The influence of an anterior cruciate ligament injury on behavioral and cortical dynamics associated with superior pass accuracy in football

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Declaration of authorship

I hereby confirm that I have read and accepted the PhD regulations of the Faculty of Sciences at the University of Paderborn (no. 50 / 12, dated 11-12-2012). Additionally, I affirm that the work presented in this thesis is original and solely the result of my own work, except where explicitly acknowledged. This work has not been submitted, in whole or in part, for any other degree or qualification at any university. All content and ideas derived from other sources are cited appropriately to the best of my knowledge and belief. Furthermore, I declare that the research presented in the included studies was conducted without any commercial or financial relationships that could be perceived as a potential conflict of interest.

Dağhan Pişkin, September 27, 2024

Acknowledgements

My passion of understanding and researching human movement with physiotherapy background embarked me on an adventure to Germany six years ago. I still remember motivating myself saying “Go after your dreams…”, as this passion occasionally had to strive with the feeling of leaving everything…

It’s been a way of ups and downs, challenges and cheers, but it’s thoroughly worth. Having completed my dissertation today, I’m proud to see where I am, to contribute to the research realm of human movement, and more passionate than yesterday as a growing scientist to run after knowledge and help people.

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Abstract

Football is one of the most played sports worldwide and is significantly impacted by anterior cruciate ligament (ACL) injuries. The existing literature indicates that athletes experience considerable declines in performance following an ACL injury, which are accompanied by alterations in various domains of the central nervous system (CNS). However, current evidence lacks insights into the specific consequences of these alterations within the context of football. The present dissertation aims to investigate the potential effects of an ACL injury on pass accuracy - a critical determinant of success in football - from a neuroscientific perspective. Initially, a literature review was conducted to compile neurophysiological and related neurocognitive changes observed in athletes after an ACL injury. The review highlighted the presence of visuospatial and attentional deficits while revealing a paucity of sport-specific tasks used in experimental paradigms. In Study I, a passing task compatible with mobile electroencephalography (EEG) was designed and its reliable cortical correlates were identified using a repeated-measures design. The consistent activity of posterior and frontal brain regions indicated the prominence of visuospatial and attentional processes during target-directed passing. Study II explored how modulations in these dynamics promote pass accuracy within a novice-expert paradigm. The findings extrapolated that experienced football players sustain a more accurate passing behavior through refined visual and attentional strategies. Finally, Study III investigated differences in kicking behavior and associated cortical activity between healthy and injured players during passing. The results suggested sensorimotor changes and their compensation through increased attentional focus at the expense of visuospatial processing in injured players, which may ultimately hinder their ability to effectively integrate task-related information into neural networks. Collectively, this cumulative work illustrates how the neurophysiological consequences of an ACL injury can impact cortical processes related to skilled passing in football and underscores the potential for further research in the field of sports-related injuries.

Zusammenfassung

Fußball gehört zu den populärsten Sportarten weltweit. Durch das dynamische Anforderungsprofil werden Spielerinnen und Spieler erheblich durch Verletzungen des vorderen Kreuzbands (VKB) beeinträchtigt. Bestehende Evidenzen weisen darauf hin, dass Athleten nach einer VKB-Verletzung signifikante Leistungseinbußen erleiden, die u.a. auf Veränderungen der Funktion und Struktur des zentralen Nervensystems zurückzuführen sind. Allerdings fehlen in den aktuellen Studien spezifische Erkenntnisse über die Folgen dieser Veränderungen im Kontext des Fußballs. Die vorliegende Arbeit zielt darauf ab, die potenziellen Auswirkungen einer VKB-Verletzung auf die Passgenauigkeit aus neurowissenschaftlicher Perspektive zu untersuchen. Dafür wurde zunächst eine Literaturrecherche durchgeführt, um bestehende Erkenntnisse zu neurophysiologischen und damit zusammenhängenden neurokognitiven Veränderungen bei Athleten nach einer VKB-Verletzung zusammenzufassen. Diese Recherche wies insbesondere auf visuell-räumliche und aufmerksamkeitsbezogene Defizite hin. Es stellte sich jedoch auch heraus, dass es an Erkenntnissen zu sportartspezifischen Aufgaben in experimentellen Paradigmen mangelt. Im Zuge dessen wurden drei experimentelle Studien durchgeführt. In Studie I wurde eine Passaufgabe entwickelt, während der mittels mobiler Elektroenzephalografie (EEG) kortikale Daten erhoben wurden, um durch ein Messwiederholungsdesign reliable kortikale Korrelate des Passens zu identifizieren. Die Beobachtungen zeigten, dass posteriore und frontale Hirnareale während des Passens konsistent aktiv sind und die Rolle visuell-räumlicher und aufmerksamkeitsbezogener Prozesse beim zielgerichteten Passen hervorheben. Studie II untersuchte, inwiefern die sportartspezifische Expertise diese Prozesse moduliert, indem Experten und Novizen in der Passaufgabe verglichen wurden. Die Ergebnisse legten nahe, dass erfahrene Fußballspieler präziser passen und Unterschiede in den frontalen und posterioren Aktivitäten aufzeigen. Diese Beobachtungen deuteten auf eine optimierte visuelle und aufmerksamkeitsbezogene Strategie bei der Passausführung hin. Schließlich untersuchte Studie III Unterschiede im Passverhalten und in der kortikalen Aktivität zwischen gesunden und im VKB verletzten Spielern beim Passen. Die Ergebnisse deuteten veränderte Bewegungsstrategien und Aktivierungsgrade in frontalen und posterioren Hirnarealen zwischen den Gruppen an. Dies lässt darauf schließen, dass verletzungsinduzierte propriozeptive Veränderungen in verstärkter Aufmerksamkeitsfokussierung auf Kosten der visuell-räumlichen Verarbeitung resultieren. Dies könnte letztendlich die Fähigkeit verletzter Spieler

beeinträchtigen, aufgabenbezogene Informationen effektiv in neuronalen Netzwerken zu integrieren. Zusammenfassend verdeutlicht diese kumulative Arbeit, wie die neurophysiologischen Folgen einer VKB-Verletzung die kortikalen Prozesse beeinflussen können, die mit der Fertigkeit des Passens im Fußball verbunden sind, und unterstreicht das Potenzial für weiterführende Forschung im Bereich sportbedingter Verletzungen.

Table of contents

List of publications

This cumulative dissertation is based on the following studies:

Literature view	Piskin, D., Benjaminse, A., Dimitrakis, P., & Gokeler, A. (2022). Neurocognitive and neurophysiological functions related to ACL injury: a framework for neurocognitive approaches in rehabilitation and return-to-sports tests. *Sports Health*, *14*(4), 549-555.
Study I	Piskin, D., Büchel, D., Lehmann, T., & Baumeister, J. (2024a). Reliable electrocortical dynamics of target-directed pass-kicks. *Cognitive Neurodynamics*, 1-15.
Study II	Piskin, D., Müller, R., Büchel, D., Lehmann, T., & Baumeister, J. (2024b). Behavioral and cortical dynamics underlying superior accuracy in short-distance passes. *Behavioural Brain Research*, *471*, 115120.
Study III	Piskin, D., Cobani, G., Lehmann, T., Büchel, D., & Baumeister, J. (2024c). Cortical changes associated with an anterior cruciate ligament injury may retrograde skilled kicking in football: Preliminary EEG Findings. *Submitted for publication.*

List of figures and tables

List of abbreviations

ACL	Anterior cruciate ligament
ACLR	Surgical reconstruction of an ACL
CNS	Central nervous system
EEG	Electroencephalography
EMG	Electromyography
ERP	Event-related potential
ERSP	Event-related spectral perturbations
fMRI	Functional magnetic resonance imaging
fNIRS	Functional near-infrared spectroscopy
IC	Independent component
ICC	Intraclass correlation coefficient
IMU	Inertial measurement unit
KOOS	The Knee and Osteoarthritis Outcome Score
LPI	Lateral Preference Inventory
MAS	Marx Activity Scale
MoBI	Mobile brain imaging
MRI	Magnetic resonance imaging
MSE	Multiscale entropy
RTP	Return to play
SE	Sample entropy
SPM	Statistical parametric mapping
TMS	Transcranial magnetic stimulation
UEFA	Union of European Football Associations
VAS	Visual Analogue Scale

1. BACKGROUND

Football is one of the most widely played sports globally, yet injuries represent a significant burden for the teams, adversely affecting sporting success (Hägglund et al., 2013; Eirale et al., 2013). Among these, ACL injuries are particularly prevalent (Grassi et al., 2020; Schiffner et al. 2018) and often result in diminished performance after return to play (RTP), with severe consequences for football players (Barth et al., 2019; Szymski et al., 2023; Walden et al., 2016). The literature increasingly reports a trend towards earlier career termination due to a decreased level of play post-injury (Borque et al., 2024; Della Villa et al., 2021; Manojlovic et al., 2024). Therefore, the optimization of return-to-sports / play protocols, as well as preventative and therapeutic approaches, remains focal in the current ACL research (Davies et al., 2017; Gokeler et al., 2018, 2022; Johnson et al., 2016; Meredith et al., 2021; Sandon et al., 2015; Zaffagnini et al., 2015).

In recent years, research has increasingly approached ACL injuries from a neurophysiological perspective (An et al., 2019; Baumeister et al., 2008, 2011; Gokeler et al., 2021; Onate et al., 2019). Numerous studies have reported neuroplastic changes following ACL injury, attributing these to attenuated sensory input (for review: Neto et al., 2019). While mechanoreceptors in an intact ACL provide accurate proprioceptive input to the sensory system (Banios et al., 2022), a reconstructed or residual ACL can pursue this function only partially (Dhillon et al., 2012). Consequently, the diminished sensation of static and dynamic joint position is supplemented by compensatory strategies detectable across various domains of the CNS, both at rest and during movement (Baumeister et al., 2008, 2011; Criss et al., 2020; Lehmann et al., 2021; Zarzycki et al., 2018). Neuroimaging studies have frequently documented increased attentional demands (Baumeister et al., 2008, 2011; Criss et al., 2020) and reliance on visual cues (Criss et al., 2020; Grooms et al., 2017; Lehmann et al., 2021) as compensatory mechanisms.

In sport scenarios, interacting with a dynamic environment requires the perception and processing of external stimuli, prediction of the upcoming scenes, and production of motor responses to achieve successful outcomes. This situational awareness is underpinned by complex cognitive processes, including the domains of attention, inhibitory control, working memory, cognitive flexibility and decision-making

(Diamond, 2013; Hunzinger & Swanik, 2019). The concurrent cognitive and sensorimotor demands during complex movements share the limited processing capacity of an individual (Buschman & Kastner, 2015). If one demand exploits more cortical resources, it may lead to performance decrements in the other domain (Kim et al., 2016). Structural inference, particularly when the same cortical areas are engaged, can deteriorate both cognitive and motor performance depending on the task (Papegaaij et al., 2017). The reliance on attentional and visual resources in individuals with ACL injuries has been corroborated by the increased activity and connectivity of frontal and posterior cortices during motor tasks (Baumeister et al., 2008, 2011; Criss et al., 2020; Grooms et al., 2017; Lehmann et al., 2021). These regions play crucial roles also in cognitive and visual domains (Erickson et al., 2019; Fuster, 2002; Ridderinkhof et al., 2004; Worden et al., 2000), suggesting that tasks with cognitive demands may constrain available cortical resources, leading decreased cognitive or motor performance in injured individuals. Burcal et al. (2019) postulate that increased cognitive load impairs motor performance in ACL-injured individuals, particularly in dual task paradigms, with motor task complexity being a key determinant for the extent of impairment. However, other studies report negligible effects on cognitive performance or no impairment, indicating that the strategies employed may be task-dependent (Lion et al., 2018; Mohammadi-Rad et al., 2016).

The impact of cognitive load on motor performance has been predominantly investigated using segregated cognitive and motor tasks in behavioral studies, where the cognitive task serves as a distractor (Lion et al., 2018; Mohammadi-Rad et al., 2016; Negahban et al., 2009, 2013; Shi et al., 2018; Stone et al., 2018). However, in real-world sports situations, cognitive processes are integral to movement and are essential for achieving goals (e.g., tracking and running to the ball; Herold et al., 2018; Schott, 2015). Recent advancements, particularly in mobile EEG, have enabled studies to extend neurophysiological investigations from simple to more dynamic tasks (Giesche et al., 2022; Lehmann et al., 2021; Miao et al., 2017; Sherman et al., 2023). However, the understanding of cognitive load in real sport tasks remains underdeveloped, limiting our comprehension of the neurophysiological consequences of ACL injuries in sport-specific contexts.

In football, kicking is a predominant movement used to forward or pass the ball, as well as to score goals. These actions require the integration of visuospatial (e.g., detecting the target and determining the kicking direction) and proprioceptive information (e.g., leg positioning) into a coordinated motor behavior, demanding significant cognitive and motor resources (Davids et al., 2000). While the biomechanics of kicking have been extensively studied (Amiri-Khorasani et al., 2011; Blair et al., 2018; Manolopoulos et al., 2006; Kellis & Katis, 2007; Ross et al., 2004), only one EEG study has examined its cortical dynamics up to now (Palucci-Vieira et al., 2022). This study highlighted the importance of the posterior and frontal cortices in kicking, particularly in relation to visual and attentional processes, which were found to correlate with key performance metrics such as ball velocity and radial error (Palucci-Vieira et al., 2018; van den Tillaar & Ulvik, 2014). Given that individuals with ACL injuries compensate for weakened sensory information by relying more on these cortical areas, it is plausible that the cortical sources required for effective kicking may interfere with compensatory strategies, potentially impairing performance in injured football players.

Performance decrements may manifest either in cognitive or motor domain during dual-tasking paradigms. The structural interference between compensation and task demands during kicking could lead to either adequate sensory compensation at the cost of restricted resources for target and environmental interaction or vice versa, using resources to process external information while insufficiently compensating for sensory deficits (Papegaaij et al., 2017). This potential conflict might underlie the observed decrease in completed passes in the RTP and post-RTP seasons, a statistical indicator of reduced athletic performance after ACL injury (Niederer et al., 2018). The electromyography (EMG) study of Cordeiro et al. (2015) provides the only existing evidence of behavioral changes in ACL-reconstructed football players during kicking. While their findings show differences in muscle activation and kinematics between healthy and injured players, the lack of target interaction in their experimental setup may have mitigated the demands of kicking, reducing performance only to an ability to generate speed. Thus, it remains unclear whether cortical mechanisms that enhance kicking accuracy may be compromised by a conflict between task demands and compensatory strategies following ACL injury.

