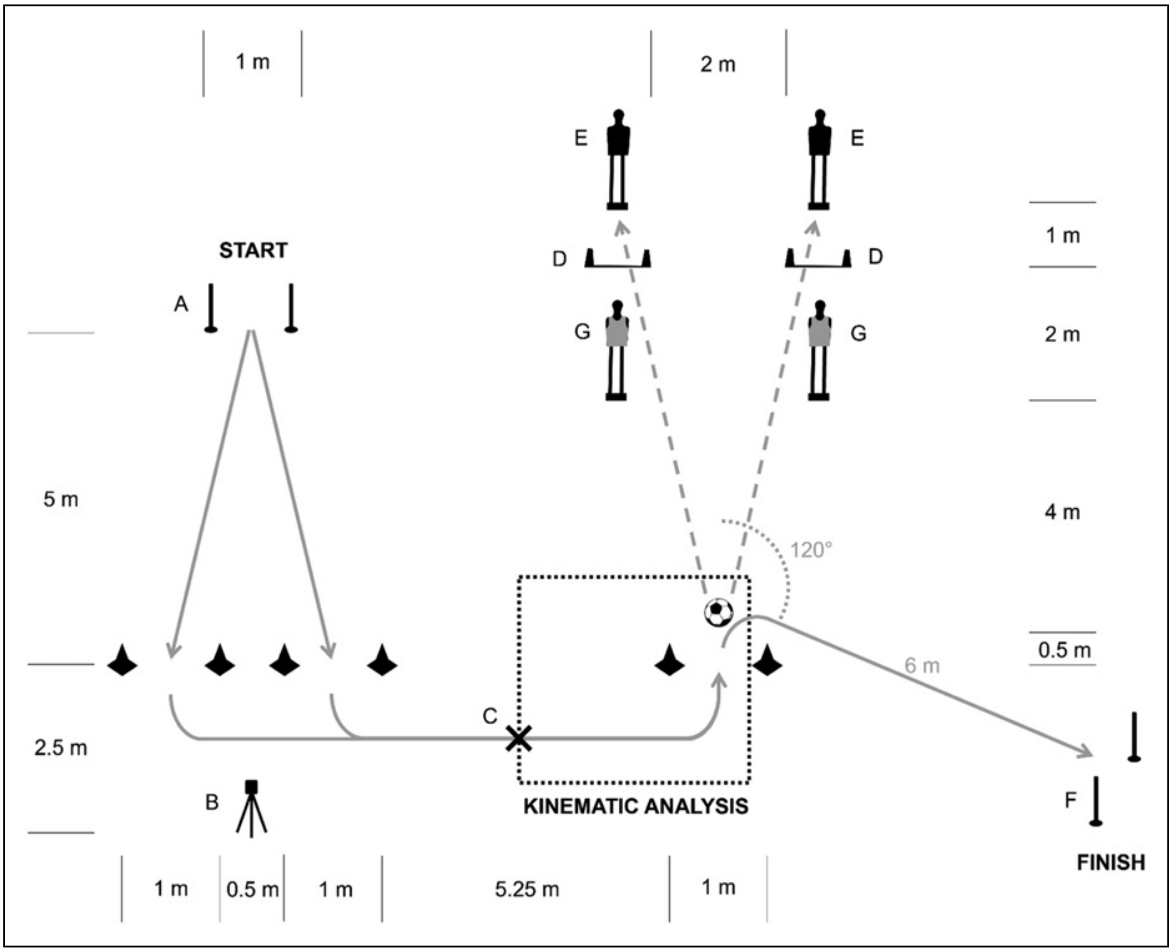


Figure 1. Illustration of the Football-Specific Drill.
Note. After a visual start cue (i.e., arrow pointing to the left or right) from the Microgate LED indicator (B), the player sprinted from the timing gate at the start (A) through the left or the right set of cones. Following a 90-degree turn, the player then sprinted towards the football. When the player was at 3 m (C) from the football, one of the two SmartGoals (D) was manually activated by the same operator using a SmartRemote (SmartGoals B.V., the Netherlands). The SmartGoal that was activated indicated which direction the ball had to be passed to, hitting the target dummy (E) standing behind. The target dummy represented a teammate. After passing the ball, the player made a 120-degree turn and sprinted to the timing gate (F) at the finish line. Note: the vest-wearing dummies (G) representing opponents in front of the SmartGoals (D) were only included in conditions 2 and 4.

anthropometric data from players and used it for the calibration of the inertial sensors, following manufacturer's guidelines.

Football Drill. Players performed a football-specific drill on a course marked by cones, timing gates, SmartGoals, and dummies (Figure 1). Instructions for this drill included a demonstration run-through of the task and an explanation of the different conditions a player might face during the performance. Furthermore, players were instructed to (a) sprint at maximum speed and (b) score as many correct passes as possible, since both speed and accuracy are important aspects of football kick performance (Kellis & Katis, 2007). A correct pass was defined as hitting the target dummy behind the lit up SmartGoal. Players performed a standardized warm-up and were familiarised with the conditions and the course. Every player completed five trials of each condition in ascending order (non-randomized). Athletes had 30-second breaks between each trial and 2-minute breaks between each condition.

Manipulated Constraints

The constraints or conditions under which players had to perform were as follows:

- Condition (1) Basic constraints: After a visual start cue (i.e., arrow pointing to the left or right) from a Microgate LED indicator, the player sprinted for 5 m, from the timing gate at the start through the left or the right set of cones. Following a 90-degree turn, the player then sprinted for approximately 7 m towards the football. When the player was at 3 m from the football, one of the two SmartGoals was manually activated by the same operator using a SmartRemote (SmartGoals B.V., the Netherlands). The SmartGoal that was activated indicated in which direction the ball had to be passed to hit the target dummy standing behind. The target dummy represented a teammate. After passing the ball, the player made a 120-degree turn and sprinted for 6 m to the timing gate at the finish line.
- Condition (2) Added task constraint: Dummies with orange vests representing defenders were placed in front of the SmartGoals (Figure 1). These obstacles reduced the opportunities for the ball trajectory to pass through the SmartGoals to hit the target dummy, and therefore represented an environmental task constraint for the player.
- Condition (3) Added athlete constraint: Players were instructed to perform the drill whilst wearing stroboscopic glasses. Hence, this constraint affected the athlete's visual perception.
- Condition (4) Added task *and* athlete constraint: Included both the defender dummies and the stroboscopic glasses to simultaneously impose both an athlete constraint and a task constraint.

Dependent Measures

The dependent variables we measured were:

- Execution time;
- Passing accuracy;
- Lower extremity and trunk kinematics.

Execution time was defined as the time elapsed from start to finish of the drill. Passing accuracy was calculated as the percentage of successful passes (i.e., hitting the dummy behind the lit up SmartGoal) for each condition. Lower extremity and trunk (thorax) kinematics were processed in a custom MATLAB script (The MathWorks, Natick, MA, US). A time-normalized window was defined for each trial by means of the center of mass trajectory in the anterior-posterior direction: the ultimate change of direction at 120° after the ball contact was considered as the final point of measurement (100%), while the penultimate change of direction was computed as the starting point of measurement (0%) (Figure 1). This window allowed the investigation of the footballers' motion while approaching and kicking the ball and was not affected by the time or the number of steps taken. Inter-joint coordination was quantified through a modified vector coding technique with circular statistics (Chang et al., 2008).

Player Joint Coordination Responses

We examined joint coordination for the following joint couplings:

- hip (+flexion/-extension) and knee (+flexion/-extension);
- knee (+flexion/-extension) and ankle (+flexion/-extension);
- trunk (+flexion/-extension) and hip (+flexion/-extension).

Sagittal plane joint coordination provides information about propulsion and deceleration strategies (Weir et al., 2019). We used a coordination pattern classification method (Figure 2(A)) to classify the joint coordination at each time point into anti or in-phase coordination with distal or proximal dominancy using the coupling angle obtained from vector coding (Needham et al., 2015). This classification method describes the relative motion between two joints and indicates which joint was the dominant mover at each time point. Furthermore, this method considers the direction of joint movement so that it can distinguish between, for instance, in-phase flexion and in-phase extension. As a result, we identified eight different coordination patterns (Figure 2(A)). To quantify the prevalence of each pattern, we calculated coordination pattern frequencies (CPFs) as the number of time points classified into a coordination pattern divided by the total number of time points. We performed vector coding and coordination pattern classification for each trial and averaged CPFs per player per condition to obtain coordination profiles. Coordination profiles were then averaged for each

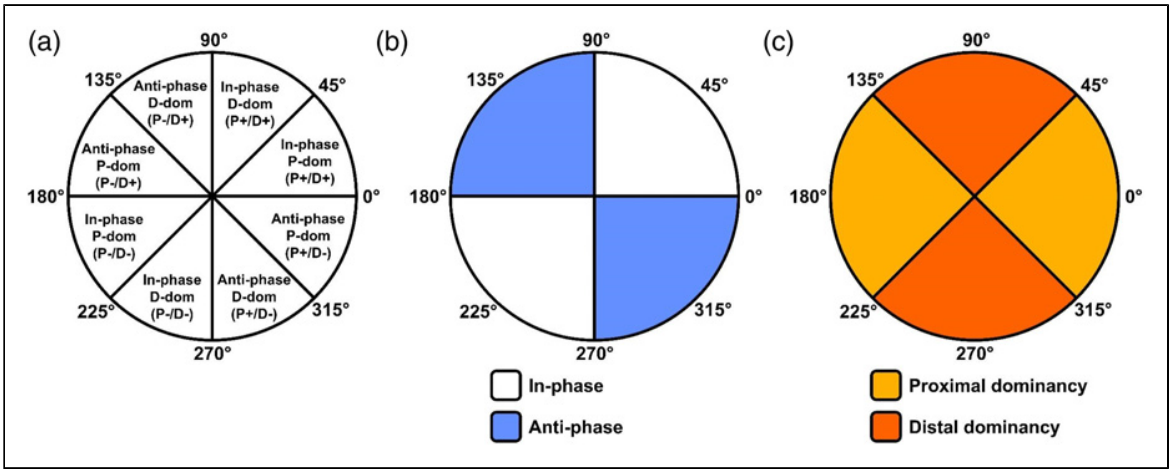


Figure 2. Schematic Polar Plots.
Note. (A) The classification of coordination patterns based on the convention proposed by Needham et al. (2015); (B) the segments corresponding with in/anti-phase coordination; and (C) the segments corresponding with proximal/distal dominant coordination. P: proximal joint, D: distal joint, dom: dominancy, (+): flexion, (−): extension.

condition. As these coordination profiles provide detailed overviews of players' movements, they are informative descriptors. However, to facilitate the interpretation of statistical analyses, we compared conditions on the sums of CPFs in anti-phase coordination (Figure 2(B)) and CPFs in distal dominancy (Figure 2(C)), respectively. We used a custom Python script in Spyder IDE (Python 3.9.9, Spyder 5.1.5) to conduct vector coding, coordination pattern classification, and CPF analyses.

Statistical Analysis

We used the Shapiro-Wilk test to assess the normality of the data. We presented continuous variables as means and standard deviations and categorical variables as percentages of the total. We used a repeated measures analysis of variance (ANOVA) to assess any statistical differences between the four conditions on the measures of execution time, passing accuracy (i.e., 5/5 correct passes = 100% accuracy), anti-phase coordination, and distal dominant coordination. We set $p < .05$ to determine statistical significance. We used partial eta-squared for effect size and considered effect size categories as small, moderate, and large for values of .01, .06, .14, respectively (Cohen, 2013), and we reported effect size with Cohen's d for multiple comparisons (small, moderate, and large effects for d values of .2, .5, .8, respectively). We investigated post-hoc comparisons among the single conditions through t-tests with Bonferroni corrections for multiple comparisons.

We also computed a stepwise linear regression model to investigate the association between joint coordination (hip-knee, knee-ankle, and trunk-hip distal dominancy and anti-phase coordination as independent variables) and performance data (execution time or passing accuracy as dependent variable). We reported effect sizes of the interactions with R^2-adjusted and f^2 values (small, moderate, and large effect for f^2 values of .02, .15, .35). All statistical analyses were conducted in MATLAB.

Sample size was estimated according to previous literature (Besier et al., 2001; Heiderscheit et al., 2002; Seay et al., 2011). In particular, Seay et al. (2011) reported an effect size (Cohen's d) of .34 for sagittal plane joint coordination analysis. We calculated a power analysis, using an ANOVA repeated measures with within-between factor interaction in G*Power (v3.1, Brunsbüttel, Germany), assuming a conservative effect size of .31, statistical power of 80%, and an alpha of .05, we found that a minimum of 16 participants was required.

Results

Three players were excluded from further analysis due to their left-leg dominance. Therefore, we conducted final analyses on 14 players. There was a statistically significant difference in execution time between the conditions ($F(3,39) = 7.17$, $p < .001$, $\eta^2 p = .36$) (Table 1, Figure 3(A)). Specifically, condition 2 ($M_{\text{execution time}} = 9.3$, $SD = .5$ seconds) was significantly faster than condition 3 ($M_{\text{execution time}} = 9.6$, $SD = .4$ seconds, $d = .67$, $p = .002$) and condition 4 ($M_{\text{execution time}} = 9.6$, $SD = .6$ s, $d = .56$, $p = .010$). There was also a statistically significant difference in passing accuracy between conditions ($F(3,39) = 8.87$, $p < .001$, $\eta^2 p = .41$) (Figure 3(B)), with accuracy in condition 2 ($M_{\text{accuracy}} = 64.3$, $SD = 24.8\%$) significantly higher than condition 1 ($M_{\text{accuracy}} = 34.3$, $SD = 19.9\%$, $d = 1.25$, $p = .005$), condition 3 ($M_{\text{accuracy}} = 21.4$, $SD =$

Table 1. Performance and Joint Coordination in the Different Constraint Conditions.

	Basic constraints	Dummies	Glasses	Dummies + glasses	*p*-value	η^2p
Performance						
Execution time (s)	9.4 (.4)	9.3 (.5)	9.6 (.4)	9.6 (.6)	**< .001**	**.36**
Passing accuracy (%)	34.3 (19.9)	64.3 (23.8)	21.4 (21.4)	32.9 (30)	**< .001**	**.41**
Joint coordination (%)						
Hip-knee anti-phase	41.5 (8.8)	42.5 (7.4)	38.5 (3.8)	36.5 (6)	**.027**	**.21**
Hip-knee distal dominancy	71.7 (5.1)	71 (7.4)	67.4 (5.3)	69.5 (4.9)	.071	.16
Knee-ankle anti-phase	41 (5.8)	40.9 (7.6)	40.8 (7.1)	42.1 (7.9)	0.9	.02
Knee-ankle distal dominancy	33.6 (6.5)	35.2 (7.3)	36.3 (5.7)	34.1 (4.3)	.322	.09
Trunk-hip anti-phase	40 (7.6)	40.6 (6.2)	39.5 (7.7)	39.7 (7.2)	.866	.018
Trunk-hip distal dominancy	77.9 (4.9)	77.8 (5.9)	79.7 (4.7)	78.8 (3.8)	.554	.052

Note. Values are mean (standard deviation). Bold values represent statistically significant differences among the four conditions according to the repeated-measures ANOVA.

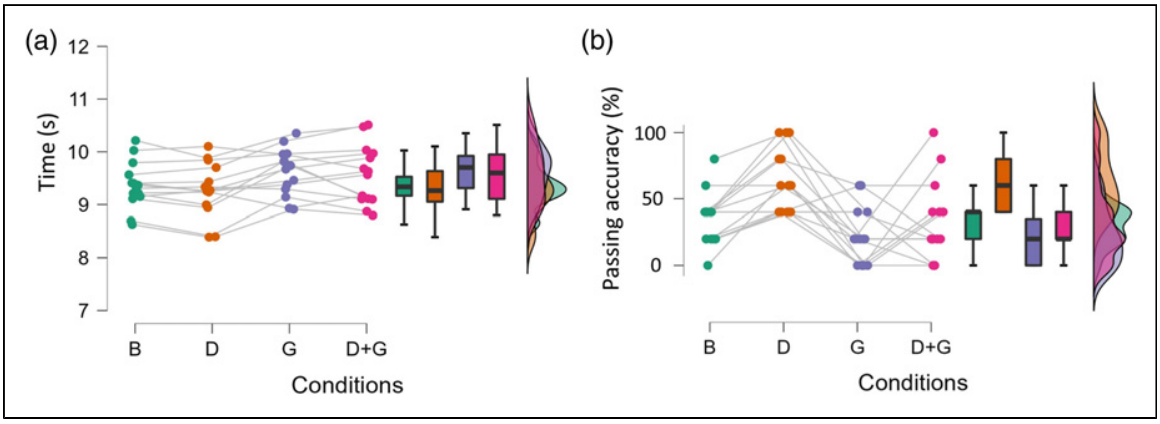


Figure 3. Distributions of Execution Time (A) and Passing Accuracy (5/5 passes = 100%, (B) per Condition with Connected Dots Representing Player Means.
Note. B: basic constraints, D: defender dummies, G: stroboscopic glasses.

21.4%, d = 1.78, $p < .001$), and condition 4 ($M_{\text{accuracy}} = 32.9$, $SD = 30.0\%$, d = 1.30, $p = .004$).

There was a statistically significant condition difference in hip-knee anti-phase coordination ($F(3,39) = 3.4$, $p = .027$, $\eta^2 p = .21$) (Table 1, Figure 4(A)), with hip-knee anti-phase coordination in condition 2 ($M_{\text{hip-knee anti-phase coordination}} = 42.53$, $SD = 7.41\%$) significantly higher (d = .89, $p = .041$) than condition 4 ($M = 36.53$, $SD = 6.01\%$). Stepwise linear regression analysis identified a statistically significant relationship between execution time and hip-knee anti-phase coordination (Figure 4(C)) and trunk-hip distal dominant coordination (Figure 4(D)), respectively ($p < .001$, $R^2_{\text{Adjusted}} = .28$, $f^2 = .46$).

Discussion

In this study we set out to investigate (a) the performance and joint coordination of talented youth football (soccer) players during a football-specific drill and (b) the effect of introducing additional constraints. Three main findings emerged. First, the performance measures, execution time and passing accuracy, were affected by the added constraints. Second, there were constraints-related changes in joint coordination (Appendix 1). Third, there was a significant relationship between execution time and hip-knee anti-phase and trunk-hip distal dominant coordination.

The players were instructed to complete the football-specific drill as fast as possible. Such a requirement is common in football training and many agility drills focus on speed. High intra-player performance variability was observed for execution time. The main trend was an individual increase in execution time from condition 2 to conditions 3 and 4 (Figure 3(A)). These observations were expected, as they represent intra-individual adaptations to the increased complexity imposed by the additional constraints. We also included ball passing accuracy as another football-specific performance measure. Only a small number of players showed high passing accuracy, with

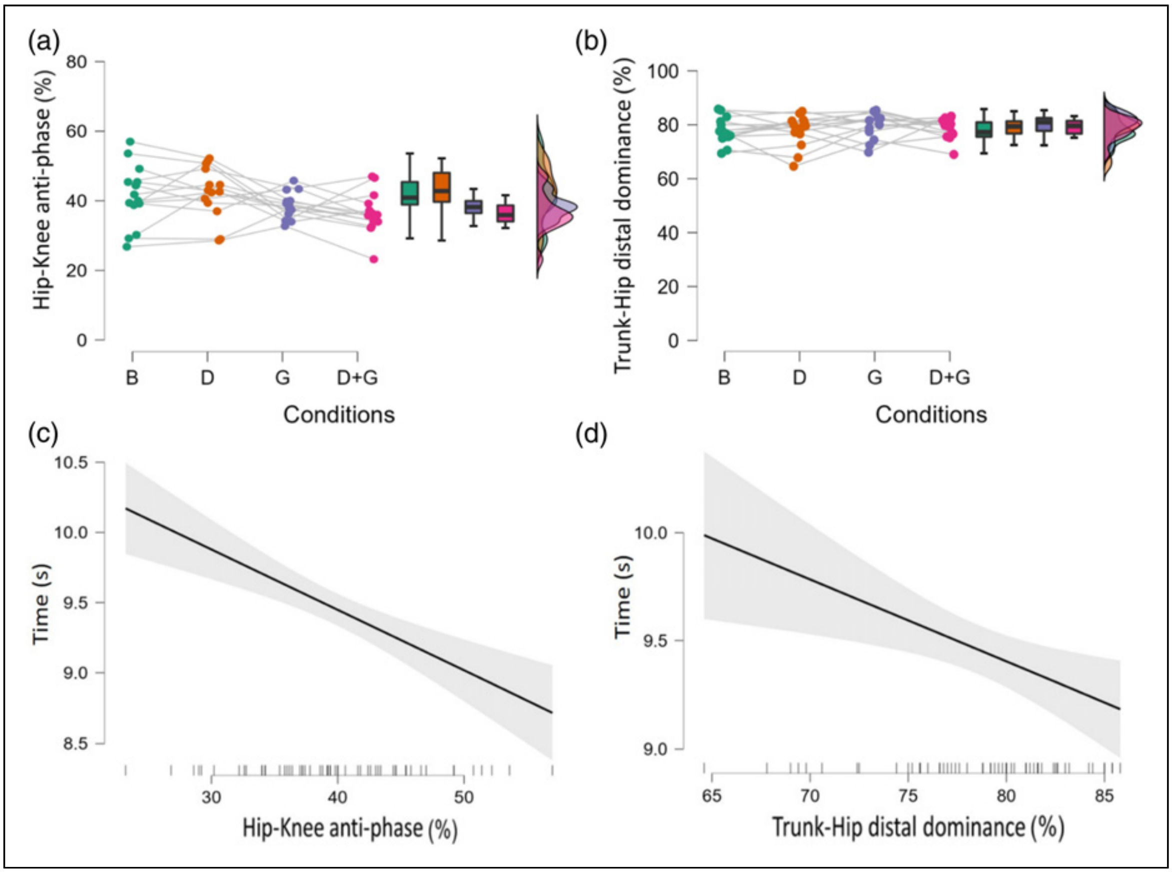


Figure 4. Distributions of hip-knee anti-phase coordination (A) and trunk-hip distal dominant coordination (B) per condition with connected dots representing player means. Stepwise linear regression analysis between execution time and hip-knee anti-phase coordination (C) and trunk-hip distal dominant coordination (D), respectively.

Note. The explained variance in the regression model was $R^2 = .30$, $R^2_{Adjusted} = .28$ ($p < .001$). B: basic constraints, D: defender dummies, G: stroboscopic glasses.

average passing accuracy below 40% in three conditions (Table 1, Figure 3(B)). Previous investigators have identified a trade-off between accuracy and velocity in kicking performance (Kellis & Katis, 2007; van den Tillaar & Fuglstad, 2017). This finding suggests that most players prioritized speed over accuracy, although we hypothesised that passing accuracy would increase if players were given more repetitions to learn and adapt their movement strategy. However, in real-life playing situations (i.e., a match), players are usually not offered multiple repetitions to optimize their motor strategy for successful performance. Therefore, sport-specific drills that introduce constraints with a limited number of attempts are likely to be effective in distinguishing players that adapt quickly from those who adapt slower (Supplementary Material).

Passing accuracy decreased with the introduction of the stroboscopic glasses, whilst average execution time increased (Table 1; Figure 3). Thus, the visual perturbation was sufficient to reduce overall performance. Training with stroboscopic devices is apt to improve perceptual-cognitive skills, which in turn transfers to enhanced sporting performance (Singh et al., 2021; Wilkins & Appelbaum, 2020; Wilkins & Gray, 2015; Wohl et al., 2021). We confirmed the strong interaction effect between visual perturbation and players' coordination and performance. We conducted a single measurement. Future studies should consider the effect of added constraints after a period of visual perturbation training.

An interesting secondary finding from this study was the differences in performance measures among the conditions. Although condition 1 was used to represent baseline performance, execution time was lowest and passing accuracy was highest in condition 2. Since condition 2 introduced defender dummies which reduced the opportunities for ball trajectory in passing, we had expected instead an increase in execution time and/or decrease in passing accuracy. Two inferences may be drawn from these findings. On one hand, since conditions were non-randomized, a learning effect might have occurred, but, on the other, players may have had more focus and/or motivation for passing accuracy when the task complexity more closely resembled actual play, increasing sport-specific affordances to better perceive the task.

Hip-knee coordination showed a constraints-related change at the group level: average anti-phase coordination dropped by 6% in condition 4 compared to condition 2 (Table 1; Figure 4(A)). In other words, players moved their hip and knee more in-phase when they were simultaneously subjected to the stroboscopic glasses and the defender dummies, compared to when they only faced the dummies. Interestingly, a stepwise linear regression identified that hip-knee anti-phase coordination was significantly associated with execution time. Together with trunk-hip distal dominant coordination, hip-knee anti-phase coordination could explain 28% of the variance in execution time (Figure 4). These findings are exemplary first attempts at uncovering the mechanisms that underlie performance, by linking different types of joint coordination with a specific performance measure. Future studies that adopt the EDA may further contribute to understanding these mechanisms. Future investigators should study smaller windows of analysis for specific movements (e.g., braking, turning, kicking) to improve the resolution of coordination analysis.

The presence of defender dummies (conditions 2 and 4) and stroboscopic glasses (conditions 3 and 4) required a higher cognitive effort than the basic constraints (condition 1): the dummies narrowed the space for passing the ball and forced a specific trajectory, while the stroboscopic glasses reduced the players' vision and their spatial perception (Beavan et al., 2021). The introduction of stroboscopic glasses (condition 3) coincided with a drop in average passing accuracy as well as an increase in execution time at the group level. However, intra-individually, some players managed to maintain or even increase their own performance (Figure 3). These results suggest that the incremental introduction of more demanding constraints may induce non-linear changes in motor control that are difficult to detect at the group level but which can affect individual performance, both positively and negatively. Previous investigators suggested an interaction between task complexity and joint coordination variability (Weir et al., 2019), and this interaction might ultimately affect movement efficiency and injury risk (Hamill et al., 2012).

Limitations and Directions for Further Research

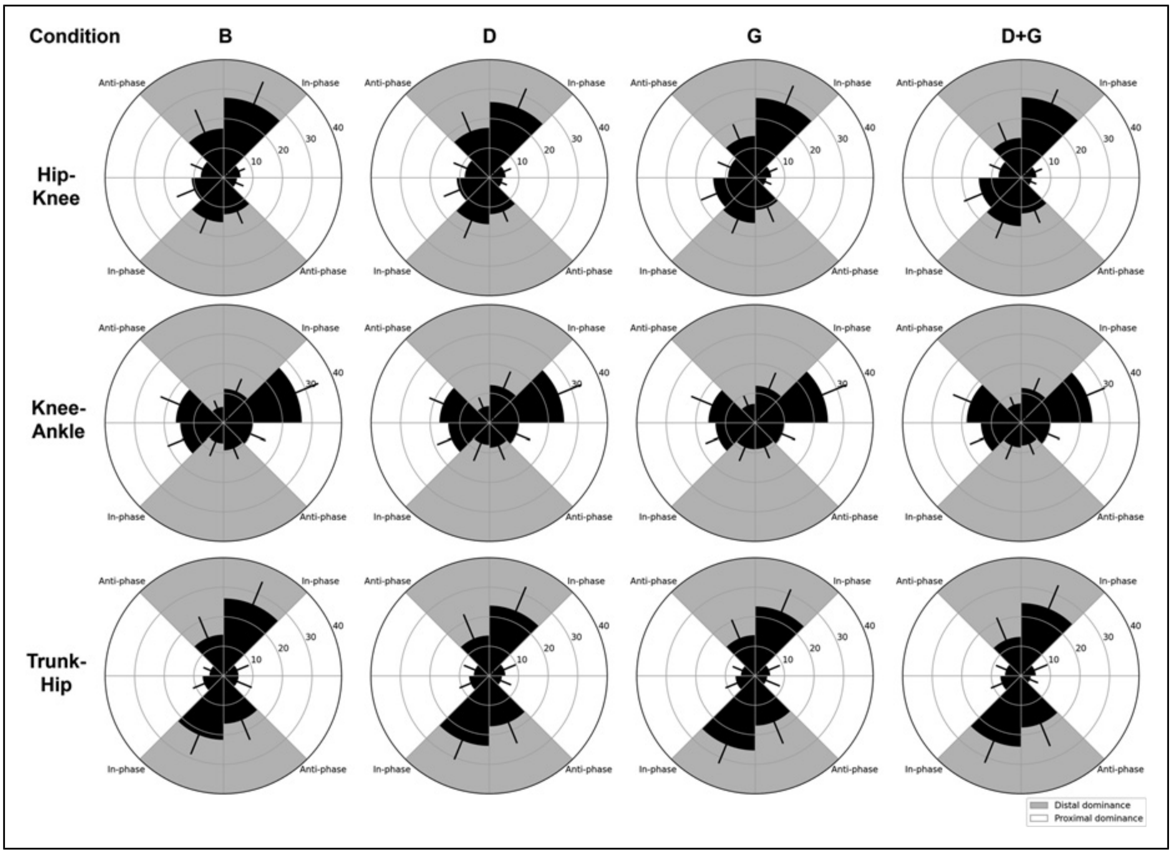
The present study had limitations to acknowledge. First, the football-specific drill (Figure 1) has not been previously validated. However, this drill included many aspects of game-like scenarios: visual information, decision-making, team-mate and opponent (dummies) factors, ball-kicking, and changes of direction. Second, the experimental setup favored right-side dominant players, since players had to make a left turn prior to kicking. Unfortunately, due to the exclusion of three left-dominant players, our sample size was below the target number set with power analysis; also, it was not possible to inspect the variability of individual responses through a model including IDs of the players as a random effect. Additionally, apart from statistical power associated with this small sample size, generalization from this small number of talented youth athletes to other populations is limited. Future investigators using similar drills should therefore design mirrored drills to accommodate both right and left-legged players equally. Third, the non-random order of conditions may have induced a learning effect. However, this possibility was not confirmed by statistical analysis. We assessed joint coordination for sagittal plane motion only, because of its importance in propulsion and braking. However, the frontal and transverse planes of motion may hold important information as well. Individual adaptations or compensatory movement strategies have potential implications for injury risk, and future investigators might explore joint coordination in the other planes of motion, using the methodology presented here.

Conclusions

Our study was the first to propose and demonstrate an EDA based kinematical assessment of football players' agility performance (Bolt et al., 2021). In particular, ours was the first study to investigate the effect of cognitive and physical constraints on players' inter-joint coordination and performance during a sport-specific drill. Our findings have several practical implications. First, cognitively demanding agility drills seem to be effective in differentiating player performance, and they may be used for performance evaluation for talent selection and development. Importantly, however, our participant sample was relatively young. In this age group, the executive functions may not have yet been fully developed (Davidson et al., 2006). As such, a low-performing player from this demographic group may not only benefit from physical training, but may also require cognitive training and/or additional time to develop. A second practical implication concerns the observation that introducing new constraints to a drill (e.g., obstacles, rules) will likely affect players differently in accordance with the motor strategies players adopt. Since these adaptations are highly individualized, coaches/trainers should be cautious about interpreting constraints-induced player changes at a group level. Monitoring players individually may help in performance evaluation and injury risk assessment.

Appendix 1

Coordination Profiles for Hip-Knee, Knee-Ankle, and Trunk-Hip Sagittal Plane Coordination Per Condition. *Note.* The bars in the polar plots represent the mean coordination pattern frequencies (CPFs), error bars indicate the pooled standard deviations. B: basic constraints, D: defender dummies, G: stroboscopic glasses.



Declaration of Conflicting Interests

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ORCID iDs

Pieter Heuvelmans https://orcid.org/0000-0002-9957-7963
Alli Gokeler https://orcid.org/0000-0002-6427-4225

Supplemental Material

Supplemental material for this article is available online.

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Author Biographies

Pieter Heuvelmans is a PhD candidate at Paderborn University, Germany. His work focusses on anterior cruciate ligament injury prevention.