To elucidate whether these neurophysiological drawbacks of an ACL injury lead to a decreased kicking performance, it is crucial to primarily understand the dynamics underlying skilled performance. Examining changes in cortical activity as players progress from a novice to expert level may reveal if injury-related adaptations occur within the neural processes that contribute to higher level performance. Mobile EEG studies have shown how expertise in sports can be translated into cortical dynamics associated with skilled motor behavior in other self-paced sporting tasks, such as golf-putting (Baumeister et al., 2008), dart-throwing (Cheng et al., 2015) and rifle-shooting (Doppelmayr et al., 2008; Hung et al., 2008). A meta-analysis by Filho et al. (2021), synthesizing findings from novice-expert and optimal / suboptimal performance studies, suggests that optimal performance is characterized by a "relaxed but focused brain", with enhanced attention and sensorimotor efficiency. This focused cognitive state is sustained across pre-, during and post-movement stages. However, the study of Palucci-Vieira et al. (2022) suggests that the neural mechanisms underlying enhanced kicking performance may be more complex, involving specific brain responses at particular phases of the kicking process. This underscores the significance of task-specificity (Barros et al., 2017) and the temporal dynamics of neural processes in skilled performance. Moreover, while visuospatial processes are known to be influenced by injury, their modulation by sport-specific expertise remains unexplored. To determine if the neurophysiological consequences of an ACL injury overlap with the neural correlates of expert performance, a more detailed analysis of dynamics specific to kicking is required.

Based on this background, the present dissertation aims to investigate cortical dynamics associated with skilled kicking in football and to determine how ACL injuries may affect these dynamics and kicking performance in injured players. Identifying potential deficits could provide a neurophysiological basis to investigate kicking performance prospectively, elaborate diagnostics and interventions with greater specificity, and ultimately contribute to a higher levels of performance following injury.

1.1. Anterior cruciate ligament injuries

1.1.1. Anatomy, stabilizer and proprioceptive function of the anterior cruciate ligament

The ACL is a dense connective tissue composed of primarily collagen fibers, which impart significant tensile strength essential for stabilizing the knee joint. Anatomically, the ACL originates from the posteromedial aspect of the femoral condyle and inserts into the anterior intercondylar eminence of the tibial plateau **(Fig. 1)**. The ligament is composed of two distinct bundles: the anteromedial and posterolateral. These bundles play critical roles in preventing the anterior translation of the tibia relative to the femur during knee flexion and hyperextension, respectively. Additionally, due to their cruciate structure, they also contribute to the rotational stability of the knee. During dynamic activities such as running, jumping or cutting, these biomechanical properties enable the ACL to resist substantial forces and maintain joint stability (Amis & Dawkins, 1991; Woo et al., 1991).

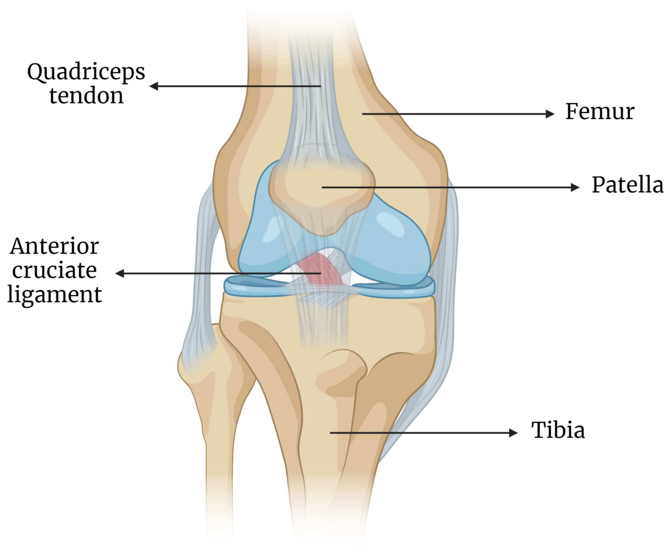

Fig. 1: Anatomy of the knee

Beyond its mechanical stabilizing function, the ACL plays a vital role in the proprioception of the knee. Proprioception refers to the body's ability to sense position and movement of its parts, allowing individuals to perceive the location and orientation of their limbs in space without the need for visual input. This afferent sensory information is transmitted to the nervous system primarily via mechanoreceptors located in muscle spindles and connective tissues throughout the body (Gandevia, 2001). In cadaveric studies, specialized mechanoreceptors, including Ruffini endings, Pacinian corpuscles, and Golgi tendon organ-like receptors have been identified within the specimens of the ACL (Banios et al., 2022), These receptors are responsible for detecting static joint position, intra-articular pressure, and joint motion, particularly in terms of velocity and amplitude (Hillier et al., 2015). Given the critical nature of this sensory information, the ACL significantly contributes to sensorimotor control with its proprioceptive functions (Baumeister et al., 2013).

1.1.2. Mechanisms of an anterior cruciate ligament injury

ACL injuries are caused by complex mechanisms that involve both contact and non-contact scenarios (Boden et al., 2000). Understanding these mechanisms is crucial for developing effective preventative and rehabilitative strategies. Non-contact mechanisms, which account for 55 to 70% of all ACL injuries, are particularly prevalent in team-sports (Boden & Sheehan, 2022; Chia et al., 2022). The main mechanism involves a combination of knee valgus, anterior translation, and internal or external rotation of the tibia (Fleming et al., 2001). Vigorous eccentric activity of the quadriceps, combined with valgus alignment and/or knee abduction, increases strain within the ACL, making axial loading the primary shear force responsible for injury. Movements such as deceleration, pivoting, or landing from a jump are typical scenarios that strain the ACL and lead to injury (**Fig. 2-A**; Boden & Sheehan, 2022)

Contact injuries, although less common, occur mainly in sports that involve physical collisions such as rugby and football (Boden & Sheehan, 2022; Chia et al., 2022). These injuries result from direct blows to the knee or shank, which generate abnormal forces that exceed the tensile strength of the ACL. A typical contact mechanism involves a lateral blow to the knee while the foot remains planted on the ground. The force drives the knee into a valgus position while the femur internally rotates, causing the ACL to stretch beyond its tensile threshold and consequently tear. Another contact scenario includes hyperextension of the knee due to direct anterior impact on tibia, which facilitates translational forces and may also result in a tear (**Fig. 2-B**; Boden et al., 2000). Despite their lower prevalence, contact ACL injuries are more likely to be associated with concomitant injuries. The external forces sufficient to tear the ACL often cause accompanying pathologies, particularly chondral damage and collateral ligament tears (Salem et al., 2018).

Distinguishing between the mechanisms of non-contact and contact ACL injuries highlights the importance of addressing both internal and external risk factors in prevention and treatment (Bahr & Krosshaug, 2005). Non-contact injuries are largely influenced by internal predisposing factors, such as anatomical features (e.g., knee valgus angle, femoral notch), physical characteristics (e.g., high body mass index), neuromuscular control (e.g., poor proprioception), and neurocognitive skills (e.g., errors in information processing). Consequently, preventative and therapeutic approaches focus on modulating these aspects through interventions such as neuromuscular training, technical skill improvement, and the incorporation of cognitive aspects (Dai et al., 2018; Emery & Pasanen, 2019; Gokeler et al., 2021). In contrast, contact injuries are driven by external forces such as impacts (e.g., collisions), environmental conditions (e.g., playing surface), and playing style (e.g., aggressive play, inadequate rule enforcement and illegal tackles). Prevention strategies for these injuries typically involve protective equipment, strict rule enforcement, environment adjustments, and player education (Marshall et al., 2002; Jones & Rocha, 2011). Analyzing injury mechanisms within specific sports allow for the implementation of tailored approaches that significantly reduce the incidence and reoccurrence of ACL injuries, ultimately promoting safer sports participation.

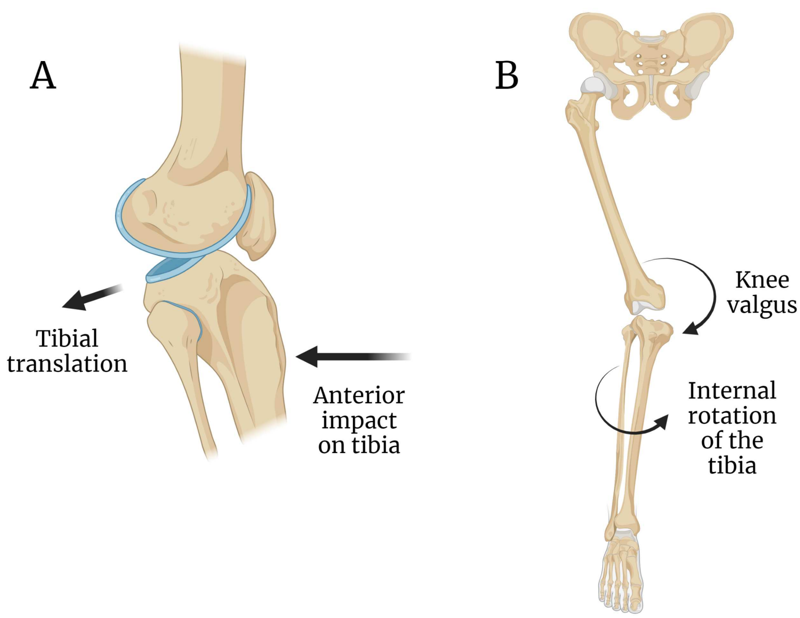

Fig. 2: Contact (A) and non-contact (B) mechanisms of anterior cruciate ligament injuries

1.1.3. The treatment of anterior cruciate ligament injuries

Treatment options for ACL ruptures generally fall into two main categories: conservative (non-surgical) and surgical, each with distinct advantages and considerations. The choice between these approaches depends on several factors, including the patient's age, activity level, expectations for post-operative function, participation in sports, degree of knee instability, and the presence of any concomitant injuries (Delince & Gaphil, 2013; Frobell et al., 2013).

Conservative management of ACL ruptures focuses on non-surgical interventions such as physical therapy, rehabilitation, bracing, activity modification and pharmacological treatments (Focke et al., 2020; Kostogiannis et al., 2007; Park et al., 2021). A well-structured rehabilitation program that takes the mechanism of the rupture and any associated injuries into account is the cornerstone of conservative treatment. These programs typically include various modalities aimed at reducing pain and swelling (such as electrotherapy, cryotherapy, and elevation), restoring range of motion, strengthening the muscles of the lower extremity, and enhancing proprioception (Eitzen et al., 2010; Ellis et al., 2017).

Surgical reconstruction of the ACL (ACLR) is indicated in cases of complete ligament rupture, particularly in young and active individuals who wish to return to sports that involve pivoting and cutting movements, or when there is a concomitant injury that heightens the risks of poor outcomes (Rodriguez et al., 2021). The most common surgical procedure for ACLR involves replacing the torn ligament with a graft, which may be an autograft, allograft, or a synthetic graft. Autografts are harvested from the patient's own tissues, mostly from the patellar, hamstring, or quadriceps tendon, while allografts are obtained from a donor tissue (Cerulli et al., 2013). Although there are conflicting reports, allografts and synthetic grafts often require longer follow-up periods due to generally poorer outcomes and are therefore less commonly preferred by orthopedic surgeons (Legnani et al., 2010; Maletis et al., 2017; Sun et al., 2020; Ventura et al., 2010).

Post-operative rehabilitation is crucial for achieving successful outcomes and returning to daily activities or sports after ACLR. Recent recommendations also suggest pre-operative rehabilitation to prepare patients physically and mentally for surgery, as well as to enhance post-operative functional outcomes (Failla et al., 2016; Gokeler et al., 2017; Thomeé et al., 2008). Most post-operative protocols follow a phased approach, beginning with pain management, effusion control, and range of motion exercises, and gradually progressing to muscle strengthening, stability training and neuromuscular control exercises, ultimately leading to a return to functional activities (Gokeler et al., 2017; van Grinsven et al., 2010; Wilk & Arrigo, 2017; Wright et al., 2015). In addition to conventional therapeutic approaches, recent studies advocate incorporating interventions based on neurophysiological principles, recognizing the neuroplastic and neurocognitive alterations associated with ACL injuries, particularly as this understanding has advanced over the past decade (Faltus et al., 2020; Gokeler et al., 2019; Grooms et al., 2015; Lepley et al., 2018; Machan & Krupps, 2021; Onate et al., 2019; Wohl et al., 2021).

1.1.4. Neurophysiological changes related to anterior cruciate ligament injury

Ligaments are essential for human movement, providing joint stability and proprioceptive feedback through their embedded mechanoreceptors. Ligamentous injuries, particularly those of the lower extremities such as lateral ankle sprains and ACL tears, result not only in increased joint laxity due to the loss of static joint stabilizers, but also in functional deficits that may persist even after surgical intervention (Evans et al., 2004; Hertel, 2000; Lehmann et al., 2017). Following an ACL injury, the loss or reduction of sensory input coming from damaged mechanoreceptors compromises proprioceptive acuity and movement perception, subsequently disrupting sensorimotor control (**Fig. 3;** Baumeister et al., 2008, 2011; Muaidi et al., 2019; Yosmaoglu et el., 2011). Emerging evidence suggests that this malfunction provokes a cascade of neuroplastic adaptations within the CNS (An et al., 2019; An et al., 2022; Baumeister et al., 2008, 2011; Criss et al., 2020; Kapreli et al., 2009; Lehmann et al., 2021; Lepley et al., 2020).

Various neuroscientific techniques have elucidated injury-related changes operating across different domains of the CNS (for reviews: Needle et al., 2017; Neto et al., 2019). Magnetic resonance imaging (MRI) and functional magnetic resonance imaging (fMRI) studies have highlighted structural reorganization (Lepley et al., 2020), changes in activity patterns (Criss et al., 2020; Grooms et al., 2017; Kapreli et al., 2009) and functional connectivity of networks (Criss et al., 2020). These studies collectively suggest reduced excitability in the motor cortex and the compensatory reliance on visual input, characterized by increased activity of motor and visual cortices, and decreased activity in somatosensory cortex. Despite their high spatial resolution, MRI and fMRI studies are limited by their static nature, confining their findings to rest conditions or simple tasks such as the knee and hip flexion/extension.

Transcranial magnetic stimulation (TMS) is another technique frequently employed to investigate injury-related changes (Lepley et al., 2019, 2020; Luc-Harkey et al., 2017; Pietrosimone et al., 2015; Zarzycki et al., 2018). TMS studies have reported increased motor threshold (Norte et al., 2018; Ward et al., 2019), higher motor evoked potential amplitudes (Zarzycki et al., 2018), and greater intracortical inhibition in individuals with ACL injuries (Luc-Harkey et al., 2017). These findings posit changes in cortical excitability, specifically revealing the need for higher activity levels to produce an efferent drive and subsequent changes in motor pathways. As in MRI studies, the technique is implemented either at rest or during quadriceps contraction constraining the transferability of findings to more complex motor tasks.

EEG, with its high temporal resolution, has become a popular method for exploring adaptive changes associated with ACL injuries (An et al., 2022; Baumeister et al., 2008, 2011; Lehmann et al., 2021, Miao et al., 2017; Sherman et al., 2023). Advances in artifact removal algorithms and wireless technologies (Gorjan et al.,2022; Park et al., 2018) have facilitated the transition from simple tasks to postural and dynamic tasks, enhancing the applicability of findings to real-world scenarios (An et al., 2022; Lehmann et al., 2021; Miao et al., 2017; Sherman et al., 2023). Spectral analyses have consistently shown increased theta activity in frontal regions, suggesting greater attentional resource allocation (Baumeister et al., 2008, 2011; Miao et al., 2017), and heightened alpha activity in sensory cortices, indicating altered sensorimotor processing during simple, postural and dynamic tasks (An et al., 2022; Baumeister et al., 2008; Miao et al., 2017; Sherman et al., 2023). With the possibility of analyzing event-related changes in short-scale time windows, An et al. (2019) revealed altered responses in the somatosensory cortex activation induced by tibial translation. Additionally, Lehmann et al. (2021) conducted a functional connectivity study whose findings support the hypothesis of compensatory reliance on visual information by demonstrating increased functional connectivity between somatosensory and visual cortices during single-leg stance.

The synthesis of current evidence indicates that ACL injuries induce changes in the function of the CNS and elicit compensatory strategies detectable across multiple domains. The diversity of analytical approaches and the dynamic task applicability of EEG suggest its potential for examining the task-specificity of these changes and their implications in real-world and sport contexts.

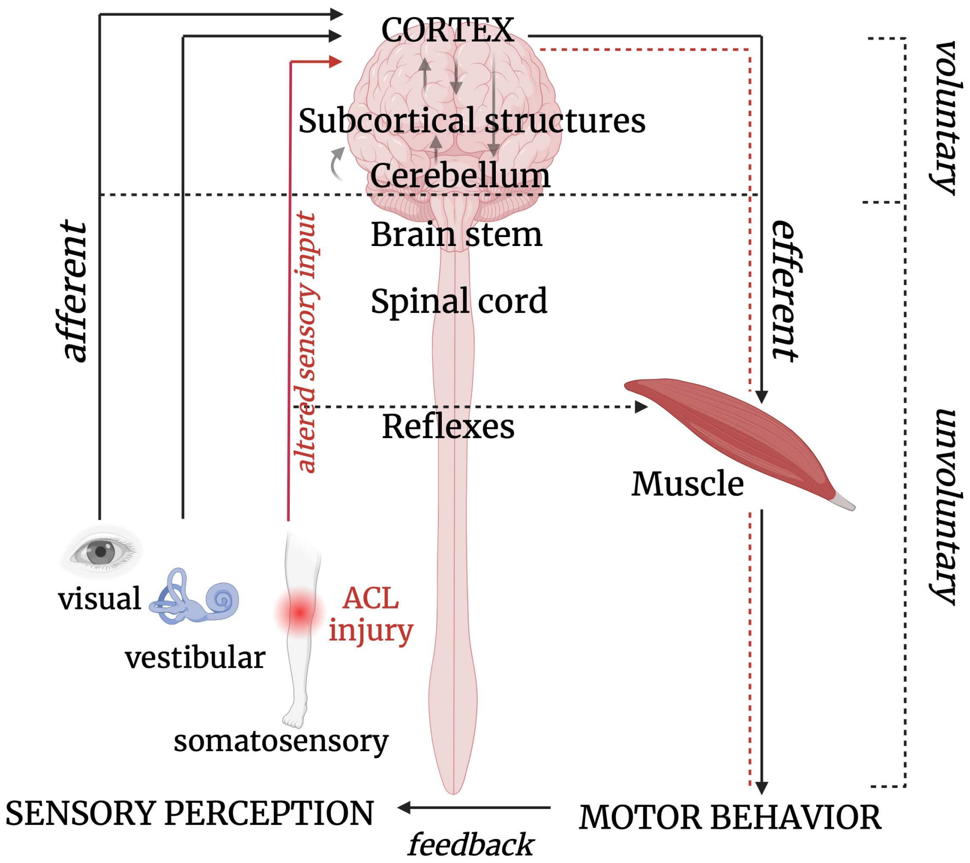

Fig. 3: Altered sensorimotor control following ACL injury
(Adapted from Baumeister, 2013)

1.1.5. Anterior cruciate ligament injuries in football

Among the most prevalent lower extremity injuries, ACL ruptures exhibit some of the highest incidence rates (Lopez-Valenciano et al., 2020) - particularly in team sports - with significant implications for athletes' performance, career longevity, and overall well-being (Mazza et al., 2022; Montalvo et al., 2019). In the top 8 European football leagues - Serie A (Italy), Premier League (England), Ligue 1 (France), La Liga (Spain), Bundesliga (Germany), Jupiler Pro League (Belgium), Liga NOS (Portugal), and Premier

Liga (Russia) - 195 players sustained ACL injuries between 2014 and 2017, summing a mean annual incidence rate of 1.42% (Mazza et al., 2022). According to a study by the Union of European Football Associations (UEFA), elite teams can expect an ACL injury approximately every two seasons (Ekstrand et al., 2013).

Research indicates that non-contact mechanisms are predominantly responsible for ACL tears in sports (Chia et al., 2022; Walden et al., 2015). A recent review with meta-analyses (Chia et al., 2022) reported an incidence rate of 0.07 per 1000 player hours and 0.05 per 1000 player exposures for non-contact injuries. Transcending the average with an incidence rate of 0.08 per 1000 player hours, football was given as the second most affected team-sport for non-contact ACL injuries following floorball at 0.17 per 1000 player hours. The meta-regression in this review revealed that non-contact injuries occur significantly more frequently among female football players (0.13 per player hours) compared to their male counterparts (0.04 per player hours). Numerous studies have highlighted multifactorial risk factors contributing to this gender disparity (Larruskain et al., 2018; Montalvo et al., 2019; Prodromos et al., 2007; Walden et al., 2011), including hormonal influences (Slauterbeck et al., 2002; Wojtys et al., 2002), biomechanical predisposition due to anatomical variations – such as increased knee valgus associated with a wider pelvis and greater quadriceps angle (Griffin et al., 2000) - and differences in neuromuscular control strategies (Mandelbaum et al., 2005; Myer et al., 2004). In light of these findings, prevention programs have been developed with gender- and etiology-specific considerations (for review: Bisciotti, 2016).

Epidemiological studies with extended follow-ups unveil the debilitating consequences of ACL injuries for both players and teams (Krutsch et al., 2020; Larruskain et al., 2018; Walden et al., 2016). A 15-year follow-up study involving 78 clubs across the top leagues in 16 European countries reported an average layoff time of approximately 6.6 months before returning to training and about 7.4 months before resuming competitive play following an ACL injury (Walden et al., 2016). Among surgically treated players – who constituted approximately 98.6% of total ruptures - 6.7% suffered from a reinjury. A three-year follow-up indicated that while 85.8% of these players continued to participate in football, only about 65% were able to compete at the same level as before their injury. Another study focusing on teams in Germany's first football league over a 10-year period reported a reinjury rate of 10.53% (Krutsch et al., 2020). The mean time of RTP after the initial injury was recorded around 7.6 months, while reinjured players took an average of 8.2 months to return. Although 98% of the injured players returned to play, only 54.9% of them played in the same league for three years. Both studies illustrate that although a high RTP rate is statistically evident among football players post-injury, the decline in competitive level underscores the serious ramifications of ACL ruptures in football.

Studies contextualizing performance through follow-up game statistics provide deeper insights into how injury impacts the level of play in football (Barth et al., 2019; Forsythe et al., 2021; Niederer et al., 2018; Szymski et al., 2023). Utilizing retrospective match-cohort designs, Forsythe et al. (2021) and Niederer et al. (2018) documented reductions in performance metrics among injured players relative to their healthy counterparts. In their study with a 10-year follow-up, Forsythe et al. (2021) identified a cohort of 51 players with complete ruptures competing in one of the five elite UEFA leagues, revealing that attackers accounted for the majority of injuries at 37% (n=19), surpassing midfielders, defenders and goalkeepers. While 41 players (80%) returned to play post-injury, they exhibited reduced participation in terms of games played, minutes on the field per season and game, as well as scoring less relative to their healthy matches during the first two seasons after injury.

Similarly, over a 5-year follow-up period, Niederer et al. (2018) found significantly lower metrics regarding minutes played per season and total scoring points among injured players up to two years post-injury compared to pre-injury levels. Additionally, these injured players demonstrated fewer passes, dribbles, and tackles per game during this period and had shorter career survival times than their healthy peers. The authors posited that declines in performance could contribute to early retirement from professional play and emphasized the importance of analyzing not only RTP rates but also performance indicators.

Barth et al. (2019) and Szymski et al. (2023) further elucidated injury-associated declines by comparing pre- and post-injury game statistics within individual athletes. The 20-year follow-up of Barth et al. (2019) identified 176 professional footballers who underwent ACLR. Although 93.2% (n=164) returned to international level play, they experienced declines in games played per season, minutes played per game, and goals scored compared to their pre-injury performance levels.

Szymski et al. (2023) tracked ACL injuries among professional, semi-professional, and amateur players over four seasons from 2014 to 2018. Out of 607 registered injuries, 36.7% (n=92) of semi-professional and 20% (n=24) of professional players ended their careers within three seasons post-injury. Only 47.5% of professionals managed to pursue their previous level of competition. Although no significant differences were found for professional players, semi-professional and amateur players demonstrated a decline in average playing time in minutes per season within the third season post-injury compared to their performance in pre-injury season.

While statistics regarding post-injury performance vary based on follow-up duration, geographical scope, sample size – including number of teams and players - and methods used to retrieve data across studies, there is a consensus that despite the high RTP rates following ACL injuries in football, athletes often experience declines in performance during subsequent seasons. Several studies focus on preventative strategies aimed at minimizing reinjuries or enhancing ecological validity within RTP programs (Bortone et al., 2021; Kamath et al., 2014; King et al., 2021; Meredith et al., 2021; Paterno et al., 2017; Petersen et al., 2014; Schweizer et al., 2022; Sugimoto et al., 2015; Wiggins et al., 2016). However, beyond statistical indicators regarding RTP outcomes, further research is needed to understand the physiological underpinnings associated with performance declines, while also characterizing "performance decline" through sport-specific lenses.

1.2. Kicking performance in football

Target-directed movements are fundamental components in many team and individual sports, encompassing actions that involve aiming or reaching toward a specific goal or object. Examples include hitting a baseball, throwing a basketball, or serving a tennis ball. The ability to execute accurate target-directed movements is paramount across various sports disciplines and is closely linked with an increased likelihood of winning. For instance, while scoring in basketball or a golf is directly measured as points, successfully passing the ball to the appropriate teammate at the right moment can be viewed as a skilled maneuver that facilitates scoring opportunities (Freeston & Rooney, 2014; Lyons et al., 2006; Vickers et al., 2017).

In football, kicking serves as the primary action for advancing or passing the ball, and for scoring goals (Andersen & Dörge, 2011). The precision of kicking – whether alone or in conjunction with kicking speed – plays a vital role in successful maneuvers by directing the ball to the intended location, whether it be a teammate, an open area of the goal, or a position that allows a teammate to score a goal (Bauer, 1993). When players need to propel the ball over long distances, they typically employ the instep kick, which emphasizes speed as its key component (Kellis & Katis, 2007; Lees & Nolan, 1998). The instep kick involves a coordinated sequence of body movements that begins with an approach and ends with follow-through. This approach can be static, or consist of multiple running steps, with the latter generally producing higher speeds (Opavsky, 1988). An approach angle of 30 to 45 degrees relative to the ball has been identified as another significant determinant of resultant speed, promoting maximum velocity of both the shank and ball for optimal force generation (Lees & Nolan, 1998). The support leg stabilizes the body and acts as a pivot point for rotation. Through pelvic rotation, mechanical energy is transferred from distal to proximal segments, contributing to the proximal-to-distal motion sequence of the kicking leg (Inoue et al., 2014). This momentum causes the kicking leg to swing backward, yielding a pre-stretch tension in the hip flexor and knee extensor muscles. This tension enhances muscle contraction that generates accelerative forces and propels the kicking leg forwards for an effective ball impact. Consequently, achieving a greater range of motion is essential for executing powerful kicks aimed at long distances (Langhout et al., 2016).

However, when accuracy takes precedence over speed, alterations in kicking biomechanics become evident. Research indicates that linear and angular joint velocities - and consequently ball speed – decrease when kicks are executed toward specific targets (Lees & Nolan, 1998; Teixeira, 1999). This phenomenon is known as the speed-accuracy trade-off (van den Tillaar et al., 2017), suggesting an optimal speed associated with achieving optimal accuracy at a given distance. Findings from Katis et al. (2013) demonstrate distinct muscle activity patterns for accurate versus inaccurate kicks and indicate that optimal accuracy for specific distances and targets is attained through congruent motor behavior that aligns with biomechanics suited for those conditions (Katis et al., 2013).