Stefano Di Paolo is a PhD candidate at the University of Bologna, Italy. His interests are orthopaedic biomechanics, injury prevention, and rehabilitation in sports.

Anne Benjaminse is a postdoctoral researcher and assistant professor at the University of Groningen, Netherlands. Her interests are motor learning, injury prevention, and transferring knowledge to the field.

Laura Bragonzoni is postdoctoral researcher and associate professor at the University of Bologna. Her work focusses on knee reconstructive surgery and interventions for patients with osteoporosis.

Alli Gokeler is a postdoctoral researcher at Paderborn University, Germany. His interests are anterior cruciate ligament injury prevention and rehabilitation.

Study IV

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Human Kinetics
ORIGINAL RESEARCH REPORT

Unveiling the Distinctions: Computer Versus Sport-Specific Neurocognitive Tests

Benedict Gondwe,[1] Pieter Heuvelmans,[1] Anne Benjaminse,[2] Daniel Büchel,[1] Jochen Baumeister,[1] and Alli Gokeler[1]

[1]Exercise Science and Neuroscience Unit, Department of Exercise & Health, Paderborn University, Paderborn, Germany; [2]Department of Human Movement Sciences, Faculty of Medical Sciences, University of Groningen, Groningen, The Netherlands

Context: Traditional assessments of high-order neurocognitive functions are conducted using pen and paper or computer-based tests; this neglects the complex motor actions athletes have to make in team ball sports. Previous research has not explored the combination of neurocognitive functions and motor demands through complex tasks for team ball sport athletes. The primary aim of the present study was to determine the construct validity of agility-based neurocognitive tests of working memory (WM) and inhibition. ***Methods:*** Twenty-seven athletes (5 females; mean age 24.2 [4.7] y; height 183.6 [9.1] cm; body mass 77.5 [11.2] kg) participated in the construct validity assessments that included computer-based tests (working memory capacity and stop-signal reaction time) and sport-specific assessments performed on the SpeedCourt system. ***Results:*** Construct validity analysis of sport-specific working memory yielded acceptable construct validity ($r = .465$, $P < .05$), whereas the sport-specific stop-signal task resulted in low construct validity ($r = .179$, $P > .05$). The poor construct validity results highlight the large variance between computer-based and sport-specific neurocognitive assessments. ***Conclusion:*** Sport-specific assessments are more complex and include more degrees of freedom potentially due to athletes' center of mass displacement during task execution. These findings suggest that future research should focus more on the development of sport-specific assessments. These should include the cognitive and motor demands encountered during practice and competition, not use computer-based/pen and paper assessments for return to play decisions.

Keywords: neurocognition, inhibition, working memory, agility, validity

Key Points

- Sport-specific neurocognition, which involves the integration of complex motor tasks with additional working memory (WM) or stop-signal task demands, differs from computer-based neurocognitive tests that only require simple motor responses.
- This distinction highlights the importance of considering the unique cognitive challenges athletes face in their respective sports when assessing neurocognitive function and its impact on performance and injury risk.

Neurocognition plays a crucial role in the performance of team sports. The demands of team sports often involve goal-directed thinking and behavior, requiring the utilization of various executive functions such as inhibitory control, attention, working memory, and cognitive flexibility.[1,2]

Assessment of neurocognition is traditionally conducted using domain-generic tests (ie, using a pen and paper or computer-based tests). However, these tests do not account for the intricate motor actions combined with perceptual-cognitive processes that team ball athletes must execute during a match.[3]

Researchers emphasize the need for ecologically valid assessments in sports injury and rehabilitation research to address the complexity of complex motor actions and neurocognitive demands in sports.[4–6] Recently, it was shown that neurocognitive errors may contribute to noncontact anterior cruciate ligament injuries in soccer players.[7] Specifically, inhibitory control errors have been identified as a potential factor in noncontact anterior cruciate ligament injuries in soccer. Deficits in inhibitory control, which is the ability to suppress impulsive or inappropriate responses, may lead to errors in movement execution and decision making on the field, increasing the risk of anterior cruciate ligament injuries.[6]

Furthermore, working memory (WM) plays a crucial role in team ball sports, where athletes must constantly process and retain information to make quick decisions on the field.[8] In team ball sports such as basketball or soccer, players need to remember their teammates' positions, anticipate opponents' movements, and execute complex plays in real time. WM enables athletes to hold and manipulate this information, allowing them to adapt to changing game situations and make split-second decisions. Assessments involving open-skill motor tasks that integrate neurocognitive stimuli can bridge the gap between computer-based neurocognitive measurements and the above-described specific demands of sports.[6]

In sum, computer-based neurocognitive tests typically involve simple motor tasks, such as clicking a key on a keyboard, which may not accurately reflect the complex motor actions that athletes

Heuvelmans https://orcid.org/0000-0002-9957-7963
Büchel https://orcid.org/0000-0002-1451-5393
Baumeister https://orcid.org/0000-0003-2683-5826
Gokeler https://orcid.org/0000-0002-6427-4225
Gondwe (gondwe.benny@gmail.com) is corresponding author, https://orcid.org/0009-0005-9731-7841

must perform on the field. In sports, athletes are required to execute intricate movements that involve coordination, agility, and quick decision making, which are not fully captured by traditional computer-based tests.[3] The discrepancy between the simplicity of computer-based tasks and the complexity of real-world athletic movements highlights the need for more ecologically valid assessments that better simulate the demands of sports performance.

The main goal of this study was therefore to assess the construct validity of sport-specific tests measuring neurocognitive functions associated with inhibition and WM. Construct validity referring to the degree to which a test or measurement tool accurately represents the theoretical construct it is intended to measure. It involves evaluating whether the operational definitions and methods utilized in a study accurately reflect the underlying theoretical framework.[9] Construct validity was determined by analyzing the associations between the computer-based and sport-specific neurocognitive tests in a sample of recreational team sports athletes. It was hypothesized that the construct validity of sport-specific neurocognitive tests would be low, attributed to notable differences between computer-based and sport-specific assessments, such as varying degrees of freedom impacting task performance variability.

Methods

Subjects

Twenty-seven team ball sports (14 football, 7 basketball, 5 handball, 1 rugby) athletes (5 females; mean age 24.2 [4.7] y; height 183.6 [9.1] cm; body mass 77.5 [11.2] kg) participated in the study. Each athlete was assigned to 2 testing sessions on separate days: inhibition and WM. The order of the sessions was counterbalanced across the athletes. The present study was approved by the university ethics committee. All participants provided written informed consent prior to participation.

The SpeedCourt system (Globalspeed GmbH) was used to measure the outcomes of sport-specific tasks (Figure 1). The system is a 6.3 m by 6.5-m floor with 9 integrated contact sensors (0.5 m × 0.5 m, sampling at 1000 Hz, triggered at 50 N) positioned in a 3 by 3 grid (Figure 1).

Procedure

Upon arrival, participants were briefed on the testing procedure and asked to change into sports clothing with their preferred indoor sports shoes. The warming-up protocol started with a 5-minute run on a treadmill at a self-selected pace. This was followed by a 2-minute familiarization on the SpeedCourt using a simple chase game (ie, similar to whack-a-mole) with the specific instructions to “treat it as a warm-up” and to “get a feeling for the contact sensors.”

Computer-Based Neurocognitive Tests

Computer-Based Working Memory Task

The computer-based WM task was conducted using the Corsi Block-Tapping Task (Inquisit 6 [Windows 10, 2022]), which is a widely used cognitive assessment tool for visuospatial short-term memory.[10] This assessment tool is also frequently utilized as a sports psychological tool within the Vienna Test System.[11] For the present study, the position of the squares was modified (Figure 2) to match the contact sensor layout of the SpeedCourt system (Figure 1). The participants sat behind a computer monitor (Dell 1908FPc, 19 in, 1280 × 1024 pixels, 60-Hz refresh rate) with their arms resting on the desk and their dominant hand positioned at the computer mouse. Participants were presented with a screen of 9 squares. The squares lit up in a prefixed sequence, and participants were asked to click on the squares in the same order they were lit. The sequence length started at level 3 (3 squares) and could increase up to level 8 (8 squares). Participants were allowed 3

Figure 1 — The SpeedCourt system with a television monitor displaying the target sensor.

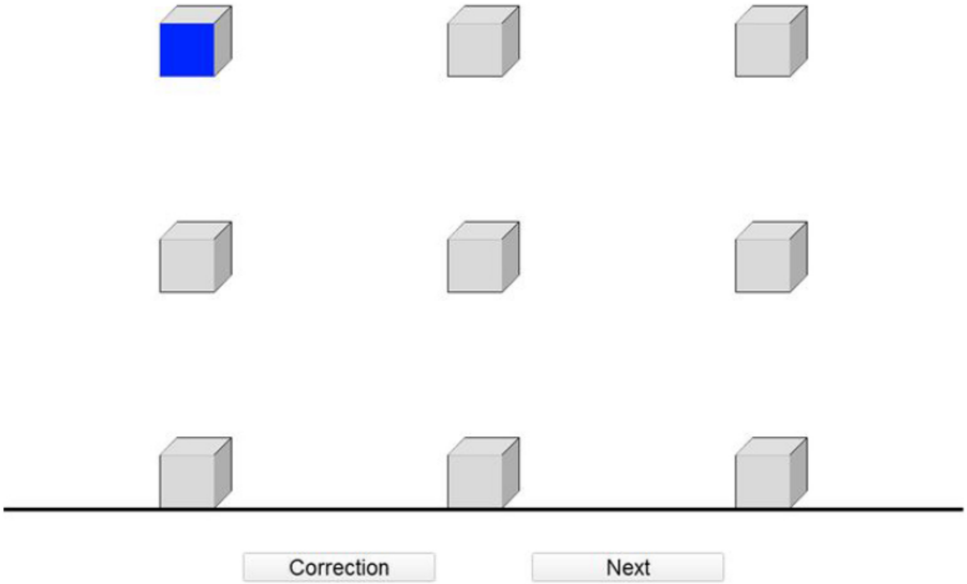

Figure 2 — Modified Corsi Block-Tapping task matching the 3 by 3 target layout of the SpeedCourt system.

attempts at each sequence length. If one of the sequences was entered correctly, the next sequence started. The test terminated with 3 incorrect responses in a row. The penultimate sequence length (ie, the level prior to termination) was taken as the computer-based working memory capacity (WMC_{PC}). Two practice trials were provided to the participants before the performance was recorded. Each participant performed the computer-based WM task twice: before and after the sport-specific assessments.

Computer-Based Stop-Signal Task

The computer-based stop-signal task was conducted using the open-source software "STOP-IT-JS" available at: https://github.com/fredvbrug/STOP-IT. This software complies with the recommendations for stop-signal tasks.[12] The stop-signal task was designed to provide a sensitive measure of the time taken by the brain to inhibit or suppress inappropriate motor responses. The participants sat behind a computer monitor with their dominant hand positioned at the arrow keys. The participants were instructed that they have to perform a 2-choice reaction task in which they have to respond as fast and accurately as possible to left or right pointing arrows presented on the computer monitor by pressing the corresponding arrow key on a keyboard. Participants were also instructed that on a minority of the trials (25%) the arrow is replaced by a stop-signal (ie, the arrow is replaced by a double "X"), which indicates that they should cancel their response but that they should not wait for the stop-signal to appear. The stop-signal task started with a practice phase (1 block of 32 trials) followed by an experimental phase (4 blocks of 64 trials). Stimuli were presented using the default settings: a fixation dot was presented for 250 ms, go stimuli (ie, left or right pointing arrow) were presented until a response was given or until 1250 ms (ie, maximum reaction time) had elapsed, and the interstimulus interval was 750 ms. The stop-signal was presented after a variable stop-signal delay (SSD) starting at 300 ms. The staircase tracking procedure increased the SSD by 50 ms after a successful stop and decreased the SSD by 50 ms after an unsuccessful stop.[12] The computer-based stop-signal reaction time ($SSRT_{PC}$) was estimated through the recommended integration method with the replacement of go omissions.[12] Each participant performed the computer-based stop-signal task twice: before and after the sport-specific assessments.

Sport-Specific Neurocognitive Tests

Sport-Specific Working Memory Task

Participants performed a sport-specific adaptation of the WM neurocognitive test through replication of the stimulus provided by the Corsi Block Task[10] onto the SpeedCourt. For each trial, participants were presented with 9 square targets on a television, each target representing a square on the SpeedCourt (Figure 3). One of 9 displayed squares lit up for 1 second in a prefixed sequence where the sequence length started with 3 squares and could increase to up to 8 squares. Each test block consisted of 3 random sequences of the same length. Participants were asked to run the sequence of the squares in the same order they were lit as quickly and as accurately as possible. The test terminated with 3 incorrect responses in a block. The penultimate sequence length (ie, the block prior to termination) was taken as the outcome variable: sport-specific WMC (WMC_{SS}).

Sport-Specific Stop-Signal Task

Participants performed a sport-specific adaptation of the stop-signal task[12,13] on the SpeedCourt. Participants were instructed to start in a standing position between 2 targets on the SpeedCourt, at a distance of 1.25 m to the center of each target, marked by tape (Figure 4). Participants had to respond as fast and accurately as possible to an arrow pointing to the left or right presented on a television screen (Telefunken D55F389X4CW, 55 in, 1920 × 1080 pixels, 600-Hz refresh rate, 170 cm from the starting position, 70 cm off the floor) and step on the corresponding SpeedCourt target before returning to their starting position. Again, participants were instructed that in a minority of the trials (25%) the arrow is replaced by a stop-signal (ie, the arrow is replaced by a double "X") which indicates that they should cancel their response but that they should not wait for the stop-signal to appear. The sport-specific

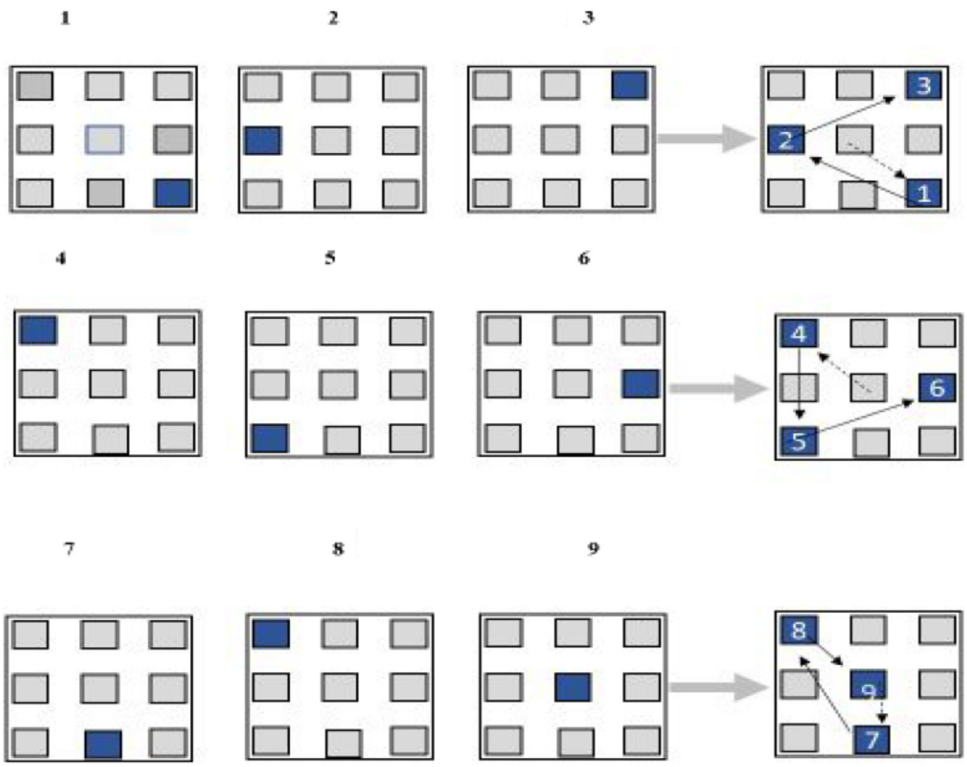

Figure 3 — Diagram depicting stimuli provided to participants on the television screen and the running path to be memorized and run following stimulus presentation, that is, 3 boxes × 3 trials.

Figure 4 — Image depicting starting position of the sport-specific stop-signal task. Participants stood between 2 targets on the SpeedCourt, at a distance of 1.25 m to the center of each target, marked by tape.

stop-signal task started with a practice phase (1 block of 16 trials) followed by an experimental phase (maximum 5 blocks of 32 trials). Stimulus timings and intervals were adjusted to facilitate whole-body movement and the return to the starting position. The fixation dot was presented for 250 ms and go stimuli (ie, left or right pointing arrow) were presented until a response was given or until 5000 ms (ie, maximum reaction time) had elapsed. After each response, there was a black screen for 450 ms due to video buffering followed by a white screen for 2000 ms which preceded the fixation dot (total interstimulus interval = 2450 ms). The practice phase and first experimental block featured an SSD of 200 ms. The SSD increased by 100 ms with each experimental block. Participants continued until they had completed an experimental block with a probability of responding on a stop-signal (ie, error rate) of 0.5 or higher.[12] The sport-specific stop-signal reaction time ($SSRT_{SS}$) was estimated for the final experimental block using the integration method, as long as the error rate was not higher than 0.75.[12] In case the final experimental block featured an error rate >0.75, the previous block was considered for SSRT estimation.

Data Analysis

Data were analyzed using SPSS Statistics (version 28.0). All computer-based data were averaged per athlete for the 2 computer tests. Normality of data distribution was tested using the Shapiro–Wilk test. Spearman rho coefficient was used to correlate outcomes of WMC_{PC} and WMC_{SS}, and Pearson correlation coefficient was used to investigate the correlation between $SSRT_{PC}$ and $SSRT_{SS}$. Correlation was considered small, moderate, large, very large, and near perfect with r values < .30, <.50, <.70, <.90, and >.89, respectively.[14] The level of significance was set at $P < .05$.

Results

Analysis of construct validity (Figure 5) yielded moderate validity ($r = .465$, $P < .05$) for WMC_{SS} and low validity ($r = .179$, $P > .05$) for $SSRT_{SS}$.

Discussion

This study investigated the construct validity of sport-specific tests of inhibition and WM. Low to moderate construct validity was found in the domains of inhibitory control and WM. The results offer valuable insights for conducting ecologically valid assessments in sports by utilizing sport-specific modifications of established neurocognitive tests.

The WMC_{SS} yielded significant moderate construct validity, whereas the $SSRT_{SS}$ displayed low construct validity. Previous research on comparisons between computer-based and sport-specific assessments reported the validity and reliability of cognitive performance in badminton players utilizing a badminton reaction inhibition test.[15] In contrast to the present study's findings, good construct validity was reported for a badminton sport-specific inhibitory control test.[15] These differences may be attributed to the design of the assessments where the sport-specific adaptations utilized in this study provided 3D stimulus presentation, whereas the computer-based assessment gave 2D stimulus presentation. For the WM construct, the sport-specific assessment included multidirectional changes of direction which greatly influences spatial awareness and orientation demands compared to a computer-based assessment. Specifically, athletes were commonly observed making mistakes in the WM sequence after performing 180 degree turns. This observation indicates that the spatial representation of the WM sequence was likely orientation specific.[16] To further improve the sport specificity of neurocognitive assessments, future research should include stimuli positioned at different locations surrounding the athlete which increases the demands on scanning for visual information.

The moderate to low construct validity between the computer-based and sport-specific neurocognitive tests may be explained in part by the large discrepancy in degrees of freedom of the motor behavior. Whereas the computer-based assessments required only the click of a button, the sport-specific tests required whole-body movements with displacement of the center of mass. As a result, athletes had numerous different ways of

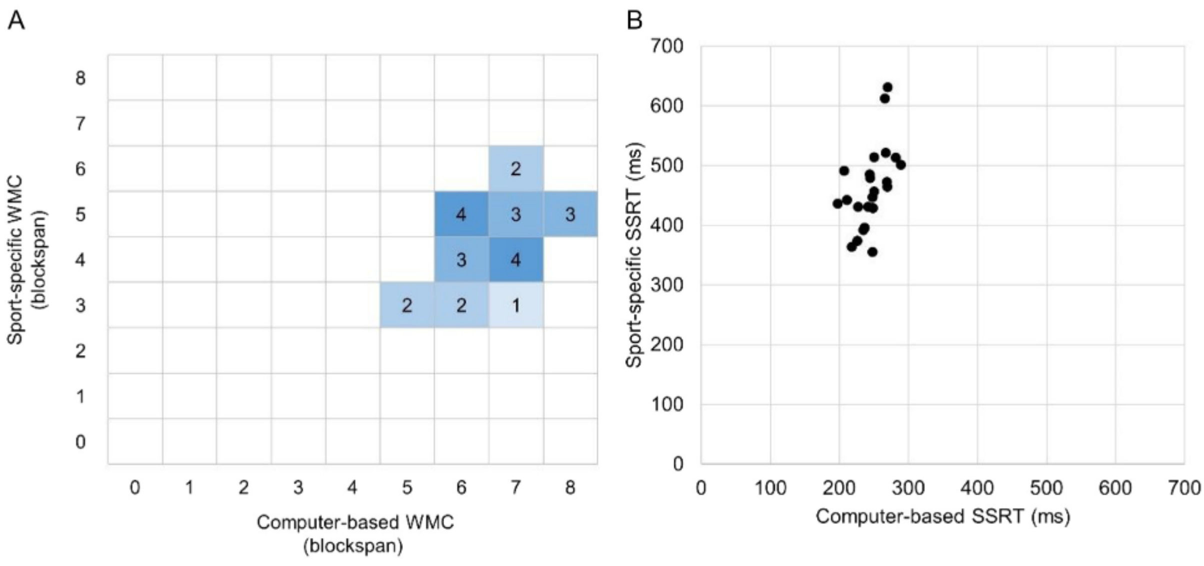

Figure 5 — Distributions of computer-based versus sport-specific performance for (A) WMC and (B) SSRT. SSRT indicates stop-signal reaction time; WMC, working memory capacity.

executing the agility task, for example, by varying their lower-extremity joint coordination and postural control. In fact, coordination variability is known to increase as a function of task complexity.[17] Similarly, the athletes were presented with various different manners by which to correct and abort their movement response during the sport-specific task, while the computer-based test did not provide such opportunities. For example, when faced with a stop-signal in the sport-specific SST, the athlete had several different movement strategies (ie, combination of upper body movement and lower-extremity coordination) available to them by which to prevent the foot from landing on the target. Consequently, it is important for researchers and practitioners to note that computer-based assessments are useful to assess neurocognitive functions; however, they can barely be attributed to sporting performance. Future research may explore further physical tests that include neurocognitive loads as more valid measures of athletic performance. Additionally, the inclusion of more sport-specific stimuli may be more useful than utilizing generic stimuli during such assessments.

The present study has some limitations that require acknowledgement. First, the SpeedCourt software does not include the option to adjust stop-signal delay time based on the response given by the athlete. Therefore, the sport-specific stop-signal task featured a block-wise increase for SSD rather than the recommended tracking procedure.[12] However, this approach has previously been used to develop more sport-specific SSRT.[15] Additionally, the sport-specific WM task terminated at the end of a testing block rather than at the occurrence of a third consecutive error. Furthermore, the current study serves as exploratory work as it is the first to adapt the stop-signal paradigm to the SpeedCourt system. Future research on sport-specific assessments of the stop-signal task should therefore attempt to include a tracking procedure for stop-signal delay adjustments.

Practical Implications

Sport-specific assessments of neurocognition in sports are gaining more attention. For example, recent research investigated how different levels of neurocognitive demands may interact with motor abilities in complex perception–action coupling tasks on the SpeedCourt system.[18] The study showed that neurocognitive demands influence whole-body motor activities; however, the study lacked information in relation to the computer-based neurocognitive status of the athletes (ie, WMC). A meta-analysis exploring the role of sport-specific and computer-based neurocognitive functions and skills in sports performance concurred with this previous literature stating that elite athletes perform better on cognitive function assessments in comparison to nonelite athletes.[3,19] In contrast, there is no evidence that supports the usefulness of using generic, nonsport-specific cognitive function assessments to predict future sports performance.[19]

Conclusion

The study findings suggest that traditional computer-based neurocognitive assessments, when adapted into sport-specific assessments, may demonstrate low to moderate construct validity. This discrepancy could be attributed to the increased complexity and greater degrees of freedom involved in executing whole-body movements in sport-specific tests compared to the simple actions of clicking a key on a keyboard. Future research should focus on developing sport-specific assessments that combine the neurocognitive and motor demands that team ball sports athletes' encounter during practice and competition.

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Study V

Stop-Signal Task on a Training Platform Induces Player-Level Adaptations in Team Sport Athletes

Pieter Heuvelmans[1], Benedict Gondwe[1], Anne Benjaminse[2], Eline Nijmeijer[2], Jochen Baumeister[1], Alli Gokeler[1]

1. Paderborn University, Faculty of Science, Department of Exercise and Health, Exercise Science and Neuroscience Unit, Paderborn, Germany.
2. University of Groningen, Faculty of Medical Sciences, Department of Human Movement Sciences, Groningen, Netherlands.

Corresponding author

Pieter Heuvelmans
Exercise Science and Neuroscience Unit
Department of Exercise & Health
Faculty of Science
Paderborn University
Warburger Str 100
33098 Paderborn
Germany
pieter.heuvelmans@upb.de

Abstract

Neurocognitive abilities such as response inhibition are linked to athletic expertise and may contribute to injury risk. Screening for neurocognitive deficits requires effective assessments. These assessments must integrate neurocognitive and motor demands rather than evaluate them in isolation if transfer to sport is desired. The objective of this study was to investigate how team sport athletes adapt to the addition of a stop-signal constraint. Twenty-four players executed a reactive lateral stepping task on a SpeedCourt system with (stop-signal task; SST) and without (choice reaction task; CRT) random stop-signals. Outcome measures included reaction time (RT), movement time (MT), and stop-signal reaction time (SSRT). Group-level analysis identified 50–53 milliseconds higher RT in SST compared to CRT ($p < .05$), but no significant difference was found for MT. Player-level analysis revealed distinct performance profiles, with some players exhibiting both higher RT and higher MT in SST, while others demonstrated higher RT but lower MT in SST. In conclusion, this study highlights the importance of evaluating constraints-induced effects at the player-level. Moreover, it provides insight into the mechanisms between neurocognitive and motor strategies and capacities of team sport athletes.

Introduction

In team sports, such as football, basketball, and handball, neurocognition plays a vital role in athletes' performance. Neurocognitive abilities, including decision-making, attention, memory, and motor response inhibition (Diamond, 2013), are essential for athletes to process information quickly, anticipate opponents' movements, and execute precise actions on the field or court (Davids et al., 2015). Strong neurocognitive skills enable athletes to adapt to the dynamic and fast-paced nature of team sports, which contributes to their success in competitive environments (Huijgen et al., 2015; Voss et al., 2010). Inhibitory control is a critical neurocognitive function in team sports, where split-second decisions and rapid adaptations are often required. Athletes with strong inhibitory control can effectively suppress impulsive actions, resist distractions, and adjust their responses based on changing game situations. This ability allows players to maintain focus, make strategic decisions, and execute precise movements under pressure, ultimately enhancing their performance. Neurocognitive errors have been shown to contribute to noncontact anterior cruciate ligament (ACL) injuries in professional football (Gokeler et al., 2021, 2024). Hence, the identification of deficits in response inhibition through screening may prove valuable for injury prevention (Piskin et al., 2022). To date, neurocognitive abilities are most commonly assessed with computer-based tests (Verbruggen et al., 2019). While such generic tests are reliable in assessing isolated neurocognitive functions, they may not fully capture the intricate interplay between cognitive processes and motor behavior. Likewise, traditional pre-planned change-of-direction training can improve performance within pre-planned settings, but it fails to transfer to sports-specific performance (Friebe et al., 2024). In contrast, previous research has shown that integrating neurocognitive demands into motor tasks results in increased sports-specific performance (Friebe et al., 2024). By incorporating assessments that evaluate both neurocognitive responses and their influence on motor behavior, researchers and practitioners can gain a more comprehensive understanding of how cognitive functions impact athletes' movement execution, coordination, and decision-making in real-world sporting scenarios (Renshaw et al., 2019). These effects are often highly individual and can be of opposite nature, thus averaging each other out when analysis is done at the group level (Button et al., 2006; Nijmeijer et al., 2024). Therefore, the aim of the current study was to investigate how team sport players performing a reactive lateral stepping task adapt to stop signals. To account for interindividual differences, the analysis will incorporate both group-level and player-level comparisons. It is hypothesized that distinct individual performance adaptations arise due to variations in cognitive and motor strategies and capacities, with some individuals being able to compensate for slower reaction times by optimizing movement execution time, while others may be quick to initiate but slow to complete their movement response.

Methods

Study population

Twenty-four young adult players (mean age 22.4 ± 5.7 years, height 186.0 ± 11.0 cm, weight 78.6 ± 11.9 kg) participated in this study. The participants (21 male, 3 female) actively practiced a team sport (12 basketball, 7 football, 4 handball, 1 rugby); training at least two times per week for 90 minutes. Prior to inclusion, written informed consent was obtained. The study and its procedures were approved by the university's ethics committee.

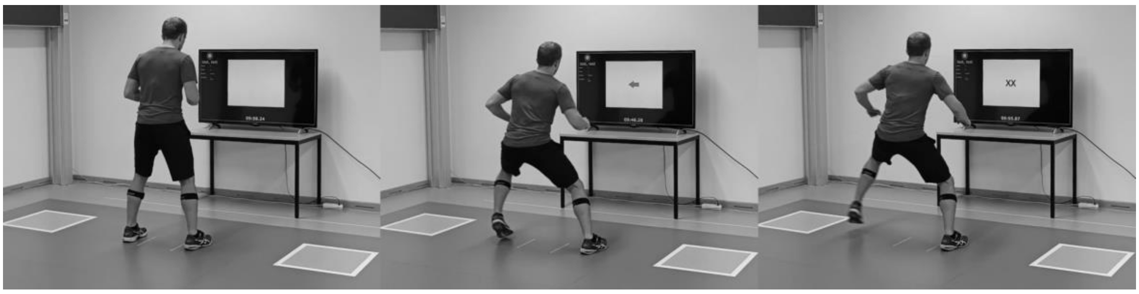

Figure 1. Experimental setup with (from left to right) starting position, go-signal, and stop-signal. Note that the player is already moving when the stop-signal is presented after a delay.

Experimental protocol

The testing took place on a SpeedCourt SC650 Q10 system (Globalspeed GmbH, Hemsbach, Germany) linked to a TV screen for stimulus presentation (Telefunken D55F389X4CW, 55 inch, 1920×1080 pixels, 600 Hz refresh rate, 1.7 m from the starting position, 0.7 m off the floor). The SpeedCourt measures 6.3 m × 6.5 m and features a 3-

by-3 square grid of contact plates, each 0.5 m × 0.5 m in size, positioned at 2.5 m center-to-center distance. The starting position was centered between two contact plates, so that the player had to travel approximately 1.25 m in response to a stimulus (Figure 1). Stimulus presentation consisted of a white screen (2000 ms), fixation dot (250 ms), and a go-signal (left or right pointing arrow) until a response was given or until 5000 milliseconds had elapsed. Players were instructed that they should react as quickly and accurately as possible to the go-signal, contact the target plate with their foot, and return to the starting position. The experiment comprised conditions with (stop-signal task; SST) and without (choice reaction task; CRT) random stop-signals. At the start of each condition, players completed a practice trial of 16 consecutive stimuli; 8 responses to the left/right in a randomized sequence. For the CRT, players completed a trial of 32 consecutive stimuli; 16 to the left/right in a randomized sequence. For the SST, players were instructed that in some instances, the go-signal would be followed by a stop-signal ('XX'), indicating that they should stop their response. Additionally, players were reminded of the objective of the exercise (to react as quickly and accurately as possible) and they were instructed not to wait for the stop signals. Each SST trial consisted of 32 randomized stimuli; 24 regular go-signals (12 left/right) and 8 go-signals which were followed by a stop-signal after a delay. The stop-signal delay (SSD) was initially set to 200 milliseconds and increased by 100 milliseconds with each SST trial, making it more difficult to stop successfully. Based on the idea of the horse-race model (Band et al., 2003), players continued until they had completed a trial with an error rate of 0.5 (4/8 stops were unsuccessful) or higher. Stop-signal reaction time (SSRT) was estimated for the final trial using the integration method by Verbruggen and colleagues as long as the error rate was not higher than 0.75 (Verbruggen et al., 2019). In case the final SST trial featured an error rate > 0.75, the previous trial was considered for SSRT estimation. The order of SST and CRT was counterbalanced across players.