In scenarios where precision and control are paramount during gameplay, skilled players often utilize side-foot kicks executed with the medial aspect of their foot. Also referred to as "inside of the foot kick", this technique provide enhanced directional control due to unique biomechanical dynamics that produce lower speeds (Hunter et al., 2018; Sterzing et al., 2009). Studies have shown that hip external rotation torque governs this kick's spatial pattern by inducing clockwise rotation in the thigh-shank plane while allowing controlled forward velocity of the foot. As a result, this configuration increases perpendicularity between the velocity vector and longitudinal axis of the foot, facilitating a more square impact against the ball. (Levanon & Dapena, 1998; Nunome et al., 2002). These characteristics render side-foot kicks essential for executing precise plays on the field.

In summary, both kicking speed and accuracy are pivotal elements influencing kicking performance across various game scenarios. Each serves distinct yet complementary purposes: kicking speed is critical for long-distance shots and powerful clearances where overwhelming opponents or quickly relieving defensive pressure is necessary. On the other hand, kicking accuracy is vital in situations requiring precise ball placement - such as short passes, penalty kicks, and crosses into the penalty area. Mastery of both aspects enables players to adapt effectively to dynamic game demands and optimize their performance on the field (Ali, 2011).

1.2.1. Pass accuracy as a skilled performance marker

In football, kicking typically refers to striking the ball with high velocity to achieve long-distance propulsion, whereas passing is strategically employed in team play to transfer the ball effectively (Kellis & Katis, 2007; Rosch et al., 2000). Short-distance passes are essential for maintaining possession, controlling game tempo, executing strategic maneuvers, and creating scoring opportunities (Adams et al., 2013; Lago-Peñas et al., 2011; Redwood-Brown, 2008). Precision in passing is critical for both the efficiency and effectiveness of a team's overall performance and is considered as a significant determinant of success (Lepschy et al., 2018, 2020; Oberstone, 2009).

Build-up play is a crucial phase where accuracy in passing becomes particularly vital. To progress effectively on the field, passes must be delivered precisely to teammates without interception, often through a tight corridor between defenders. Accurate passing minimizes the risk of turnovers and thereby enhances ball possession (Hughes & Franks, 2005). Moreover, quick and precise passing allows teams to dictate the pace of the game - accelerating to launch an attack or decelerating to regroup and reorganize. The effectiveness of crosses also relies heavily on the precise positioning and timing of both the crosser and the receivers. Accurate short passes ensure that the ball reaches the crosser at the optimal moment and location, facilitating well-timed crosses into the box. This synchronization is critical for breaking down defenses and positioning the ball advantageously, thereby increasing the likelihood of scoring (Orth et al., 2014; Rampinini et al., 2009).

Given its importance in various game situations, pass accuracy is a fundamental metric in football, reflecting a player's technical skill and overall performance (Aquino et al., 2017). Various tests have been developed to evaluate pass accuracy alongside speed (Ali et al., 2007; Haaland & Hoff, 2003; Rostgaard et al., 2008; Rosch et al., 2000). Empirical studies implementing these tests across different skill levels indicate that higher skill levels are associated with marked improvement in pass accuracy (Ali et al., 2007; Huijgen et al., 2013; Russel et al., 2010). Recognizing its practical significance, recent research focuses increasingly on the development and efficacy of both traditional and innovative equipment-based interventions designed to enhance this skill and contribute to team success (Asrul et al., 2021; Dunton et al., 2020; Robin et al., 2020; Thomas et al., 2021).

1.2.2. Dynamics associated with skilled pass accuracy

In the context of goal-directed movements, skilled behavior emerges as a product of an interplay between perceptual, cognitive and motor processes. Effective coordination of actions to achieve desired outcomes depends on accurate perception of the environment. Cognition plays a crucial role and serves to both ends as a holistic domain in this interaction to perform both effectively and efficiently (Araujo et al., 2006, 2019; Newell, 1986). In football, accurate passing involves encoding, storing and translating spatial information into coordinated motor behavior (Davids et al., 2000). The rapid and precise detection – or, in some cases, the prediction – of dynamic targets relies on perceptual skills such as spatial awareness, which are supported by cognitive processes (Noël et al., 2015). As targets become more unpredictable, players should coordinate perceptual, cognitive and motor processes more intricately (Boynton, 2005; O'Brien et al., 2021). Once the direction and distance of a pass are determined, accuracy hinges on the action cycle, which compromises cognitive and sensorimotor feedback loops. Players must adjust their leg position based on the available sensory information and prior experience, making real-time corrections through feed-forward and feedback mechanisms to execute a precise pass toward a target (Bear et al., 2007; Yarrow et al., 2009). The trade-off between speed and accuracy is influenced by the required precision and plays a crucial role in kicking biomechanics. Van den Tillaar and Fuglstad (2017) found that prioritizing accuracy led football players to reduce speed, resulting in higher accuracy but lower segmental velocities achieved by decreased maximal knee extension angle and pelvic rotation. These findings align with other studies (Andersen & Dörge, 2011; Lees & Nolan, 1998; Teixeira et al., 1999) that observed a reduction in ball speed when players kicked to a target despite instructions to attain maximum ball speed. Furthermore, it was also found that optimal accuracy for a given distance was achieved only within a certain range of speed (Rakojevic et al., 2019; van den Tillaar & Ulvik, 2014). These results put skilled pass accuracy forth as the ability of producing an appropriate motor behavior to achieve optimal accuracy for a given target and distance. Thus, skilled pass accuracy encompasses more than just physical attributes like muscle strength and range of motion. It also involves perceptual and cognitive capabilities to interpret external information and plan actions accurately. While numerous studies have explored the biomechanical underpinnings of accurate passing with a multitude of methods (Arguz et al., 2021; Bessenouci & Haceini, 2019; Komarudin et al., 2018), they often provide limited insight into the perceptual and cognitive domains. Consistency, which is a frequently used standard measure of kicking accuracy (Bacvarevic et al., 2012; Kim et al., 2000; Rakojevic et al., 2019; Russell et al., 2010), offers a more comprehensive perspective regarding these skills. Higher consistency in skilled players not only reflects the ability to produce certain biomechanics, but also indicates the capacity to predict and sustain congruent movement parameters to achieve accuracy consistently (Avsar & Soylu, 2010; Phillips, 1985). However, current evidence provides only indirect insights into the higher-level mechanisms underlying skilled accuracy, highlighting the need for further research about neurophysiological processes underlying this skill in football.

1.2.3. Cortical correlates of skilled pass accuracy

Skilled accuracy in target-directed sports tasks, such as passing, necessitates a precise perception of available spatial information and the execution of well-coordinated movements. These complex demands engage multiple cortical and subcortical brain regions (Davids et al., 2000; Mirabella, 2014; Oppici et al., 2017). Recent advancements in the field of exercise neuroscience have facilitated the in situ investigation of these areas during motion, particularly through pioneering methods, such as mobile EEG and functional near-infrared spectroscopy (fNIRS; Park et al., 2018).

While extensive research has focused on the cortical underpinnings of target-directed sports tasks involving the upper extremities - such as golf (Babiloni et al., 2008; Baumeister et al., 2008; Ji et al., 2019), basketball (Chuang et al., 2013; Özkan et al., 2019), rifle shooting (Doppelmayr et al., 2008; Gong et al., 2018; Hung et al., 2008), and archery (Ertan et al., 2021; Gu et al., 2022) – only two recent studies have provided preliminary insights into the cortical correlates of target-directed kicking in football (Palucci-Vieira et al., 2022; Slutter et al., 2021). In their fNIRS study, Slutter et al. (2021) have addressed the accuracy of penalty kicks within an anxiety-inducing context. They identified the left motor cortex as a task-relevant brain area and demonstrated that experienced players exhibited reduced activation in this region when performing penalty kicks under varying levels of pressure – specifically, low pressure from a non-distracting goalkeeper versus high pressure from a distracting one – resulting in decreased accuracy. Based on neural efficiency theory (Hatfield & Kerick, 2007), they attributed this diminished activation in the task-relevant region to heightened activity in the prefrontal cortices due to increased pressure. This frontal overactivity was interpreted as a distraction during the kick, potentially stemming from overthinking about scoring or missing. However, EEG studies involving target-directed upper extremity tasks suggest that augmented attention influences skilled performance positively, as indicated by increased frontal theta activity (Baumeister et al., 2008; Chuang et al., 2013; Doppelmayr et al., 2008). Supporting the findings of Slutter et al. (2021), Kao et al. (2013) posited that optimal attentional engagement is crucial for successful performance, noting that excessive frontal activity correlated with poorer performance outcomes. In the study of Slutter et al. (2021), the absence of post-hoc comparison between successful and unsuccessful trials uncontaminated by pressure factors may mask the beneficial role of enhanced attention during kicking. Attention converged toward a distractor is expected to constrain available attentional resources for the task at hand, potentially impairing performance even when cortical activity suggests increased attentiveness (Song et al., 2019). Additionally, their findings highlighted the involvement of the left temporal cortex in automated skills during kicking. For experienced players, activation of this region increased under pressure, indicating a tendency to neglect their automated skills in favor of overthinking. Conversely, inexperienced players displayed higher temporal cortex activity during successful penalties, suggesting less unestablished skill sets (Wolf et al., 2015). Nonetheless, the within- and between-individuals design hinders the comprehension of how temporal, as well as frontal cortex activities contribute to skilled accuracy in penalty kicks.

In this context, the EEG study of Palucci-Vieira et al. (2022) offers more focused insights regarding accuracy. Leveraging EEG's high temporal resolution and its capacity to reveal pre-and post-event dynamics, their analyses delineate how different cortical areas contribute to enhanced accuracy before and during a kick. Their findings indicate that on-target kicks are associated with a decrease in frontal theta activity shortly before ball-impact (200 ms), whereas missed kicks exhibit significantly higher theta activity. This aligns with the assertion of Kao et al. (2013) that superior performance correlates with lower attentional levels compared to poorer outcomes in golf putting. However, when analyzed in spectral power domain, no significant differences were found between missed and on-target kicks. Furthermore, their time series diagrams show an increase in theta activity immediately following ball impact (200 ms), which is significantly greater for on-target kicks. Given their mention of an approximate ball-impact moment in their methods, it can be speculated that there may be shifts of impact-related dynamics within these brief time windows - suggesting that rather than a decline, an increase in attentional processes contributes to improved accuracy. The reported significant positive correlation between frontal theta spectral power and ball velocity further supports this hypothesis.

Another notable finding from Palucci-Vieira et al. (2022) is the significant negative correlation between the occipital alpha power during the preparatory phase (prior to approach) and radial error. A decrease in posterior alpha power is typically linked to enhanced visual processing (Babiloni et al., 2006; Clayton et al., 2018). However, during aiming tasks requiring focus on targets, an increase in alpha power has been observed during the "quite-eye" phase (Gallicchio & Ring, 2020; Janelle et al., 2000). The authors interpreted this finding as indicative of effective visual information collection during this phase. Conversely, stronger event-related desynchronization of alpha band activity - a parameter reflecting decreased power after an event relative to before – negatively correlated with radial error, reinforcing the constructive role of posterior alpha activity observed in other goal-directed tasks (Haufler et al., 2000; Loze et al., 2001). However, Janelle et al. (2000) noted potential hemispheric asymmetries in alpha responses related to performance accuracy, specifically highlighting declines right posterior hemisphere activity. The central alignment of regions of interest in the study of Palucci-Vieira et al. may obscure whether central or lateral posterior alpha activity is more sensitive to enhanced accuracy while kicking.

Additional findings unveil differences in the activities of motor and parietal areas in the same study. Specifically, successful versus unsuccessful kicks were associated with increased alpha power across both cortices and decreased theta power in parietal regions alongside increased beta power in motor cortex. The authors attributed increased alpha power to neural efficiency theory implications – suggesting more automated neural processing for accurate kicks – and linked reduced theta power to more effective velocity regulation prior to ball-impact while associating increased beta response with readiness for action at ball-impact (Cardellicchio et al., 2020).

Although the focus of Palucci-Vieiera et al. lies on dynamics associated with successful versus unsuccessful kicks, the multitude of reported parameters and their contradictory results complicate understanding which brain areas promote kicking precision within a simplified context. Regarding cortical activity underlying skilled pass accuracy, comparing different skill levels may yield better insights into learned neural strategies consolidated over time that enhance accuracy. Moreover, it is essential to consider methodological approaches when exploring cortical underpinnings associated with a motor task. Particularly for instantaneous actions like kicking, event-based EEG analyses may provide more accurate representations of dynamics since averaged spectral power across epochs can mask time-locked changes (Makeig, 1993). The intertwined nature of movement sequences involved in long-distance kicking - including approach runs and leg positioning - alongside intra- and inter-individual variances increases movement degrees of freedom (e.g., differing speeds or steps counts, positions), potentially hindering time-locked synchronization of dynamics and obstructing analyses (Davids, 2000). Investigating brain activity related to kicking through simpler designs may facilitate understanding how variables such as skill level and variations like stepping before kicking influence cortical dynamics in a progressive manner. Taken together, overall evidence concerning enhanced pass accuracy remains limited at present. While frontal and occipital cortices appear influential regarding dynamics modulating precision, contribution of other cortical areas across different contexts are also evident. To examine intrinsic cortical dynamics related specifically to short-distance pass accuracy, further studies are warranted - particularly those employing passing tasks within simpler experimental designs.

1.2.4. Potential impacts of an anterior cruciate ligament injury on passing performance

In the preceding sections, multifaceted dynamics influencing skilled pass accuracy, as well as associated cortical underpinnings offering preliminary neurophysiological insights into these dynamics, were discussed. Despite the limited evidence, particularly concerning cortical dynamics related to kicking, the presented fundament accents the importance of visuospatial perception, attention, and motor coordination in achieving superior pass accuracy (Davids et al., 2000; Kellis & Katis, 2007; Palucci-Vieira et al., 2022; Slutter et al., 2021). Additionally, the initial section addressed neurophysiological changes observed following ACL injuries, which may interfere with the demands of effective kicking performance (for reviews: Needle et al., 2017; Neto et al., 2019). This potential conflict may lead to an interplay between task demands and compensatory mechanisms, ultimately diminishing performance by prioritizing one over the other. The allocation of attentional or visual resources in response to reduced afferent input may constrain the processing of task-related information. Conversely, an emphasis on task demands could result in inadequate compensation for proprioceptive deficits.