Data collection and processing

Lower extremity kinematics were recorded with nine Noraxon (Noraxon, Inc., Scottsdale, AZ) Myomotion inertial measurement units (IMUs) at 200 Hz. The IMUs were fixed to the feet, shanks, thighs, pelvis, T12, and C7 according to the manufacturer's user manual (myoMOTION Hardware User Manual, Noraxon). IMU data were processed with proprietary filter procedures (Model Optimizer, Noraxon MR3 Software, Version 3.21).

Temporal performance was defined as the time from stimulus presentation to contact with the target plate. It was divided into two components: reaction time (RT), the interval from stimulus onset to movement initiation, and movement time (MT), the duration from movement initiation to target contact. Movement initiation was defined as the first jerk peak in the acceleration of either foot sensor following stimulus presentation (Handsaker et al., 2016). Jerk peak detection used a threshold of six standard deviations. The analysis included one trial of each participant, consisting of 32 consecutive responses, for both the SST and CRT. Median RT and MT were calculated at the player-level for SST and CRT, separating go and stop repetitions.

Statistical analysis

Data were tested for normality with the Shapiro-Wilk test. Differences in RT between SST and CRT were tested using the Kruskal-Wallis test followed by Mann-Whitney U tests with Bonferroni correction (alpha = 0.05/3) as a post hoc procedure for pairwise comparisons. Differences in MT between SST and CRT were tested using the Mann-Whitney U test. The alpha level was set to .05 for all tests.

Results

Players performed the SST with significantly different RT compared to the CRT ($H(2) = 11.559$, $p = .003$) (Figure 2). Pairwise comparisons found that median RT was 53 milliseconds higher in SST for go repetitions ($U(24, 24) = 145.0$, $p = .003$) and 50 milliseconds higher in SST for stop repetitions ($U(24, 24) = 146.5$, $p = .004$) compared to CRT. There was no significant difference in MT. Player-level analysis exposed varying performance profiles featuring significant increases or decreases in MT and RT between SST and CRT (Figure 3). Furthermore, players performed the SST with a median SSRT of 448 ± 63 milliseconds.

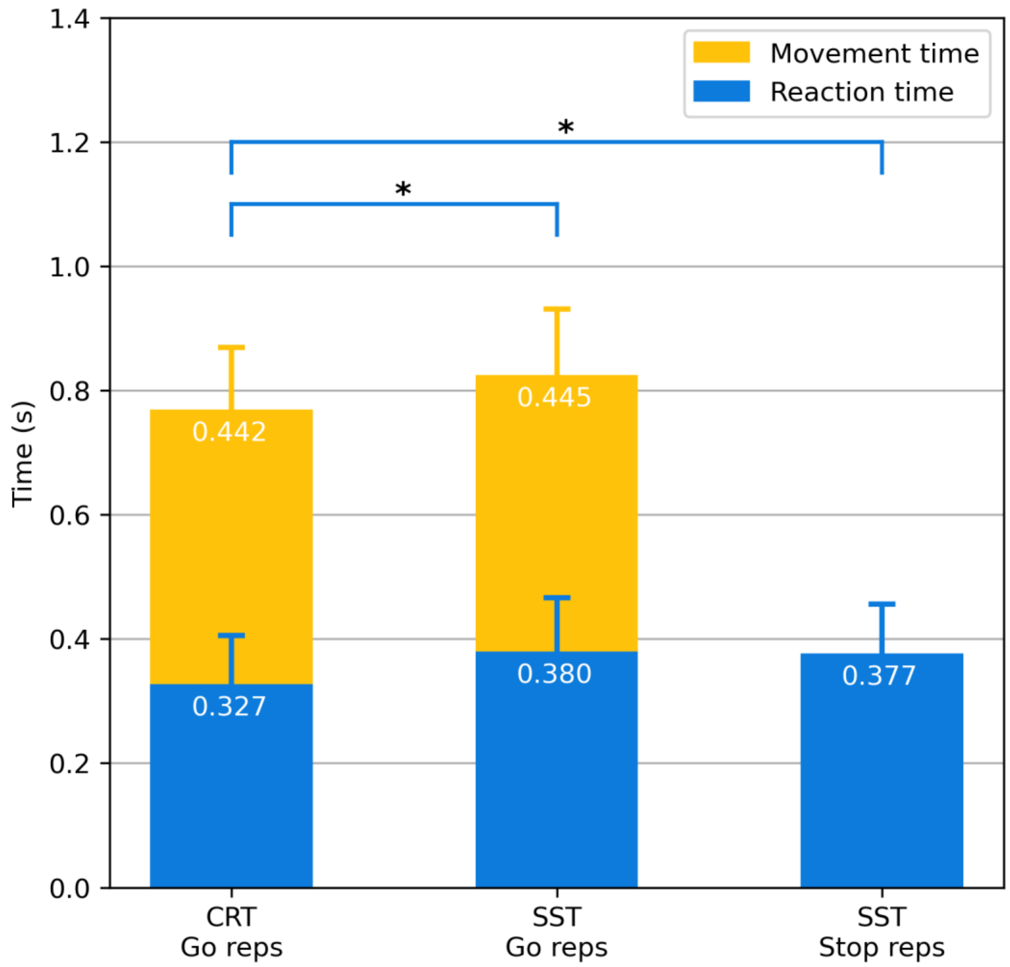

Figure 2. Group-level reaction time and movement time. Asterisks indicate a statistically significant difference ($p < .05$), values represent medians. CRT: choice-reaction task, SST: stop-signal task.

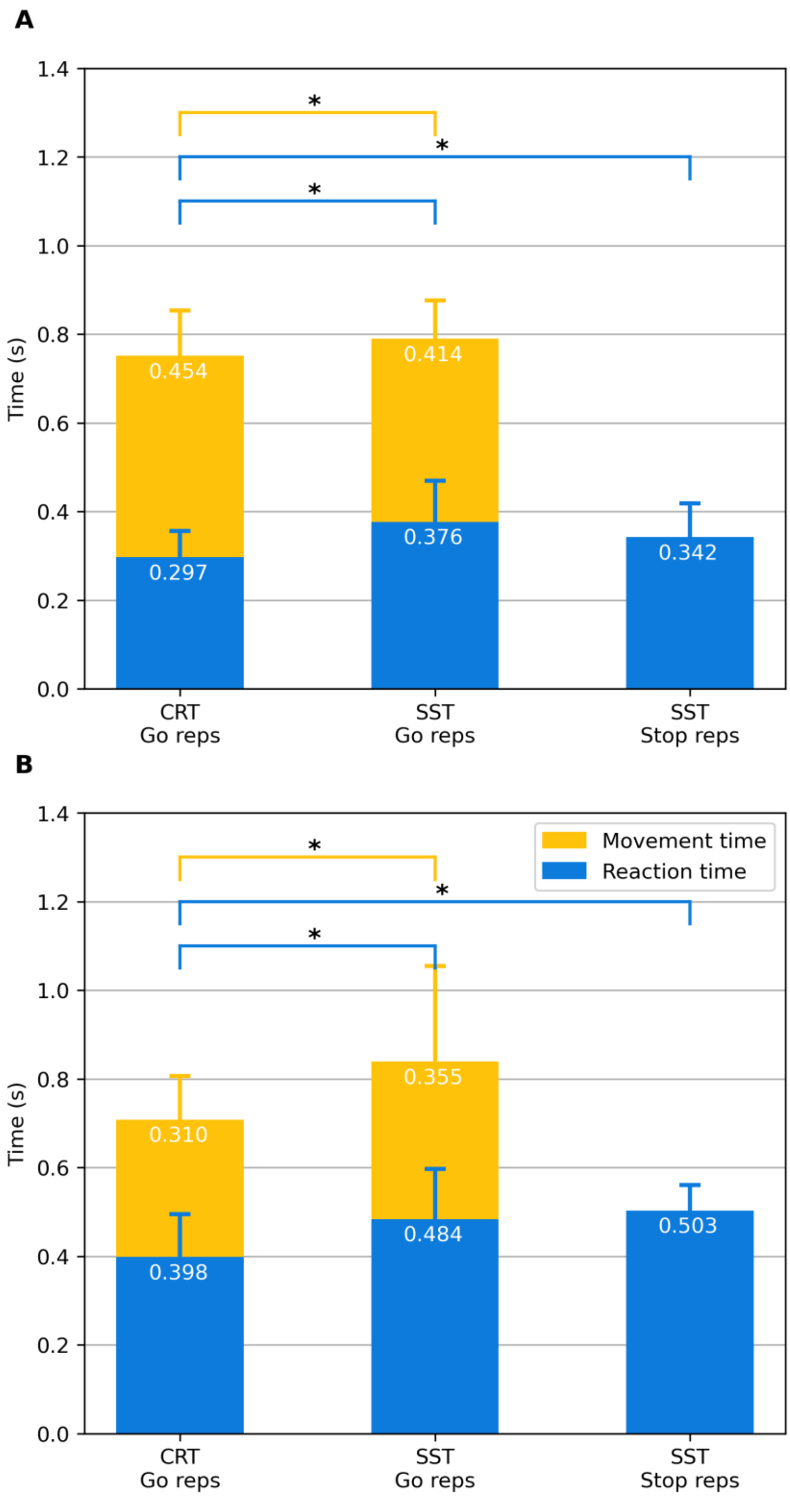

Figure 3. Examples of player-level performance profiles with A) compensatory movement time decrease and B) aggravating movement time increase, concomitant with an increase in reaction time when comparing SST to CRT. Asterisks indicate a statistically significant difference ($p < .05$), values represent medians. CRT: choice-reaction task, SST: stop-signal task.

Discussion

The objective of this study was to investigate how team sport players change their temporal performance in a reactive lateral stepping task with stop-signals. This study has two main findings. Firstly, the group-level analysis found that athletes took an additional 50–53 milliseconds on average to react during the stop-signal task compared to the simpler choice-reaction task ($p < .05$). Secondly, player-level analysis discovered distinct performance profiles that went undetected at the group-level because of their opposite natures. The increased RT at group-level was expected because the stop-signal task requires athletes to not only respond but also to process whether they need to inhibit their action, adding a layer of decision-making. The additional RT reflects the increased cognitive load or complexity of the stop-signal task. Even though team sport athletes are experienced in quick decision-making, the requirement to inhibit responses is known to introduce a delay in their RT (Brevers et al., 2018). This delay of 50–53 milliseconds is clinically relevant when you consider ACL injuries often occur within 50 milliseconds after initial contact (Koga et al., 2010; Krosshaug et al., 2007). Players performed the stop-signal task with a median stop-signal reaction time (SSRT) of 448 ± 63 milliseconds. Following the horse-race model, this means that response inhibition had an average latency of 448 milliseconds and that stop-signals had a probability of approximately 0.5 to yield a successful stop (i.e., inhibition rate) (Band et al., 2003). This is clinically relevant when you consider that video analysis of noncontact ACL injuries has shown that the time from a deceiving action (i.e., inciting event) to initial contact (i.e., point of no return) ranges from 40 to 560 milliseconds, with a mean of 256 milliseconds (Gokeler et al., 2024). Although direct comparisons cannot be made between this study's experiment and such injury events in match play, considering the relatively short time window and the resulting injury (i.e., unsuccessful stop), it is likely that stop cues were either recognized or presented too late for the player's response inhibition latency. Logically, it follows that players with higher response inhibition latency than their peers might be more susceptible to such injury events. Future studies could continue to explore the role of SSRT in injury risk and team sport performance through cohort monitoring or the development of training interventions, respectively. MT did not change significantly between the stop-signal task and the choice-reaction task at the group-level. This finding seems to contradict previous literature that found a motor-interference effect in temporal performance from increased cognitive load (Büchel et al., 2022). On the other hand, that study did not partition performance into RT and MT, which could potentially explain this paradoxical finding. Consider the following: besides the addition of stop-signals in the current study, the task constraints remained unchanged between the two conditions. Physical demands such as the number of repetitions and the distance to the contact plates were identical. Based on these facts, one could argue that MT was never expected to change in the stop-signal task. However, since movement initiation (measured with RT) and movement execution (measured with MT) are inherently linked, one could also argue that the change in RT would have a carryover effect on MT. For instance, hesitant movement initiation (high RT) may lead to lower acceleration in the target direction, resulting in lower velocity and hence higher MT. Conversely, the realization of a high RT could drive a player to compensate via rapid movement execution (low MT). The latter hypothesis presumes that players have surplus capacity in their physical ability to perform the movement, which may not be true for many players. Individual performance profiles identified through player-level analysis revealed significant differences in both RT and MT. For the purpose of conciseness, we will discuss two example profiles. First, one performance profile demonstrated a median increase of 79 milliseconds in RT for go reps during the stop-signal task compared to the choice-reaction task ($p < .05/3$), indicating a greater cognitive load and decision-making requirement. Simultaneously, this player exhibited a median decrease of 40 milliseconds in MT in the stop-signal task ($p < .05$), suggesting improved efficiency in movement execution (Figure 3A). This compensatory carryover effect enables the player to maintain some of the original temporal performance. In contrast, a second performance profile showed a median increase of 86 ms for RT ($p < .05/3$) and a median increase of 45 ms for MT ($p < .05$) between the two conditions (Figure 3B). This indicates that the player not only faced additional cognitive demands in the stop-signal task but also experienced delays in executing movements, reflecting a possible struggle with decision-making and execution under time constraints. This aggravating carryover effect suggests that this player may have a poor ability to maintain performance when exposed to greater cognitive load. These contrasting performance profiles underscore the complexity of player behaviors, illustrating how one player may thrive under new constraints while another may struggle. Consequently, group-level findings were unable to produce player-relevant implications, as they averaged out the distinct adaptations that individual analyses could reveal (Button et al., 2006). Together, this presents a strong argument for sports research to incorporate more player-level analysis rather than base implications and guidelines solely on group-level findings.

The current study has some limitations that need to be acknowledged. Some of the participants (n=7) were under the age of 18, namely 16 or 17 years old. The executive functioning of these players may not have fully developed yet (Best et al., 2009). Nevertheless, the findings of this study still provide relevant information about adaptations to stop-stimuli in this young population, especially considering the fact that some of these young players compete against opponents who are 18 years or older. Practitioners who adopt similar drills should rely on monitoring rather than a single measurement for performance evaluation to account for the developing executive functioning of these young players. The stop-signal task investigated in the current study was a successful first step on the spectrum of athlete-environment preservation, considering the computer-based paradigm it was based on (Bolt et al., 2024; Verbruggen et al., 2019). Nevertheless, the sports-specificity should be improved further before the task can be adapted into training (Friebe et al., 2021). For instance, future research could replace the generic arrow-stimuli with more game-realistic stimuli, as well as presenting them from more than one viewing angle. Furthermore, the resolution of SSRT estimation would likely benefit from an adaptive stop-signal delay (SSD) such as a staircase tracking procedure (Verbruggen et al., 2008) which was impossible to implement in the systems used for the current study.