When passing a ball toward a target, accuracy relies on the integration of visuospatial and proprioceptive information (Davids, 2000; Gallicchio et al., 2020; Kellis & Katis, 2007). Deteriorated proprioceptive acuity - a phenomenon frequently reported in individuals with ACL injuries (Bernardino, 2019; Muaidi et al., 2009) - may disrupt alignment in the lower extremities and lead to radial errors in ball trajectory. In side-foot kicks, tibial rotation plays a crucial role in determining ball direction, thus, proprioceptive errors can significantly distort kicking angle (Levanon & Dapena, 1998; Nunome et al., 2002; Smale et al., 2019). On the other hand, deficits in proprioception within the support leg may indirectly contribute to spatial errors in the kicking leg since torque generated during the swing phase facilitates pelvic rotation and subsequently influences the kicking leg motion (Nunome et al., 2002). However, due to a paucity of studies in this topic, the anticipated effects of ACL injuries on passing accuracy remains largely hypothetical. To date, only one study has compared muscular activity and biomechanical dynamics between healthy and injured football players during kicking (Cordeiro et al., 2015). In this study, injured players exhibited greater variability in knee extension angle and peak velocity while attempting to perform kicks as fast as possible. The authors attributed this increased variability to proprioceptive deficits and impaired motor control. While these findings represent an initial framework about injury-related deficits during kicking, the absence of a spatial target in their design limits the relevance of accuracy. Although existing evidence provides a foundational background to foresee a decline in accuracy performance, further researched is necessary to determine whether ACL injuries have significant consequences for passing accuracy in football.

1.3. Behavioral and cortical measures to assess dynamics associated with passing

1.3.1. Non-linear movement variability as a measure of skilled behavior

Movement variability is a commonly studied behavioral measure for understanding skilled performance in sports (Bartlett et al., 2007; Bartlett, 2008; Glanzer et al., 2021; Wagner et al., 2012). It quantifies fluctuations in the kinetic and kinematic attributes of executed movements. The context of the task determines the extent to which variability is beneficial or detrimental to performance. For instance, increased fluctuations within a single trial - termed within-trial variability - can indicate poor motor control and noise in precision tasks (van Beers et al., 2004). Conversely, it can also reflect a basketball player's skill in successfully throwing baskets using various styles from an enriched movement repertoire (Komar et al., 2016; Stergiou & Decker, 2011). On the other hand, decreased variability across trials can demonstrate an individual's ability to maintain a consistent motor behavior, which is viewed as evidence of consolidated motor patterns according to motor learning theories (Fitts, 1964; Schmidt, 1975). This ability requires accurate predictions regarding the consequences of behavior (feedforward loops), integration of predicted information with actual states (state estimation), and online adjustments based on movement outcomes (feedback loops; Yarrow et al., 2009; Qi et al., 2021). While biomechanical analysis of kicking can provide descriptive insights into dynamics that yield higher accuracy, they often lack information about these higher-level processes shedding light on skilled behavior. In stable settings where kicking is directed toward a target, lower trial-to-trial variability suggests an ability to sustain consistency in kicking - a variable commonly used to measure accuracy (Bacvarevic et al., 2012; Kim et al., 2000; Rakojevic et al., 2019; Russell et al., 2010).

Movement variability can be quantified using both linear and non-linear metrics (de Oliveira et al., 2019; Stergiou et al., 2006; Stergiou & Decker, 2011). Linear metrics tend to limit variability by averaging trials and interpreting temporal variations as random dynamics. However, physiological systems exhibit intricate temporal characteristics that may have functional origins. In this sense, non-linear metrics are particularly valuable for elucidating complex physiological processes that might be overlooked by linear measures (Decker et al., 2011; Stergiou et al., 2006). Multiscale entropy (MSE) is a non-linear metric used to quantify variability related to movement and postural control (Costa et al., 2002; Bisi & Stagni, 2016; Gow et al., 2015). MSE extends Sample Entropy (SE), which assesses the complexity of finite time series. Higher entropy values indicate greater complexity or randomness in the data, while lower values correspond to higher predictability or regularity. SE assays complexity solely in the original series ignoring the relevance of time scale in complex systems. However, certain scales may be more sensitive to pathological processes in biological signals and can differentiate clinical populations from healthy ones (Costa et al., 2002). MSE addresses this limitation by assessing complexity across a range of scales through a procedure known as coarse graining and is used as a measure to explore movement dynamics at multiple temporal resolutions (Moras et al., 2018).

1.3.2. Linear and non-linear EEG metrics to assess cortical dynamics associated with passing

High temporal resolution is a significant strength of EEG, allowing for the analysis of dynamic changes in brain activity evoked by specific events. Traditional event-related potential (ERP) analysis focuses on voltage fluctuations in the time domain that occur in response to specific stimuli or events (Nidal & Malik, 2014). However, the frequency content of an EEG signal, which remain covert in ERP analysis, provides valuable insights into the neural mechanisms underlying cognitive and motor tasks. Different frequency bands - such as theta, alpha and beta - are associated with distinct cognitive and sensorimotor processes, thereby extend our understanding of cortical phenomena involved in various tasks (Kim & Im, 2018).

Power spectral density is a widely used linear method in frequency analysis that decomposes a time-domain signal into its constituent frequencies and computes the power spectrum for each frequency band by squaring the amplitude of each frequency component (Schomer & Silva, 2011). This approach yields a representation of power across frequency bands and most studies compare mean spontaneous EEG frequency spectra between conditions and cohorts. While this analysis is appropriate for continuous tasks such as gait or stance without any specific stimuli (Bradford et al., 2016; Hülsdünker et al., 2015; Nordin et al., 2019), it falls short in settings involving repetitive stimuli or brief motor tasks where temporal information is crucial for examining dynamics occurring at short intervals. In this context, event-related spectral perturbations (ERSP) offers an advantage by integrating temporal and spectral information present in EEG signals. ERSPs refer to spectrograms that illustrate time-locked changes in the spectral content of EEG signals in response to specific events or stimuli and herewith depict spectral fluctuations that occur during rapid movements such as kicking (Makeig, 1993).

While linear metrics of EEG deliver substantial information regarding temporal and regional activation related to task-specific cortical activity (Park et al., 2015), they often oversee the complexity of the signal by averaging multiple trials or dismissing variations as background noise (Garret et al., 2013; Hutka et al., 2013, 2016). The brain activity is characterized by complex network dynamics that arise from both local and long-range communication among neuronal populations. This complexity results in spatiotemporal irregularities within brain signals, reflecting the brain's capacity for information processing (Breakspear, 2017; Sporns, 2000; Sporns et al., 2000a). While the functional increase in cortical complexity from infancy to adulthood implies cognitive evolution (McIntosh, 2019), a pathological loss of complexity has been shown to underlie impaired brain function in various disorders (Goldberger et al., 2002; Wang et al., 2017). Besides its use as an analytical approach in other biomedical signals such as electrocardiogram, oximetry and movement signals, MSE is employed as an EEG measure to study the non-linear complexity of brain signals (Azami et al., 2017; Miskovic et al., 2019; Park et al., 2007; Takahashi et al., 2009). Through the coarse-graining procedure, MSE profiles the complexity of both slow and fast dynamics across a range of temporal scales. This method has demonstrated to be capable of distinguishing between different age groups (McIntosh et al., 2014), healthy versus pathological cohorts (Azami et al., 2017; Mizuno et al., 2010), elderly individuals with low versus high physical activity levels (Wang et al., 2014), genders (Lewandowska et al., 2023), varying cognitive states (Ahammed & Ahmed, 2023; Liu et al., 2023; Zhai et al., 2022), and different sport profiles (Wang et al., 2020). The incorporation of MSE to EEG analysis can offer a more extensive perspective on cortical dynamics and ultimately enhance the interpretation of EEG data (Courtiol et al., 2016).

1.4. Rationale

Despite high rates of RTP following surgical interventions, football remains one of the sports affected significantly by ACL ruptures. In addition to recurrent injuries, a decline in performance is linked with an increased likelihood of premature career termination. Epidemiological studies have documented performance decreases primarily within a statistical framework, noting that players who have undergone ACLR tend to play fewer minutes and achieve lower goals and pass counts per game. However, the specific consequences of injury that contribute to this decline in performance remain unclear. A comprehensive physiological understanding of the underlying mechanisms is essential for improving outcomes upon returning to the field.

Recent studies have expanded the perspective on ACL ruptures from a purely peripheral injury to a complex condition with neurophysiological implications. Increasing evidence reveals adaptations within various domains of the CNS due to reduced sensory input in both athletic and non-athletic populations. Advances in mobile brain imaging (MoBI) enable the investigation of these changes across diverse motor tasks relevant to both daily activities and sport-specific movements. Injury-related alterations during movement provide valuable insights into neurophysiological mechanisms that may explain declines in sport-related performance. To date, no studies have specifically examined the potential relationship between the neurophysiological consequences of ACL injuries and football performance. It remains uncertain whether injured players experience decreased playing time due to diminished physical endurance or if they avoid executing passes and scoring goals because of confidence issues, loss of strength, or altered movement patterns. The reported neurocognitive strategies offer a compelling rationale for anticipating a regression in passing precision following ACLR. Understanding cortical dynamics underlying skilled pass accuracy – and whether injured players exhibit differences in these dynamics - may provide an evidence-based explanation for one aspect of performance decline in football while paving the way for prospective investigations into additional contributing factors. Converging evidence indicating deteriorated pass accuracy in football may encourage therapists, trainers and sport scientists to view ACL injuries as a multifaceted condition. This perspective could prompt a reevaluation of therapeutic approaches and RTP assessments, leading to the development of interventions that extend beyond general physical performance and address specific domains of athletic capability. Identifying and selectively treating individual deficits may assist players in regaining their pre-injury performance levels and enhance overall outcomes in football following ACLR. Furthermore, developing sport-specific tasks through methodological advancements in exercise neuroscience field may facilitate transitions to real-world situations and enable the investigation of skilled performance across various contexts pertinent to sports from a neuroscientific perspective.

1.5. Objectives

The present dissertation aimed to investigate EEG dynamics associated with skilled pass accuracy in healthy football players and to determine whether these dynamics differ in injured players who have undergone ACLR, following a hierarchical approach **(Fig. 4)**. Initially, a literature review was conducted to compile injury-related changes observed in athletes and operating across various domains of the CNS, providing a theoretical foundation for the anticipated decline in pass accuracy. Subsequently, a passing task applicable with mobile EEG was developed. Given the drawbacks of mobile EEG – such as movement artifacts and volume conduction – that may impact within-individual consistency of findings, reliable cortical correlates of this task were established using a repeated-measures design. Further, the investigation focused on differences in behavioral and cortical correlates of the passing task between novice and experienced players, followed by comparisons between healthy and injured players. This approach aimed to elucidate the dynamics that promote pass accuracy and how these dynamics are affected by ACLR. The individual aims of the studies are outlined below:

Literature review: The objective of the literature review was to map existing evidence regarding neurophysiological and neurocognitive changes in athletes associated with ACL injuries. This binary perspective allowed to bridge changes in the CNS with neurocognitive functions essential for meeting sport-specific demands, while also highlighting increased cognitive load resulting from sensory compensation. Additionally, the summary of the methods and tasks used provided an overview of gaps in the current literature concerning ecological validity and sport-specificity.

Study I: The first experimental study aimed to describe cortical dynamics with high internal consistency based on source-derived ERSPs in novices during a target-directed pass-kicking task. To focus on consistent patterns exhibiting low within-individual variability across sessions, measurements were repeated after one week, allowing for a detailed description of the cortical correlates associated with short-distance passes based on reliability estimates of ERSPs.

Study II: The subsequent study aimed to characterize behavioral and cortical dynamics linked to improved pass accuracy within a novice-expert paradigm. To understand differences in the ability to produce consistently accurate kicks across varying temporal resolutions, trial-to-trial variability in biomechanics was compared between 15 novices and 15 experienced football players using MSE. Furthermore, kick-related ERSPs were analyzed between groups in posterior and frontal clusters to examine differences in cortical dynamics identified in Study I.

Study III: The final study aimed to explore the influence of an ACL injury on skilled pass accuracy from both behavioral and cortical perspectives. Utilizing the same methodology in Study II, variability in kicking biomechanics was compared using MSE, alongside an analysis of kick-induced cortical patterns through ERSPs. As an innovative complementary add-on in a mobile setting, MSE analysis was performed on EEG data to assess whether task demands and compensatory strategies interfere with information flow in task-related areas.