In conclusion, this study reveals critical insights into the adaptations in temporal performance of team sport players during a reactive lateral stepping task with stop-signals. While group-level findings indicate an overall increase in reaction time to stop-signals, it is the player-level analysis that uncovers the nuanced differences in neuromotor mechanisms at play. Specifically, these individual profiles highlight the presence of both positive and negative carryover effects on movement time, underscoring the complexity of player responses to cognitive demands. This distinction emphasizes the necessity of individualized assessments in understanding performance dynamics and the consequences that cognitive demands can have on movement behavior. Ultimately, these findings advocate for a shift towards more player-level analyses in team sports research.

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Study VI

Agility in Handball: Position- and Age-Specific Insights in Performance and Kinematics using Proximity and Wearable Inertial Sensors

Pieter Heuvelmans[1], Alli Gokeler[1], Anne Benjaminse[2], Jochen Baumeister[1], Daniel Büchel[1]

1. Paderborn University, Faculty of Science, Department of Exercise and Health, Exercise Science and Neuroscience Unit, Paderborn, Germany.
2. University of Groningen, Faculty of Medical Sciences, Department of Human Movement Sciences, Groningen, Netherlands.

Corresponding author
Pieter Heuvelmans
Exercise Science and Neuroscience Unit
Department of Exercise & Health
Faculty of Science
Paderborn University
Warburger Str 100
33098 Paderborn
Germany
pieter.heuvelmans@upb.de

Abstract

Handball is a dynamic team sport characterized by high agility requirements, which feature complex motor-cognitive demands. The ability to meet these demands is critical for performance in handball but remains underrepresented in research. Existing studies highlight that cognitive demands can strongly interfere with motor behaviour, particularly in dynamic sport-specific movement tasks. Furthermore, high motor-cognitive load is associated with risk of lower limb injury. Therefore, to gain insight in the mechanisms between movement and performance dynamics in the presence of cognitive demands, this study investigated the performance of elite handball players in a novel planned and reactive agility task. Four FitLight proximity sensors (FitLight Corp, Ontario, Canada) recorded execution time. Nine Noraxon Myomotion wearable inertial sensors (Noraxon U.S.A. Inc., Scottsdale, AZ) tracked the motion of the players' trunk, pelvis, and lower extremities at 200 Hz. Execution time and kinematics were compared between adult and youth players and between different playing positions. Adult players demonstrated faster performance than youth players and exhibited differences in hip and knee flexion, potentially reflecting variations in acceleration and deceleration strategies. Backcourt players and wings outperformed pivots in speed, with pivots showing distinct hip, knee, and ankle flexion patterns likely influenced by differences in body composition. These findings highlight the influence of motor and cognitive demands on agility performance and offer valuable insights into age- and position-specific differences among elite handball players. Furthermore, these findings support the use of wearable inertial sensors for the purpose of athlete evaluation. Future research should explore the implementation into athlete monitoring.

Introduction

Handball is a team sport with seven players per side, characterized by complex and intermittent activity profiles (García-Sánchez et al. 2023). These profiles result from the dynamic play around and between the two goal areas, leading to frequent changes in activity. Players with substantial playing time (>50 mins) typically perform about 16 jumps, 13 sprints, endure approximately 48 impacts, and engage in around 55 acceleration actions (Büchel et al. 2024). Agility, defined as a motor-cognitive skill involving the ability to quickly perceive information and alter speed or direction, is a crucial attribute in handball (Sheppard & Young 2006). Handball-related research over the last decade set a major focus on the physical and neuromuscular determinants of performance (García-Sánchez et al. 2023). Despite agility being a key demand in handball, research has underrepresented it by omitting motor and perceptual tasks (Herold et al. 2018). Nevertheless, it is well-known that the co-existence of cognitive tasks strongly interferes with motor behaviour in dynamic sports-specific tasks requiring lower limb control such as jump landings or changes-of-direction (Gokeler et al. 2024, Voss et al. 2010). Since high motor-cognitive load is known to be associated with high incidences for lower limb injuries (Della Villa et al. 2020, Krosshaug et al. 2007), there is a need to develop appropriate tests for the assessment of motor-cognitive tests in handball players. Accordingly, these tests should integrate physical and cognitive demands that simulate the complex demands in handball (Spasic et al. 2015).

Using technologies such as the FitLight system, execution times (i.e., the sum of reaction time and motor execution time) can be assessed to reflect the ability to perform motor-cognitive tasks. With portable setups, tasks can be tailored to sports-specific demands (Jansen et al. 2021) and allow for ecologically valid testing of handball players (Badau et al. 2022). In addition to being reliable (Smith et al. 2024), these tests also seem valid since they allow for the differentiation between defensive and offensive handball players when building ratios between planned and reactive movement tasks (Spasic et al. 2015). We therefore suggest implementing agility tasks with cognitive cues may provide relevant insights into handball players' motor-cognitive abilities, facilitating sports-specific performance evaluation and talent identification. Here, we suggest that faster agility times indicate improved motor-cognitive abilities, for instance between youth and senior athletes (Morral-Yepes et al. 2022).

Since agility evaluations typically express performance using execution times (Pojskic et al. 2019), little is known about kinematic changes in handball-specific agility tasks under reactive conditions. Previous research provided evidence of changes in knee kinematics during unplanned, dynamic, but isolated movements such as landings and sidestep cuts compared to planned control movements (Brown et al. 2014). For instance, knee flexion at initial contact was found to decrease in sidestep cutting when performed under unanticipated conditions (Meinerz et al. 2015). In turn, not only the change in execution time, but also the change in how athletes move may provide valuable insights into the ability of handball players to cope with the strenuous challenges in match play. Here, kinematic changes in motor-cognitively challenging conditions may allow for more tailored conditioning programs for the individual handball player.

Therefore, this study set out to investigate both performance and kinematic outcomes of a novel reactive task in elite handball players, providing insights into the ability of a player in coping with handball-related affordances. The primary aim was to describe changes in execution times in elite handball players between planned and reactive agility tasks. Based on previous literature assuming that handball players' physical performance differs depending on position (Haugen et al. 2016) and age group (Wagner et al. 2022), both factors were considered to test the discriminant validity of the developed test. This subtype of validity refers to the extent to which a test or measure accurately distinguishes between constructs or variables that are theoretically expected to be distinct (Morral-Yepes et al. 2022). The secondary aim was to explore the link between performance and movement by testing the kinematics for amplitude and timing differences for significantly different comparisons in execution time.

Methods

Participants

Ninety-two male handball players participated in this study; 66 adults and 26 youths (Table 1). Fifty-three adult players competed at the highest national level, 13 at the second-highest level, and all youth players competed at the highest U19 national level. Prior to participation, written informed consent was obtained from all players. In reference to the performance calibre classification of McKay et al. (2022), the included athletes can be classified as Tier 1 (Worldclass) to Tier 3 athletes (National-Level). The study protocol was approved by the Institutional Review Board (IRB).

Experimental Design

The study was designed as a cross-sectional performance assessment to evaluate elite handball players' reactive ability and lower extremity kinematics. The FitLight system (FitLight Corp, Ontario, Canada), a wireless reaction training system that measures execution time, was used for the assessment. The system comprises a set of LED lights arranged on top of 38 cm tall cones in a trapezoid layout, with four lights programmed to activate in specific sequences. Two lights were placed at 45-degree angles relative to the starting position, while the other two lights were positioned perpendicular (90-degree angles) to the starting position, located directly to the left and right of the participant. All lights were situated 2.5 meters away from the starting position, requiring participants to deactivate them promptly using their hands in response to the activation sequences. Nine Noraxon inertial measurement units (IMUs) were used to record kinematics at 200 Hz. The IMUs were attached to the body at the feet, shanks, thighs, pelvis, T12, and C7, using proprietary straps and according to the manufacturer's instructions (Noraxon MyoMotion Hardware User Manual, Noraxon U.S.A. Inc., Scottsdale, AZ). An overview of the experimental setup can be found in Figure 1.

Procedure

Participants completed ten rounds, divided into two conditions, starting with planned movement tasks and followed by unplanned reactive movements. Planned: Five rounds were conducted with a pre-determined, consistent sequence of 10 lights (i.e., 1-2-1-2-1-2-1-2-3-4). The lights were numbered 1 to 4 for front left, front right, lateral left, and lateral right, respectively (Figure 1). The sequence remained constant across these five rounds, allowing players to anticipate the next light based on prior knowledge. Reactive movement task: Five rounds were conducted with a random sequence of 10 lights, where the activation order of the lights was unpredictable for the participants. This condition was designed to assess the players' ability to respond to unplanned stimuli.

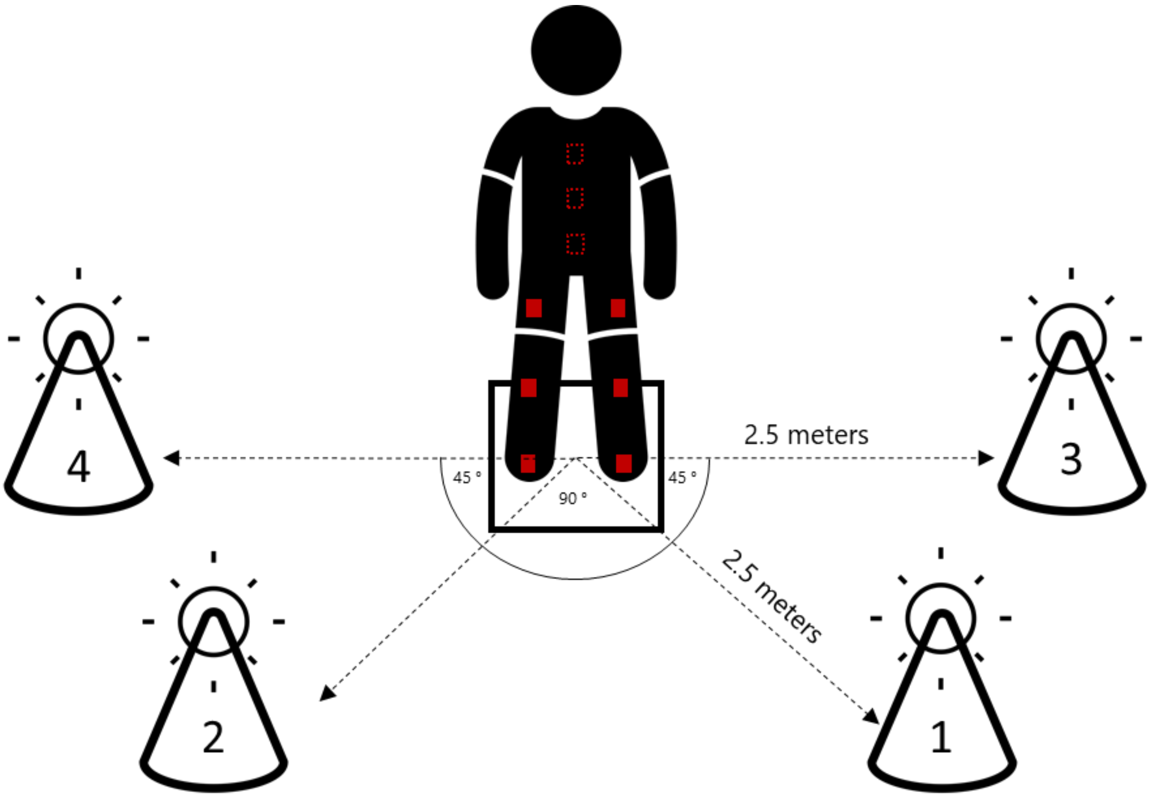


Figure 1. Graphical representation of task setup. All lights are positioned on cones 2.5 metres away from the starting square. Participants were asked to run as fast as possible to the initiated light and turn it off by swiping the hand about the light. To quantify kinematics, all subjects wore IMUs placed at the feet, shanks, thighs, pelvis, T12, and C7 (red boxes/ squares).

Data Collection

For each repetition, the FitLight system recorded the time taken by the player to deactivate each light. As a dependent variable, median execution time for both the planned and reactive conditions were extracted. During each repetition, from light activation to light deactivation, lower extremity joint kinematics were recorded and processed with proprietary software (Noraxon MR3, version 3.20.02). Kinematic data were selected for the leading leg (i.e., the ipsilateral leg to the light) for light numbers 1 and 2 as these were designed to elicit a diagonal (i.e., 45-degree) acceleration and deceleration movement, which is expected to provide insights into knee stability relevant for performance as well as return-to-play scenarios. These types of movements have previously been investigated during agility assessments (Smith et al. 2024, Büchel et al. 2022). Light numbers 3 and 4 were included as a distractor to minimize anticipatory behavioural strategies during the reactive task. Due to the limited number of repetitions collected for light numbers 3 and 4, and because the movement directions are inherently different, they were excluded from analysis. Kinematic data were time normalized to 101 equally spaced data points with linear registration using interpolation. To allow for the simultaneous assessment of amplitude and timing differences in the kinematic waveform signals, nonlinear registration using warp functions was conducted, producing coupled amplitude vectors and displacement fields (Pataky et al. 2022). All kinematic analyses were conducted in custom Python scripts using the *nlreg1d* and *spm1d* packages (Python 3.8.19).

Statistical Analysis

Data were tested for normality using the Shapiro-Wilk test. Comparisons of age, height, and weight between age groups and playing positions were conducted using Mann-Whitney U and Kruskal-Wallis H tests, respectively. Kruskal-Wallis H tests were followed by Dunn's tests for post hoc pairwise comparisons. Differences in execution time data were tested using a two-way repeated-measures ANOVA with age group (adult, youth) and playing position (backcourt, pivot, wing) as between-subjects factors and condition (planned, reactive) as a within-subjects factor. The alpha level was set to .05 for all tests. Post hoc pairwise comparisons were performed with Bonferroni correction. Partial eta squared was interpreted as negligible, small, medium, or large for values <.01, <.06, <.14, or ≥.14 (Cohen 1988). Main-effects of age group and playing position were intended to display the discriminatory validity of the handball-specific agility test. Based on any identified differences in execution time, statistical nonparametric mapping (SnPM) will be conducted on the kinematic data (Pataky et al. 2022). Kinematic data were tested for amplitude and timing differences between conditions, age group, and playing positions. For each comparison, a multivariate Hotelling's test was conducted on the coupled amplitude vectors and displacements fields. T-tests were conducted as a post-hoc procedure with Bonferroni correction on the amplitude vectors and displacements fields, respectively.

Results

At the time of testing, the adult handball players were significantly older (median difference = 7 years, $p < .001$), taller (median difference = 6.5 cm, $p = .025$), and heavier (median difference = 12.15 kg, $p < .001$) than the youth players (Table 1). Pivots were significantly taller when compared to backcourt players (median difference = 4.5 cm, $p_{adj} < .001$) and wing players (median difference = 9.5 cm, $p_{adj} < .001$) (Table 2). Additionally, pivots were also significantly heavier than backcourt players (median difference = 14.9 kg, $p_{adj} < .001$) and wing players (median difference = 22.9 kg, $p_{adj} < .001$). Backcourt players were significantly taller (median difference = 5 cm, $p_{adj} = .032$) and heavier (median difference = 8 kg, $p_{adj} = .030$) than wings. A two-way repeated-measures ANOVA on execution time data identified main effects for condition (planned, reactive), age group (adult, youth), and playing position (wing, backcourt, pivot). Execution times were shorter during the planned task than in the reactive task, with a mean difference of 182 milliseconds ($F(1, 86) = 344.41$, $p < .001$, $\eta^2_p = .80$). Adults were faster than youth, with a mean difference of 33 milliseconds ($F(1, 86) = 4.52$, $p = .036$, $\eta^2_p = .05$). Pivots were slower than backcourt and wing players ($F(2, 86) = 4.07$, $p = .020$, $\eta^2_p = .09$), with mean differences of 45 milliseconds ($p = .029$) and 50 milliseconds ($p = .033$), respectively. No significant interaction effects were found ($p > .05$).

Table 1. Demographics of the study population, per age group.

	Adult	**Youth**		
	***N* = 66**	***N* = 26**	***U***	***p***
Age (yrs)	24.00 (22.00–27.00)	17.00 (17.00–18.00)	1716.00	<.001*
Height (cm)	192.50 (189.00-196.00)	186.00 (183.00-196.25)	1116.00	.025*
Weight (kg)	95.90 (89.25–104.67)	83.75 (77.20–96.17)	1245.50	<.001*

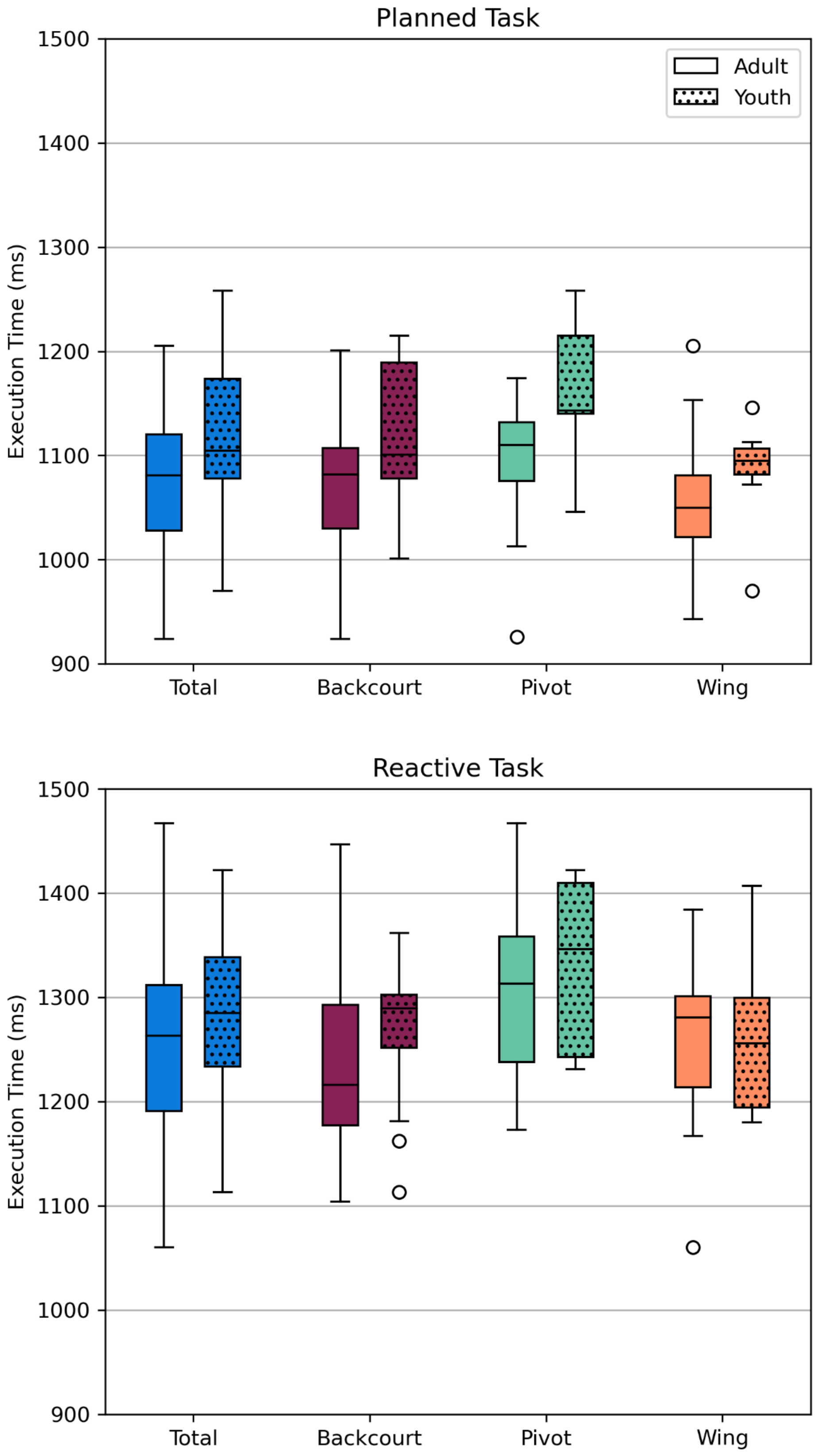
Note: values are median (Q1–Q3). *U*: Mann-Whitney U test result, *p*: p-value. All youth participants practised in the U19 handball division. Asterisks indicate significant differences ($p < .05$) between age groups.

Table 2. Demographics of the study population, per playing position.

	Backcourt ***N* = 47**	**Pivot** ***N* = 20**	**Wing** ***N* = 25**	***H***	***p***
Age (yrs)	22.00 (18.00–25.00)	24.00 (18.75–27.25)	23.00 (18.00–24.00)	1.49	.475
Height (cm)	192.00* (185.00–196.00)	196.50* (195.00–199.25)	187.00* (182.00–191.00)	28.34	<.001
Weight (kg)	94.00* (84.25–100.25)	108.90* (99.35–116.08)	86.00* (80.00–90.90)	36.29	<.001

Note: values are median (Q1–Q3). *H*: Kruskal-Wallis test result, *p*: p-value. Asterisks indicate significant differences ($p_{adj} < .05$) following Dunn's test for post hoc pairwise comparison with Bonferroni correction.

Figure 2. Execution time distributions for the planned and reactive tasks, per age group and playing position.



Based on identified differences in execution time with regards to condition, age group, and playing position, SnPM analyses were performed.

Condition

In the reactive condition, significant timing differences compared to the planned condition were found across all joints (Figure 3). These differences indicate that movement responses were delayed during the reactive task. SnPM also identified significant amplitude differences for all joints between the conditions (Figure 3). During the reactive task, players exhibited less hip flexion in two parts of the movement task, between approximately 0%-40% and 60%-90% of normalized time. Knee flexion was also significantly lower between approximately 0%-35% and 60%-70% of the movement response. Ankle dorsiflexion showed amplitude differences similar to the hip and knee, but also increased peak at around 65% of the movement response.

Age group

When comparing age groups, very few significant timing differences were identified at the hips and knees (Figure 4). Only the sagittal movement at the ankle appears to feature prevalent timing differences. Between the age groups, several significant amplitude differences were found across all joints (Figure 4). Youth players moved with less hip and knee flexion between 0%-30%, whereas they showed greater peak knee flexion at around 80% of the movement response.

Playing position

When comparing backcourt players to pivots (Figure 5A), significant timing differences were found for the hips around 70%-90% and for knees between approximately 45%-65% of the movement task. Moreover, SnPM found significant amplitude differences across all joints. Pivots moved with more hip flexion and ankle dorsiflexion, but with less knee flexion than backcourt players. When comparing wing players to pivots, significant timing differences were very prevalent in the hips and knees (Figure 5B). SnPM also identified significant amplitude differences, with pivots moving with more hip flexion than wing players around 65%-100% of the movement response. In turn, wing players moved with more knee flexion in two parts of the movement, around 40%-60% and 70%-100% of normalised time. Wing players also showed greater ankle dorsiflexion than pivots, especially for the peak at around 60% of the movement response.

Figure 3. Kinematic comparison between planned and reactive tasks using statistical nonparametric mapping. Data is pooled over age groups and playing positions. Waveforms represent average hip/knee/ankle flexion for the ipsilateral leg in the movement to the left (light #1) and to the right (light #2).

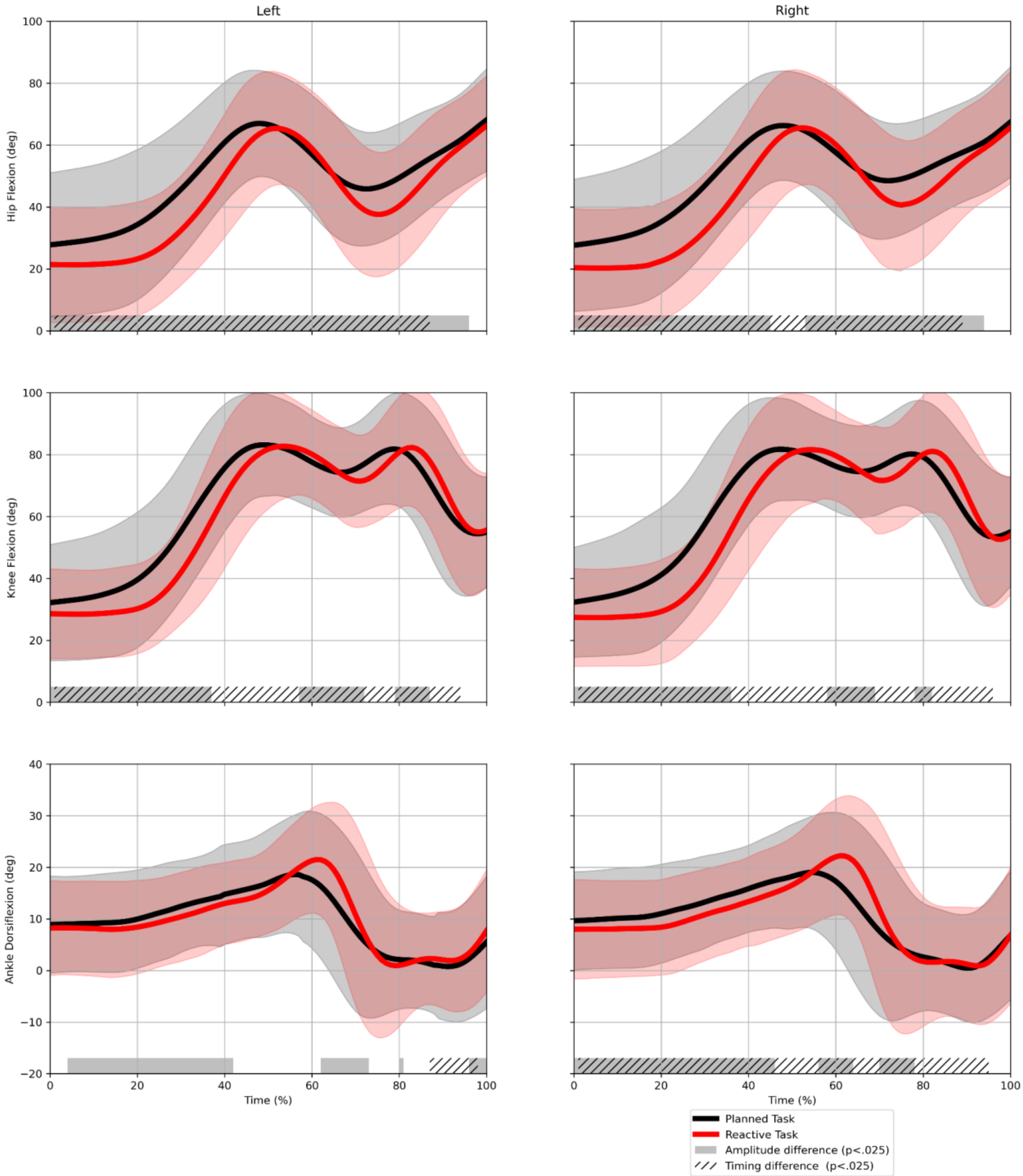


Figure 4. Kinematic comparison between adult (N = 66) and youth players (N = 26) using statistical nonparametric mapping. Data is pooled over conditions and playing positions. Waveforms represent average hip/knee/ankle flexion for the ipsilateral leg in the movement to the left (light #1) and to the right (light #2).