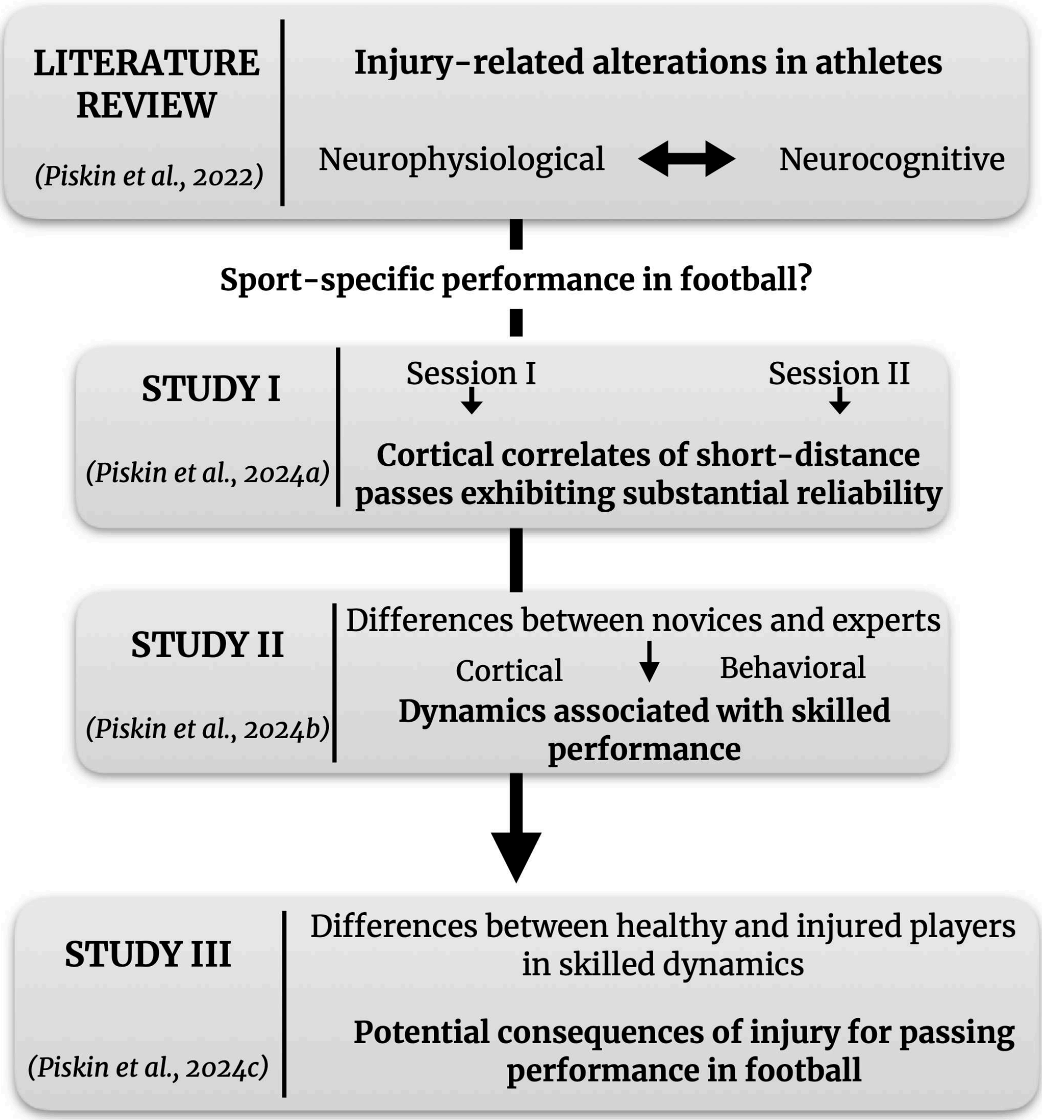

Fig. 4: Schematization of individual objectives

2. METHODS

The following sections outline the methodological approaches employed in the literature-based and empirical studies that comprise the current cumulative dissertation. To investigate cortical dynamics associated with kicking in both healthy and clinical cohorts, behavioral and cortical measures were analyzed in Study I, II and III. While some measures were common across studies, the sequential nature of the research necessitated the introduction of specific measures in subsequent studies to enhance the understanding of new findings derived from previous work. The incorporated measures will be detailed in their respective sections along with justification for their use. Statistical analyses are described individually in the methods sections of the published articles.

2.1. Study designs

The design and sample characteristics of the studies are summarized in **Tab. 1**. The literature review was conducted as a scoping review due to its binary objective structure and the diversity of methodologies used in relevant studies. In study I, a repeated-measures design was utilized to characterize cortical dynamics with low within-individual variability based on reliability estimates of ERSPs. Several studies have assessed the reliability of EEG parameters due to inherent challenges such as movement artifacts and volume conduction before applying these measures in various contexts (Büchel et al., 2021; Domingos et al., 2023; Espenhahn et al., 2017). High test-retest reliability for a given measure is accepted as indicative of task-related states exhibiting high internal consistency across sessions (Lopez et al., 2023). Therefore, Study I focused on reproducible dynamics to elucidate brain activity during kicking while providing reliable measures for subsequent investigations. In alignment with their objectives, Study II and III were designed as comparative cross sectional studies exploring differences in behavioral and cortical dynamics associated with kicking between novice and experienced football players, as well as between healthy and injured football players who have undergone ACLR.

	Study design	Sample
Literature review	Scoping review	16 studies including a total of 302 healthy (n_{female} = 123) and 295 injured athletes (n_{female} = 118)
Study I	Repeated-measures design	11 novice football players
Study II	Comparative cross-sectional	15 novice and 15 experienced football players
Study III	Comparative cross-sectional	15 healthy and 10 injured football players who have undergone ACLR

Tab. 1: Design and sample characteristics of studies

2.2. Sample characteristics

Given the sport-related structural and functional reorganization of the CNS within athletic populations (Chang et al., 2018; Nakata et al., 2010; Yarrow et al., 2009), the literature review aimed to summarize injury-related changes exclusively among athletes. Inclusion criteria dictated comparisons between either healthy and injured athletes, or pre- and post-injury measures. Studies were excluded if participants: i) were older than 40 years (due to an increased likelihood of developing osteoarthritis following joint trauma), ii) were non-athletes, iii) had experienced knee dislocation or iv) had undergone revision surgery (as these concomitant orthopedic conditions may confound results). A total of 302 healthy (n_{female}=23) and 295 injured (n_{female}=118) athletes participated in the included studies **(Tab. 1)**. Their ages ranged from 16 to 27 years and the engaged sports were football, American football, basketball, handball, volleyball, softball, lacrosse, hockey, and fencing.

Study I examined reproducible cortical patterns associated with target-directed kicking in 11 healthy participants (n_{female}=3), aged between 18 and 35 years (27.42 ± 3.68 years), all right-dominant in both upper and lower extremities and physically active at a recreational level only. Laterality was determined using the Lateral Preference Inventory (LPI; Coren & Porac, 1978), while activity levels were assessed using the Marx Activity Scale (MAS; Marx et al., 2001). Participants with expertise in any sports characterized by regular long-term participation (Silva et al., 2022; Wang et al., 2024) were excluded from the study due to potential confounding effects on precision skills related to effector- (Heppe & Zentgraf, 2019) and sport-specificity (Barros et al., 2017).

Study II recruited 15 healthy novices (n_{female}=7, 26.87 ± 3.54 years) and 15 healthy amateur football players (n_{female}=6, 22.40 ± 3.67 years) to investigate skilled behavioral and cortical dynamics linked to superior accuracy in kicking. Novices had no prior experience in football or any other sports requiring running, cutting or pivoting - movements that could enhance precision skills in the lower extremities (Wang et al., 2024). Football players had a minimum of 10 years' experience playing football with at least two training sessions and one game per week (Silva et al., 2022). Activity levels were compared using MAS between both groups. All participants were right-dominant in the upper and lower extremities as determined by LPI.

Study III compared behavioral and cortical dynamics associated with kicking between a cohort of 15 healthy (n_{female}=6, mean age: 20.50(4.50)) and 10 injured players who had undergone ACLR (n_{female}=4, mean age: 25.50(3)). No significant differences were observed regarding age, height or body mass index between groups. Among injured players, grafts were reconstructed from semitendinosus (n=6), patellar (n=3) and quadriceps tendons (n=1), with an average time interval of approximately 5.05(3.60) months between surgery and measurement. The Knee Injury and Osteoarthritis Outcome Score (KOOS) indicated reductions in self-reported knee functions across five domains including pain, symptoms, activities of daily living, sport and recreation, and quality of life (Roos et al., 1998). During execution of the kicking task, perceived pain levels were assessed using visual analogue scale (VAS; Hawker et al., 2011), which has been shown to influence cortical activity (Barber Foss et al., 2022; Iuamoto et al., 2022). Reported pain levels were recorded as zero within the ACL group. Both healthy and injured players had played football for at least 10 years prior to participation and MAS revealed no statistically significant differences in activity level between the groups.

2.3. Ethics

The local ethics committee at Paderborn University approved the conduction of Studies I, II and III in accordance with the Declaration of Helsinki. All participants received comprehensive information regarding the rationale, objectives, and procedures involved in each study, their rights to withdraw consent at any time during participation, as well as data protection regulations. Prior to measurements, investigators addressed all participant inquiries thoroughly and written consent was obtained from each participant along with corresponding dates documented accordingly. Participants received copies of their informed consent forms while original documents were securely stored by the principal investigator. To ensure anonymity throughout participation processes, all forms containing personal information required for study objectives, as well as digitally recorded physiological data, were assigned individual identification codes for confidentiality purposes. The storage protocols adhered strictly to the 13. Article of the General Data Protection Regulation established by of the European Union legislation.

2.4. Experimental procedures

Studies I, II and III were conducted in the Exercise Science and Neuroscience laboratory at Paderborn University. Prior to data acquisition, participants were briefed on the experimental procedures, and the equipment was introduced. Demographic and relevant data were collected using custom questionnaires. The MAS and LPI were administered to assess the activity level and laterality of participants, respectively (Coren & Porac, 1978; Marx et al., 2001). Injured participants completed an additional custom anamnesis form that inquired about the details of their injury and surgical procedure. The KOOS was utilized to evaluate self-reported knee function (Roos et al., 1998).

To investigate the behavioral and cortical dynamics associated with passing accuracy, a short-distance kicking task was developed and employed in all three studies, which will be detailed in the following section. Anatomical motion and EEG signal were recorded continuously during the execution of kicks using wireless devices. Given the influence of stress exposure on cortical activity during kicking (Slutter et al., 2021), participants were asked to rate their perceived level of stress using a VAS after completing the task. In injured cohort, perceived task-related pain level was also recorded using a VAS (Hawker et al., 2011).

2.4.1. The short-distance passing task

The current dissertation focused on short-distance passes due to their relevance in game scenarios as well as methodological considerations. From a practical standpoint, short-distance passes facilitate ball possession retention and create various scoring opportunities during gameplay (Adams et al., 2013; Lago-Peñas et al., 2011). Methodologically, longer-distance targets require higher kicking speeds, which may introduce greater behavioral variance influenced by anthropometric factors and the trade-off between speed and accuracy (Bekris et al., 2015; van den Tillaar & Fuglstad, 2017). Given the limited evidence pertaining to cortical dynamics associated with pass accuracy, employing a more standardized behavior may enhance the understanding about how cortical activity contributes to accurate passing while allowing for further investigation into variables such as distance and speed. In this context, a short-distance passing task compatible with wireless devices was developed for use in all three studies (**Fig. 5**). Participants executed side-foot kicks toward a target placed at a distance of three meters. The target consisted of a rectangular wooden block (10 x 15 cm), aligned perpendicular to a FIFA size 5 football. To minimize vertical kicking errors (Hunter et al., 2018), a smaller target was selected compared to wider goals typically used in field settings. This choice aimed to provide a more precise description of on-target kicks while reducing variance in motor behavior. Participants positioned their left foot neutrally next to the ball while externally rotating their right foot behind it at a distance determined by themselves. The floor was marked corresponding to the front edge of their left shoes to standardize starting position across trials. They were instructed to kick the ball as accurately as possible using the inside of their foot (Zago et al., 2014). Each participant completed a familiarization block consisting of 10 kicks before proceeding with six blocks of 15 trials interspersed with breaks. The total number of trials was determined based on pilot data analysis indicating that this quantity was sufficient for depicting clear cortical patterns associated with kicking.

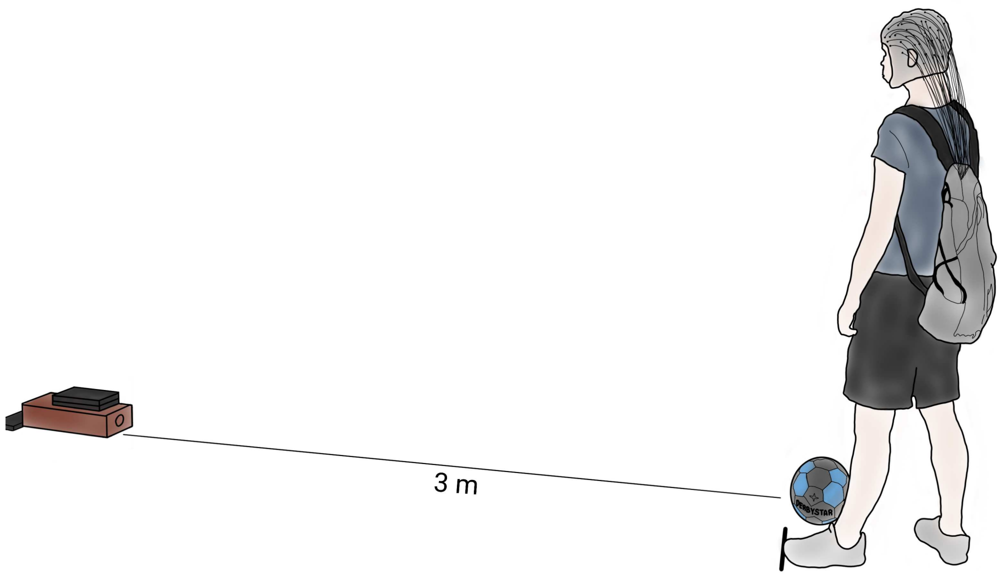

Fig. 5: The short-distance passing task *(sketched by and used upon permission of Romina Müller)*

2.4.2. Recording of behavioral data

In the current dissertation, the biomechanics of the kicking leg were recorded using an inertial measurement unit (IMU) to provide complementary data for understanding skilled behavior, its associated cortical dynamics, and how these two aspects may be impacted in injured players. The contextual definitions of the analyzed variables and their relevance to the individual objectives of the studies will be elaborated upon in subsequent sections. IMUs are motion tracking systems that typically consist of sensors equipped with integrated accelerometers, gyroscopes, and occasionally magnetometers (Hoflinger et al., 2013). These integrated instruments measure linear acceleration, angular velocity, motion range and magnetic field strengths, making them widely applicable in various research fields such as aerospace, robotics, brain computer interface, sport science and movement science. In sport science specifically, sensors with accelerometers and gyroscopes are commonly employed to measure linear acceleration, angular velocity and motion range across one or multiple axes, facilitating biomechanical analysis of movement (Alanen et al., 2021; Ghattas & Jarvis, 2021). Their validity for quantifying kicking biomechanics has been established previously (Blair et al., 2018).

In the current passing task, seven wearable IMU sensors (myoMOTION, Noraxon, USA) were utilized to record three-dimensional biomechanics of the lower extremities along the x, y, and z axes at a sampling rate of 200 Hz. Six sensors were bilaterally attached to the dorsal surfaces of the feet, tibial surfaces of the shanks, and lateral lower quadrants of the upper thighs, whereas one sensor was affixed to the sacral surface of the pelvis (Berner et al., 2020). The digitized signal for acceleration and joint angles were exported using system software (myoRESEARCH version 3.14., Noraxon, USA) for further analysis.

2.4.3. Recording of the EEG data

To elucidate cortical patterns associated with the kicking task and compare these patterns between novice and experienced players, and subsequently between healthy and injured players, a mobile EEG system (Brain Products, Germany) was used to record brain activity during experiments. Due to its high temporal resolution and mobility, EEG serves as a valuable tool to investigate movement-related cortical dynamics in both healthy individuals and clinical populations while facilitating transitions from laboratory setting to real-world tasks (Jungnickel et al., 2019). In sports neuroscience, EEG parameters are frequently used as markers of superior performance in sport-specific tasks (Park et al., 2015). Advanced source-localization algorithms combined with high-density systems featuring an increased number of electrodes help overcome issues related to volume conduction and low spatial resolution, and aid in unraveling movement-related dynamics by providing not only temporal, but also spatial information (Jung et al., 2000; Delaux et al., 2021). In the employed task, two wireless amplifiers (LiveAmp, Brain Products, Germany) and 65 active electrodes (actiCap, Brain Products, Germany), montaged according to the international 10-20 system were used to capture cortical activity. The AFz and FCz electrodes were designated as ground and reference electrodes, respectively (Pivik et al., 1993). Each amplifier is compatible with up to 32 electrodes, therefore, two combinable amplifiers were utilized to achieve a total of 64 electrodes since increasing the number of electrodes from 32 to 64 has been shown to improve source localization accuracy significantly (Sohrabpour et al., 2015). To reduce impedance levels to 25 kΩ, a high-viscosity electrolyte-gel was applied. Particularly at elevated impedance levels, active electrodes have been found to outperform passive electrodes (Laszlo et al., 2014). Additionally, a three-dimensional acceleration sensor (Brain Products, Germany), connected directly to one amplifier, was positioned posteriorly to the lateral malleolus to detect kick onset for subsequent analyses. The EEG signal was recorded continuously using BrainVision Recorder (Brain Products, Germany) at a sampling rate of 500 Hz.

2.5. Multiscale entropy analysis of kicking biomechanics

In the current dissertation, the objective of Study II was to explore skilled behavioral and cortical dynamics associated with superior accuracy in short-distance passing. Study III aimed to examine whether and how these dynamics may be compromised by an ACL injury. Therefore, in Studies II and III, trial-to-trial variability of kicking movements was analyzed using MSE as a behavioral measure. Initially, the original series was down-sampled to coarser time resolutions by averaging two consecutive non-overlapping data points in the course-graining procedure. The formula for this process is given as:

$$y_j^T = \frac{1}{T} + \sum_{i=(j-1)T+1}^{jT} x_i,\ 1 \le y_j \le \frac{N}{T}$$

here T corresponds to time scale, y_j represents the new constructed time series, x_i denotes a data point in the series, and N indicates the length of the original time series (Costa et al., 2002). At scale one, the coarse-grained series equals the original time series. At scale two, it is constructed by averaging two consecutive data points; at scale three by averaging three consecutive data points; and so forth **(Fig. 6)**.

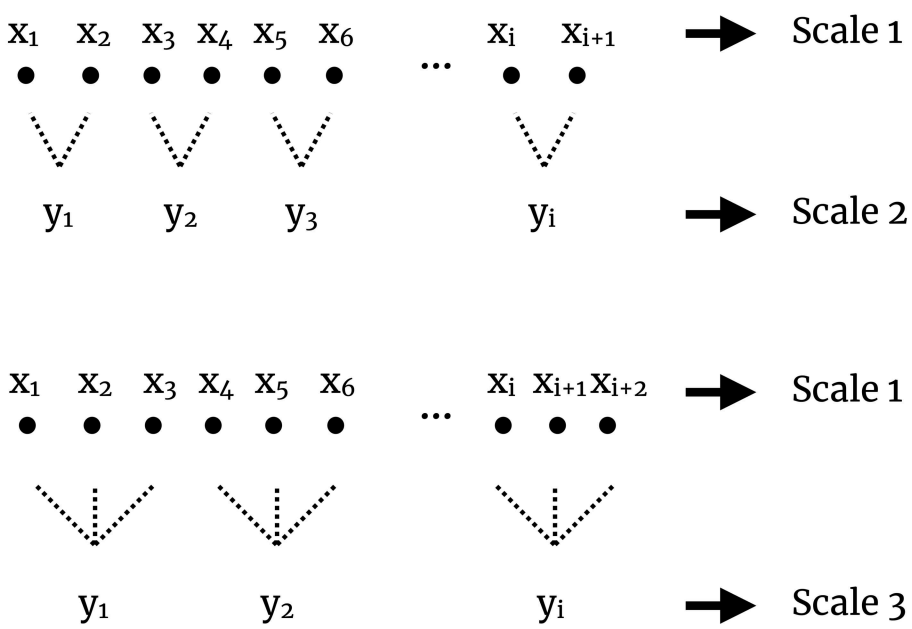

Fig. 6: Coarse-graining procedure

Subsequently, SE is computed for each constructed time scale. Typically, this involves measuring the probability of matched amplitude templates at a sequence length of *m* (embedding dimension) data points when a new sequence is introduced at length *m* + 1 is introduced. Matched templates are determined based on a predefined similarity criterion (*r*). For example, when *m* = 2 and *r* = 0.50, the template starting with data point x_i is searched within $x_i \pm r$ x SD of the signal. This process is repeated for data points x_{i+1} and x_{i+2}, with proportions calculated for matched templates consisting of two and three components **(Fig. 7)**. The SE is then computed as the natural logarithmic of this ratio as follows:

$$S_E(m,\ N,\ r) = \ln\frac{A}{B} \ = \ln\frac{\sum_{i=1}^{N-m} n_i^m}{\sum_{i=1}^{N-m} n_i^{m+1}}$$

where *m* represents embedding dimension, *N* denotes total number of data points, *r* signifies similarity criterion, and *n* indicates the number of vectors close to a template vector *i* with the dimension of *m* (Costa et al., 2002).

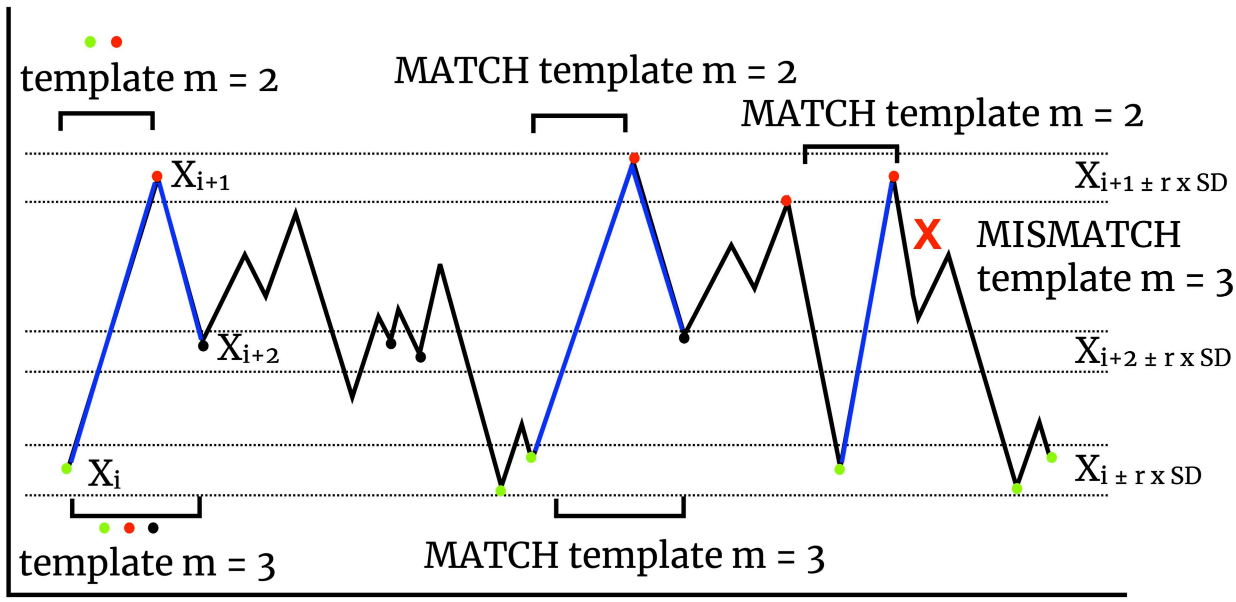

Fig. 7: The determination of matched templates for the embedding dimension of *m*=2 and *m*+1 based on the similarity criterion *r*

In Studies II and III, MSE was computed for foot acceleration and motion ranges including hip flexion, knee flexion, and foot external rotation to compare kinematic consistency during kicking between cohorts of interest. The analyses focused on three primary joints involved in kicking (Kellis & Katis, 2007; Lees & Nolan, 1998). Digitized signals were imported into MATLAB (version R2020b, The Math Works, USA) and segmented into trials based on kick-onsets. The acceleration signal along the *x*-axis (Lees et al., 2010) was rectified and smoothed using a Gaussian-weighted moving average filter with a window length of 20 data points (Mendi et al., 2013). Using MATLAB's *ischange* function - which predicates linear computational cost (Killick et al., 2012) - abrupt changes in the *x*-axis acceleration signal caused by kicking motion were detected and identified as kick-onsets. Based on these onsets, series were parsed into trials comprising 500 data points that included entire kicking sequences. Subsequently, MSE was computed on sparse signals formed by concatenated trials to profile variability on an intertrial basis using a custom script predicated on the work by Grandy et al. (2016).

In study II, an embedding dimension of $m = 2$ and a similarity criterion of $r = 0.15$ were employed to compute entropy estimates across 20 scales (Busa & Emmerik, 2016). Although varying values for r – ranging between 0.15 and 0.50 – have been implemented in studies performing MSE analysis on biological signals (Bisi & Stagni, 2018; Heisz et al., 2012), Grandy et al. (2016) found no significant effect of different values on entropy estimates. However, recent studies caution against using constant r values, as suggested by the original MSE algorithm. As SD decreases towards higher scales due to coarse-graining, entropy values may become inflated at shorter scales with broader similarity ranges (Kosciessa et al., 2020; Shafiei et al., 2019). Therefore, in Study III, MSE analysis was modified such that r was recalculated for each scale using updated SD (Nikulin & Brismar, 2004). Another aspect influencing reliability of entropy estimates pertains to the number of data points included in the analyses. A minimum threshold of $N = 1000$ for original series and $n = 100$ for shortest scale has been recommended for reliable estimates (Costa et al., 2005; Pincus & Goldberg, 1994). In both studies these suggested minima were assured with respect to included number of trials.

2.6. The analysis of event-related spectral perturbations

To compute ERSPs from epoched data, a baseline period - typically just before an event onset - is selected for normalization. The epoch is subsequently divided into overlapping data windows, and a moving average of spectral amplitude is calculated for each window using methods such as sinusoidal wavelets or short-time Fourier transforms. The spectral estimates are normalized by subtracting the mean baseline log power spectrum and averaged across trials. For *n* trials, if $F_k(f, t)$ represents the spectral estimate of trial *k* at frequency of *f* and time *t*, the ERSP in dB is computed as follows (Delorme & Makeig, 2004):

$$ERSP(f,t) = \frac{1}{n}\sum_{k=1}^{n} \left| F_k(f,t) \right|^2$$

Given the rapid nature of kicking movements, Study I aimed to describe fluctuations in kick-related cortical dynamics by means of ERSPs. An inherent problem in EEG analysis is volume conduction, which results in a summed projection of electrocortical activity onto scalp electrodes (Bell & Sejnowski, 1995). This means that when analyzing the activity of a region of interest at the channel level, recorded signal under an electrode may be contaminated by the activity of other regions. However, advanced source localization algorithms have rendered the decomposition of summed signals into mathematically independent components (IC) possible, making source-level analyses increasingly regarded as the gold standard in EEG research (Gwin et al., 2010; Protzak & Gramann, 2021; Peterson & Ferris, 2018). Particularly during complex motor tasks, the reliability of EEG measures can be compromised due to susceptibility to movement artifacts and aforementioned limitations. Most studies assess the test-retest reliability of EEG parameters to identify measures with high internal consistency prior to further investigations (Büchel et al., 2021; Domingos et al., 2023; Espenhahn et al., 2017). However, the internal consistency of ERSPs across sessions has not been investigated so far. Therefore, Study I repeated experiments twice to evaluate the reliability of source-derived ERSPs related to kicking and provide subsequent studies with a reliable measure and baseline findings.

The EEG signals recorded following the procedures outlined in section 2.4.3. were preprocessed and analyzed using the EEGLAB toolbox (version 14.1.2b; Delorme & Makeig, 2004). Preprocessing steps, which were identical for Study I, II and III, included removal of sinusoidal line noise (50 / 100 Hz) using the Cleanline plugin (Mullen, 2012), re-filtering the signal with a basic finite impulse response filter between 3 – 30 Hz, automated detection of noisy channels based on the kurtosis, probability distribution and the spectrum of the signal, re-referencing the signal to a common average, and down-sampling to 256 Hz.