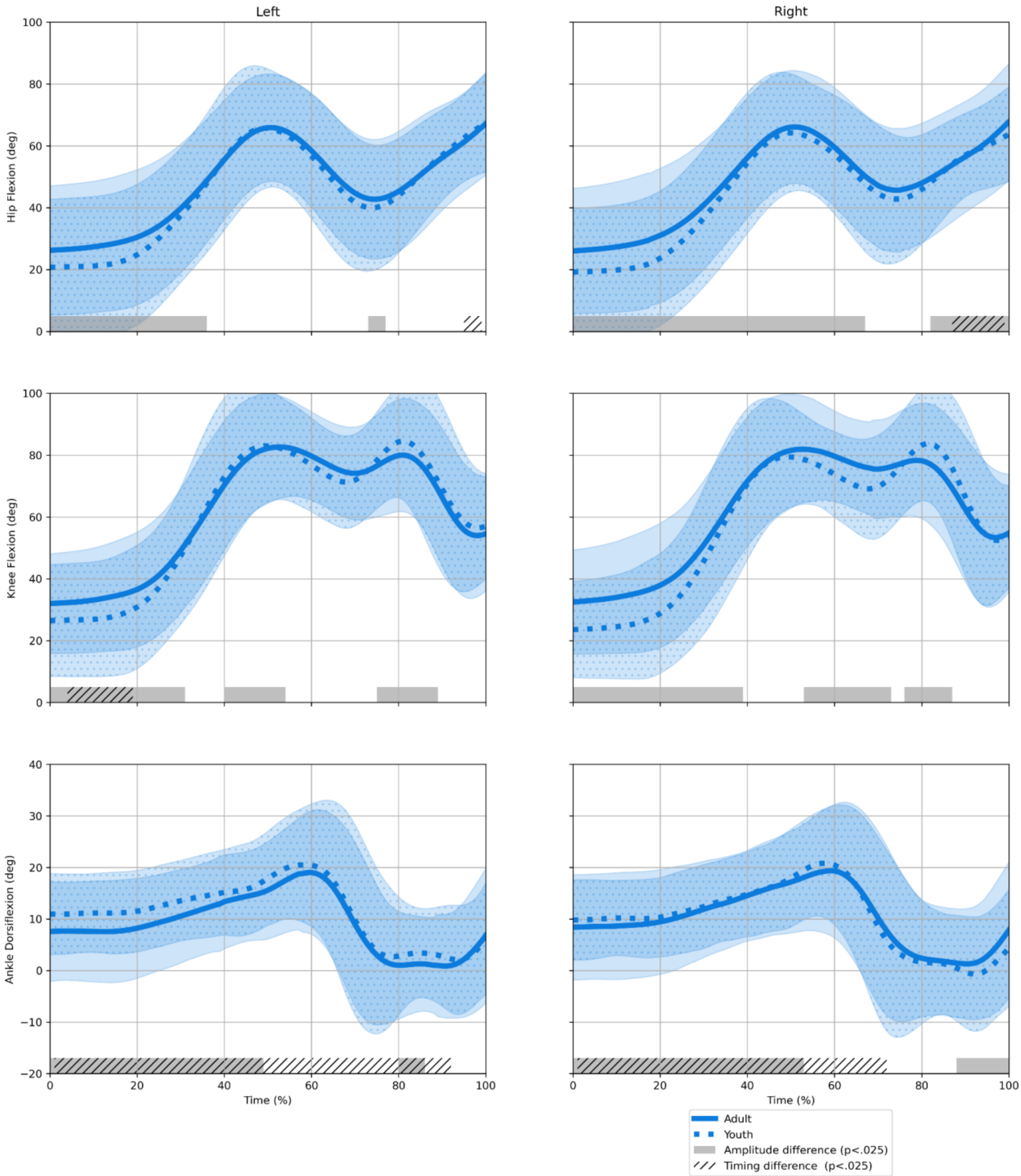
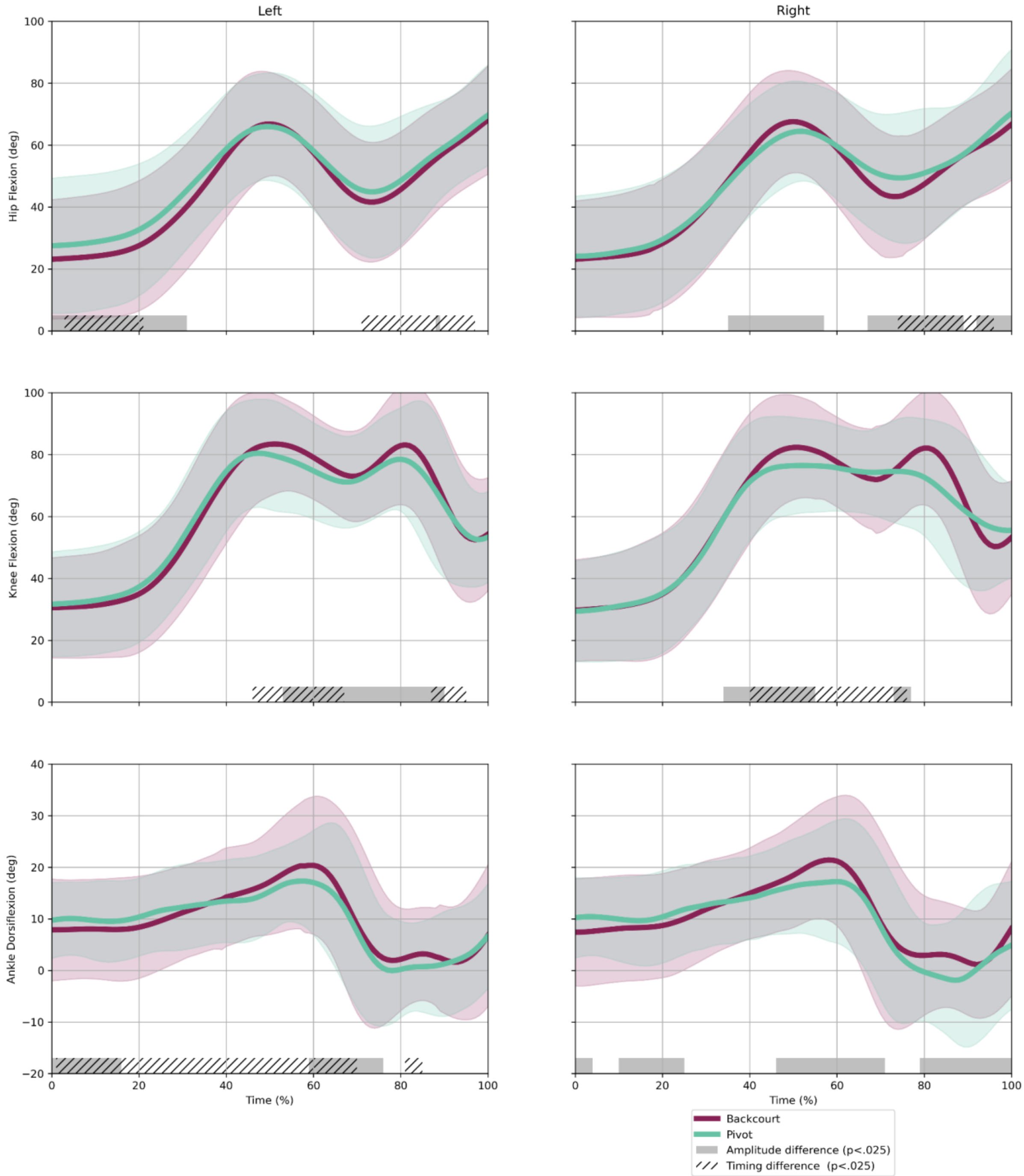
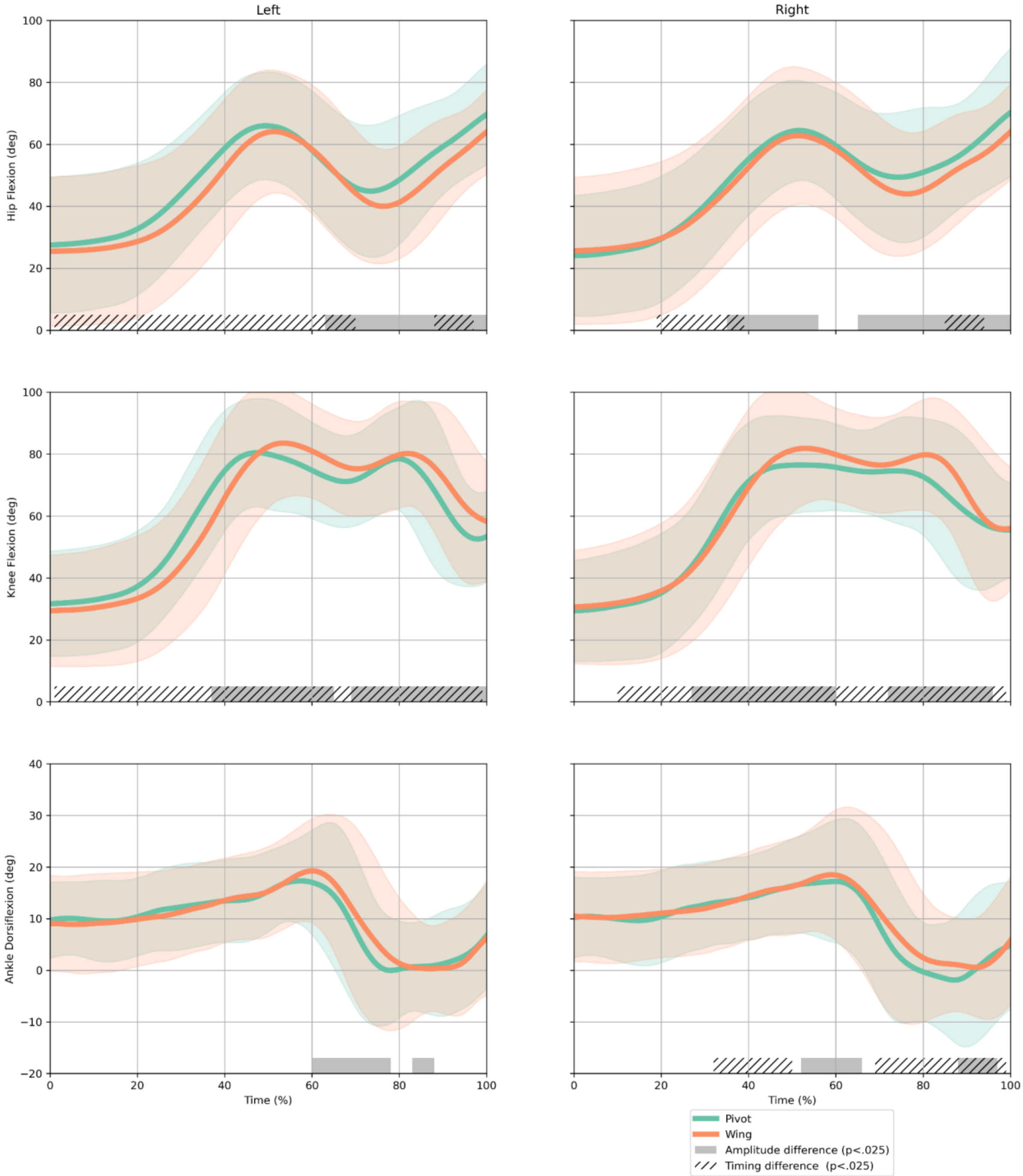


Figure 5. Kinematic comparison between A) backcourt ($N = 47$) and pivot ($N = 20$); and B) wing ($N = 25$) and pivot ($N = 20$), using statistical nonparametric mapping. Data is pooled over conditions and age groups. Waveforms represent average hip/knee/ankle flexion for the ipsilateral leg in the movement to the left (light #1) and to the right (light #2).

A



B


Left
Right
Hip Flexion (deg)
Knee Flexion (deg)
Ankle Dorsiflexion (deg)
Time (%)
Time (%)
Pivot
Wing
Amplitude difference (p<.025)
Timing difference (p<.025)

Discussion

This study assessed the execution time and kinematic performance of elite handball players in planned and reactive agility tasks. The main objective was to investigate how execution times and kinematics change to the reactive task between the different age groups and playing positions and three main findings emerged. First, during the reactive condition, the handball players executed the task significantly slower and moved with significant amplitude differences in the lower extremity joints, including less hip flexion. Second, the adult handball players were significantly faster than the youth and the adults moved with significant amplitude differences compared to the youth, notably in hip and knee flexion. Third, pivots were slower in performing the task than backcourt and wing players, and pivots also showed significant differences in the movements of their lower extremity joints compared to the other playing positions, including less knee flexion.

Condition

Analysis of execution time identified a main effect of condition, with significantly higher execution times during the reactive task compared to the planned task. This difference embodies the impact of random stimuli presentation on task execution. The planned task featured a predefined sequence of stimuli, providing a relatively high level of control to the player (Chaput et al. 2024). Switching the light sequence from planned to random increased motor-cognitive load, which slowed down task performance. This result is consistent with previous research on agility or changes-of-direction (Fasold et al. 2023, Büchel et al. 2022, Spasic et al. 2015). From a neurocognitive perspective, the observed increase in execution times during the reactive task reflects the added cognitive demands imposed by the unpredictable nature of the stimulus presentation and highlights the interplay between visual processing, cognitive decision-making, and motor responses in handball-specific situations.

SnPM analysis of the kinematic data found timing differences between the conditions, indicating that players moved with significantly delayed movements in the reactive task. These timing differences are most pronounced in the hip and knee joints, from approximately 0% to 90% of the movement response (Figure 3). The increased execution time in the reactive task, in addition to the prevalent timing effects, suggests that there was a change in *reaction time* (i.e., the time from stimulus presentation to movement initiation). This finding is consistent with that of previous research that identified a delayed reaction time to initiate movement when stop-signals were introduced to a lateral stepping task (Heuvelmans et al. 2024).

Age group

This study also identified a main effect of age group. The adult handballers were faster than the youth players. This indicates that, despite being physically larger in average height and weight (Table 1), the adult players could outperform the youth players in the agility tasks. This finding may potentially be related to greater muscle mass in the adult group, as age has been associated with increased muscle mass in elite handball players (Zsakai et al. 2024). Considering quick and reactive changes-of-direction as a key demand in handball (Büchel 2024), the discriminatory validity of the developed agility test can be confirmed, since players with higher playing level outperformed those from lower level. This finding is in line with previous research in high-level handball that described how adult players run faster, jump higher, throw faster, and have better aerobic fitness (Wagner et al. 2022). When implemented as a screening or monitoring tool alongside other diagnostic tests, this protocol may therefore prove effective for talent selection or performance optimization in elite handball.

SnPM analysis of the kinematic data found differences in the movements between the age groups (Figure 4). The adult handball players, who were on average faster in task execution than their youth counterparts, moved with no prominent timing difference in neither the hip nor the knee joints. This finding indicates that adults did not have substantial performance gains by initiating their movements earlier, otherwise the SnPM results would have resembled the persistent timing differences between conditions (Figure 3). Given the minimal timing differences and the linear registration procedure (i.e., time normalisation), the superior performance of adult players is more likely due to rapid movement execution rather than faster movement initiation. These results further support the association between handball player age and speed (Wagner et al. 2022). SnPM analysis of the kinematic data between the age groups also identified significant amplitude differences in the joint movements. Overall, the adult players moved with increased hip and knee flexion early in the movement suggesting that adults adopted a starting posture that was more crouched. Such adaptations of body posture have been reported to be beneficial for higher ground reaction forces, which may allow for a faster movement in the task due to enhanced acceleration (Hoang & Reinbolt, 2012). However, adults showed lower peak knee flexion than the youth players later in the movement, indicating that the youth players employed more of the knee flexion range-of-motion of their leading leg during deceleration. Existing research recognises the role of a *penultimate* step in decelerating for a change-of-direction and the effect of reduced planning time in reactive conditions (Mulligan et al. 2024). Together these findings potentially hint at differences in acceleration/deceleration strategies between youth and adult players. Further work is needed to better understand age-related differences in movement strategies in high-level handball.

Playing position

Pivots were slower in executing the task than backcourt and wing players, regardless of condition. While previous studies compared agility performances between offence and defence players, no study so far compared agility performance in a large sample of handball players according to playing positions. The execution time related differences indicate that backcourts and wings outperform pivots in quick changes of direction, in both planned and reactive scenarios.

In handball, the role of a pivot is to travel along the opponent's goal area line to create openings for attack on goal. Here, pivots typically need to defend their position in front of the goals and move in smaller spaces compared to wings and backcourts (Karcher et al. 2014). This role features a lot of physical contact with the defenders, hence elite pivots spend a significant amount of time in high-intensity activities with substantial strength requirements (Font et al. 2021, Póvoas et al. 2014). Consequently, pivots usually have higher body mass than other playing positions (Table 2) (Bøgild et al. 2020), and they are also reported to have greater upper body strength when assessed by one-rep-max in bench press (Haugen et al. 2016). In contrast, backcourt or wing players' tasks involve more running and sudden deceleration (Büchel et al. 2024). Previous research revealed that wings generally cover the longest distance at high speed or by sprint (Carton-Llorente et al. 2023, Font et al. 2021). While backcourt players have the highest overall running pace and centre backs in particular endure more high-intensity decelerations (Manchado et al. 2021, Font et al. 2021). Since our test particularly tested the ability to move quickly, the superior performance of backcourts and wings may in part be based on the position-specific running demands. Furthermore, backcourt players typically face higher cognitive demands in game situations, as they perform more passes, more shots and more jumps per game (Saal et al. 2023). The greater exposure to situations requiring motor-cognitive decision-making may contribute to their ability to perform the investigated agility tasks more quickly. These inherent differences between playing positions from a motor-cognitive perspective might explain why pivots were slower to perform the agility task than backcourt and wing players. Following the present results, researchers have previously argued that the differences in on-court demands are reflected in physiological and physical differences between playing positions and, therefore, they surmise that strength and conditioning practices should be individualized and position-dependent (Haugen et al. 2016). Similar observations were made in basketball players, were the individuals also face highly position-specific demands (Scanlan et al. 2014)

In addition, SnPM analysis revealed that playing positions also showed significant differences in their movement behaviour. The most striking finding reveals that pivots execute movements with less knee and ankle flexion but increased hip flexion compared to backcourt and wing players. The first suggests that pivots move with a distinct movement strategy that is less crouched or low to the ground. Since a less crouched position opposes the generation of ground reaction forces, this posture may contribute to reduced agility performance in pivots (Hoang & Reinbolt, 2012). It might be speculated that body composition aspects such as the height, weight and mobility of the pivots may require an adaptation of movement behaviour. Further, our tests suggest that pivots employ more hip hinge when reaching for the light in the final part of the movement. Considering the standardized height of the agility task targets, the increased hip hinge may result from the differences in body height of 4.5 to 9.5 cm between pivots, wings and backcourts. These findings highlight the influence of handball positions and physical characteristics on agility performance. Coaches and trainers should consider these positional differences when designing training programs, tailoring exercises to improve agility and movement efficiency according to each player's role and body type.

Limitations

The light-based stimuli used in this investigation were not sport-specific; when playing a match, handball players typically respond to more complex stimuli like changes in body posture of the opponent. Previous research has shown that agility assessments using light-based and sport-specific stimuli test different qualities of team sport athletes (Scanlan et al. 2016). The light-based stimuli obviously lack any information used for affordance perception, however, when compared to more traditional arrow-stimuli on a TV, the lights do present a greater perceptual challenge to the player. Due to their different positions; diagonally in front and in the periphery on both sides, the lights prompt different visual behavioural strategies in the players. The choice of stimuli for the current study was based on standardization and feasibility concerns. Future research should attempt to improve the athlete-environment coupling by designing experiments with sport-specific stimuli.

In comparing kinematics between age groups, significant timing differences were identified for ankle dorsiflexion (Figure 4). However, the kinematic waveforms give no clear indication of this timing difference nor its direction. This paradoxical finding may be due to the methodology used. The SnPM analysis in this study used nonlinear registration with warp functions. Warp functions rely on waveform geometry to produce displacement fields that quantify potential timing differences (Tucker et al. 2013). In this instance, the ankle dorsiflexion features few pronounced slope characteristics (i.e., peaks and valleys) and therefore may have affected the accuracy of the warping procedure.

Conclusion

This study highlights key kinematic and performance differences among elite handball players when executing agility tasks under planned and reactive conditions. Adult players were faster than youth players and moved with different hip and knee flexion, potentially hinting at differences in acceleration/deceleration strategies. Backcourt players and wings were faster than pivots, who moved with distinct hip, knee, and ankle flexion which are possibly related to differences in body composition. The findings emphasize the impact of motor and cognitive demands on agility performance and provide valuable insights into age and playing position-dependent differences in elite handball players. Moreover, these findings reinforce the value of wearable inertial sensors in assessing athlete performance. Future research should further explore their integration into comprehensive athlete monitoring, assessing their effectiveness in tracking of performance and screening for injury risk.

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