The preprocessed data were epoched relative to kick-onset. Change points detected from the signal of the acceleration sensor (*x*-axis, Lees et al., 2010), which was connected to the amplifier, were identified as kick-onsets with linear computational cost as described in section 2.5. Epochs were extracted from -3000 to 3000 ms with 0 corresponding to kick-onset. This time window was selected to encompass dynamics associated with the preparatory phase observed up to 2000 ms before movement execution (Shibasaki & Hallett, 2006), as well as those occurring during execution itself. Due to wavelet transformation shortening epochs, a longer duration was initially selected. Following findings of Study I, Studies II and III epoched continuous signal from 0 ms to 2500 ms. Epochs containing non-stereotypical artifacts were removed after visual inspection. The epoched data were decomposed into maximally ICs using adaptive mixture independent component analysis (ICA; Palmer et al., 2011). To mitigate bias arising from unequal number of channels across sessions in Study I, removed channels were interpolated. The dimensionality reduction via principal component analysis was adjusted according to the number of channels removed to control for rank deficiency caused by spherical interpolation (Bigdely-Shamlo et al., 2015). Source localization estimation was performed using a standardized four-shell spherical head model (BESA, Germany) implemented in the DIPFIT plugin (Oostenveld & Oostendorp, 2002). Brain components were selected based on their activity patterns, source locations, and residual variance (<0.15), while non-brain components were excluded from further analysis. Subsequently, retained ICs were clustered via *k*-means algorithm. To avoid circular inference during statistical analyses, clustering was based solely on dipole locations (Kriegeskorte et al., 2009). The optimal number of clusters was determined using mathematical algorithms (Calinski & Harabasz, 1974; Davies & Bouldin, 1979; Rousseeuw, 1987). In Study I, clusters representing the same majority of the cohort (at least 50%) in both sessions, were considered for further analysis. In Studies II and III, clusters of interest were identified based on the findings of Study I. The ERSPs of these clusters were computed using the integrated STD_ERSP function within EEGLAB for a frequency range of 3 – 20 Hz since the activity of theta, alpha and beta bands are linked with cognitive and sensorimotor processes (Klimesch, 1999; Park et al., 2015; Reuter et al., 2022; Thompson et al., 2008). Frequencies above 20 Hz were sidelined due to potential contamination caused by muscular activity (Paluch et al., 2017). This process resulted in two-dimensional spectrograms depicting spectral perturbations with temporal information on the *x*- and frequency information on the *y*-axis **(Fig. 8)**. In Studies II and III, ERSPs associated with the kicking movement and described in Study I were compared between cohorts.

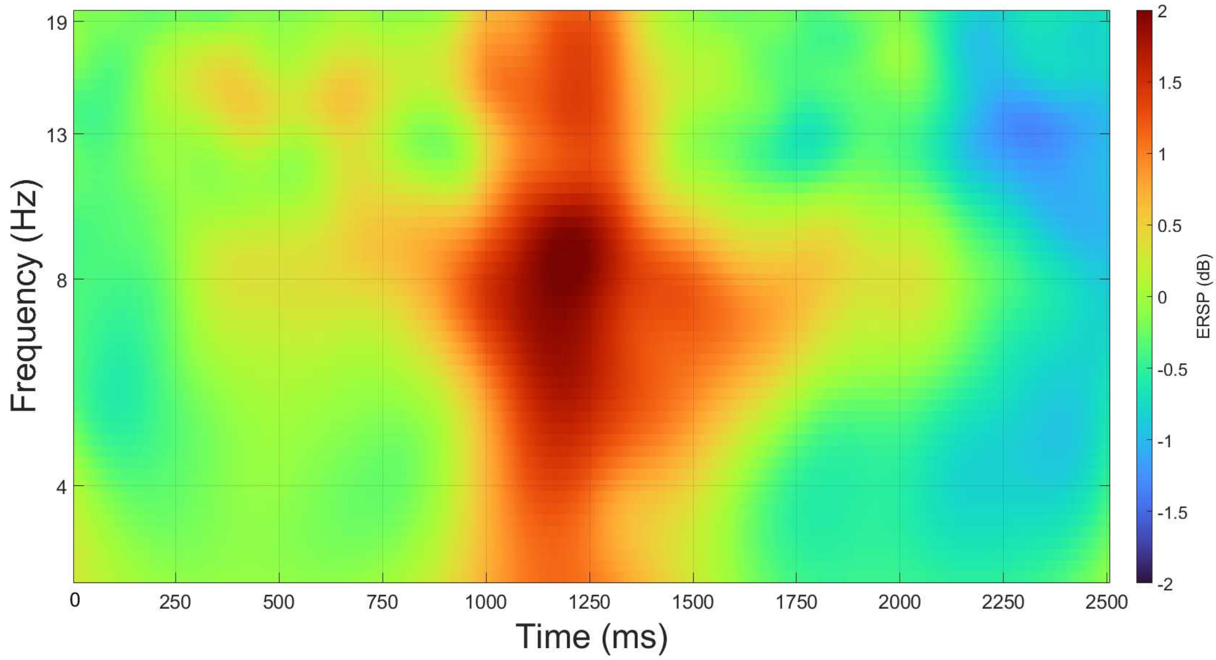

Fig. 8: An exemplary spectogram with temporal information on the *x*- and frequency information on the *y*-axis. The red pattern occurring at 1000 - 1250 ms shows an increase in spectral power (positive dB values)

2.7. Multiscale entropy analysis of EEG data

To investigate whether an ACL injury interferes with the kick-related information processing and leads to a loss of complexity in the regions examined in Studies I and II, MSE was incorporated as a complementary non-linear EEG measure in Study III. The MSE analysis was performed on EEG signals that had been preprocessed according to the steps explained in Section 2.6. Given the recognized impact of sampling rate, cut-off frequencies of band-pass filters, and artifact rejection methods on entropy estimates, customized preprocessing procedures are recommended for MSE analysis tailored to specific EEG datasets (Kosciessa et al., 2020; Puglia et al., 2022). Currently, no standardized pipelines exist for mobile settings; therefore, the preprocessing steps which were implemented in Study I and yielded reliable results, were also adopted in Study III. Removed channels were interpolated (Flo et al., 2022) and 80 random epochs - corresponding to the minimum number after removing noisy epochs across participants - were selected using POP_SELECT function to compute entropy estimation with an equal number of channels and data points x channel for each dataset. Subsequently, the epoched data were concatenated and entropy estimates were computed using the equations and custom scripts provided in Section 2.5. This approach has been shown to produce reliable entropy estimates (Grandy et al., 2016; Puglia et al., 2022). As previously mentioned, time scale one corresponds to the original series sampled at 256 Hz in MSE. The coarse-graining procedure down-samples the data, that is, when two neighboring non-overlapping data points are averaged at scale two, the sampling rate decreases to 128 Hz; at scale three, it decreases further to 64 Hz, and so forth (Kosciessa et al., 2020; Puglia et al., 2022). To include slow dynamics within the theta range - which is also represented in ERSPs starting at 4 Hz - the entropy estimates were computed across a total of 64 scales with scale one corresponding to 256 Hz and scale 64 to 4 Hz (Puglia et al., 2022). To focus specifically on kicking-related activity described in Studies I and II, entropy estimates were computed for two regions of interest over a time windows of 0 – 2500 ms. For assessing the complexity of frontal region, entropy estimates were extracted from the channels AF3, AFz, AF4, F3, F1, Fz, F2, F4; and for the complexity of the right posterior area from the channels Pz, P2, P4, P6, P8, POz, PO4, PO8, Oz, O2.

3. SUMMARY OF THE FINDINGS

The current section will summarize the main findings of the literature review and consecutive studies in relation to their objectives. The attributed figures belong to studies which are published with a creative common license (CC BY 4.0). The detailed findings with statistics are available in the original manuscripts.

3.1. Literature review: Neurocognitive and neurophysiological functions related to ACL injury: A framework for neurocognitive approaches in rehabilitation and return-to-sports tests (Piskin et al., 2022)

The primary objective of the literature was to collate existing evidence regarding neurophysiological changes observed in the athletic population subsequent to an ACL injury, and to determine whether these changes are reflected in neurocognitive functions essential for pursuing optimal performance in dynamic sports environments. The secondary objective was to emphasize the necessity of developing a framework for RTS tests and therapeutic interventions grounded in neurophysiological principles.

A total of 16 studies met the inclusion criteria **(Tab. 2 and 3)**, focusing on neurophysiological (n=10) and neurocognitive changes (n=6). The review included data from 302 healthy and 295 injured athletes. Neurophysiological measurements unveiled alterations across various structural and functional domains of the CNS, including cortical activation, connectivity between specific brain regions, corticospinal excitability, intracortical facilitation and inhibition, as well as reduced white matter volume. Notable differences were observed not only when comparing injured individuals to their healthy counterparts, but also between the injured and non-injured limbs, indicating asymmetries.

The studies reported an extensive time span between injury and measurements (from 2 weeks to 70 months), confirming that these alterations were evident during both the acute and recovered phase, persisting even years after the injury. Furthermore, studies with a prospective design indicated that athletes who later sustained an ACL injury exhibited differences in cortical activity already prior to injury compared to those who did not.

Study	Participants	Technique, Design	Time Course	Main Findings
Diekfuss et al. (2019)	ACL: n=2, female, 16±0 years Control: n=8, female, 15.9±0.8 years	fMRI, case control, prospective	Between testing and injury: 2 weeks and 3.5 months	Poorer connectivity between the left primary sensory cortex and right posterior lobe of cerebellum.
Diekfuss et al. (2020)	ACL: n=3, male, 16.33±0.58 years Control: n=12, male, 16.83±0.39 years	fMRI, case control, prospective	Between testing and injury: 57, 67 and 243 days	Poorer connectivity between the left secondary somatosensory cortex and left supplementary motor area, left primary somatosensory cortex and left primary motor cortex.
Zarzycki et al. (2018)	ACL: n=18, F:M=10:8, 21.8±3.3 years Control: n=18, F:M=10:8, 22.2±2.5 years	TMS, case control	2 weeks after ACLR	Corticospinal excitability is lower and intracortical facilitation is asymmetrical between two limbs in ACLR group.
Zarzycki et al. (2020)	ACL: n=18, F:M=10:8, 21.6±3.3 years Control: n=18, F:M=10:8, 22.3±2.5 years	TMS, case control, longitudinal	3 time points: (i) 2 weeks after ACLR, (ii) quiet knee, (iii) return to running	ICF is asymmetrical for the injured limb in ACL regardless of time point. Positive relationship between SICI and quadriceps strength at quite knee.
Tang et al. (2020)	ACL: n=20, F:M=5:15, 24.1±3.55 years Control: n=20, F:M=5:15, 22.3±2.62 years	TMS, case control	Between testing and injury: 31 months, between testing and ACLR: 27 months	SICI was lower and ICF was higher in the injured limbs.
Criss et al. (2020)	ACL: n=15, F:M=8:7, 20.9±2.7 years Control: n=15, F:M=8:7, 22.5±2.5 years	fMRI, case control	43.3±33.1 months after surgery	Increased activity and connectivity in brain regions associated with visuospatial cognition and attention.
Grooms et al. (2015)	ACL: n=1, male, 25 years Control: n=1, male, 26 years	fMRI, case control, prospective	10 months after initial, 26 days before secondary injury	Increased activity of motor planning, sensory and visuomotor areas after the initial, before the second injury.
Lepley et al. (2020)	ACL: n=10, F:M=6:4, 22.6±1.9 years	MRI, TMS cross-sectional	70.0±23.6 months after surgery	Reduced white matter volume and excitability in contralateral hemisphere.
Lepley et al. (2019)	ACL: n=11, F:M=6:5, 22.6±1.8 years Control: n=11, F:M=6:5, 23.2±1.6 years	fMRI, TMS, case control	69.4±22.4 months after surgery	Increased activation in frontal and cingulate cortex, increased active motor threshold and decreased motor evoked potentials.
Scheurer et al. (2020)	ACL: n=16, F:M=8:8, 20.4±1.8 years Control: n=16, F:M=8:8, 21.0±1.7	TMS, case control	33.9±26.1 months after surgery	Decreased corticospinal excitability and increased intracortical inhibition associate with reduced torque development.

Tab. 2: Sample characteristics, design, techniques and findings of studies investigating neurophysiological changes related to an ACL injury in the athletic population in the literature review *(Piskin et al., 2022)*

Study	Participants	Tests	Time Course	Main Findings
Swanik et al. (2007)	ACL: n=80, F:M=45:35, 20.7±1.5 years Control: n=80, age and gender matched	ImPACT: verbal memory, visual memory, reaction time and processing speed	Not given	ACL injured athletes showed slower reaction time and processing speed and had worse verbal and visual memory scores.
Mohammadi -Rad et al. (2016)	ACL: n=17 F:M=1:16, 26.8±6.5 years Control: n=17, F:M=1:16, 26.2±7.3 years	Dual tasking during postural stability (Auditory stroop test)	Between testing and injury: 6 to 12 months	ACL injured participants scarified their cognitive performance to maintain an optimal postural stability.
Ahmadi et al. (2020)	ACL: n=20, male, 26.6±3.5 years Control: n=20, male, 26.0±4.9 years	Dual tasking during postural stability (External focus and continuous cognitive tasks)	14.10±3.9 months after surgery	ACLR athletes responded to different cognitive loads with varying extents of postural sway.
Lion et al. (2018)	ACL: n=19, F:M=5:14, 24.8±6.4 years Control: n=21, F:M=10:11, 24.9.3±3.7 years	Dual tasking in double-leg stance (Silent backward counting)	9.2±1.6 months after surgery	No differences were found in sway area and path between patients and healthy controls.
Stone et al. (2018)	ACL: n=20, F:M=12:8, 22.0±3.0 years Control: n=20, F:M=12:8, 22.0±3.0 years	Trail making Reaction time Pursuit rotor task Purdue pegboard protocol Split-belt treadmill	Not given	Reconstructed participants performed better at trail making test and seemed to use different strategies for locomotor adaptation.
Negahban et al. (2013)	ACL: n=25, male, 24.9 ± 3.8 years Control: n=25, male, 24.9 ± 4.3 years	Dual tasking in single-leg stance (Backward digit span task)	14.1±1.7 months after surgery	ACLR patients demonstrated poorer postural stability in single-leg stance when performing a concurrent cognitive task.

Tab. 3: Sample characteristics, tests and findings of studies investigating neurocognitive changes related to an ACL injury in the athletic population in the literature review *(Piskin et al., 2022)*

Among the six studies investigating neurocognitive functions in injured individuals, five identified significant differences in the domains of reaction time, processing speed, visual and verbal memory, visual processing, and in dual-task performance from 6 to 14 months post-injury. Studies employing neurocognitive batteries reported decreased reaction times and processing speeds among injured athletes, whereas they performed better on tasks requiring visual attention. In dual-task paradigms, injured athletes tended to sacrifice either cognitive or motor performance.

3.2. Study I: Reliable electrocortical dynamics of target-directed pass-kicks (Piskin et al., 2024a)

The primary objectives of Study I were to characterize cortical dynamics associated with target-directed pass-kicks by means of source-derived ERSPs and to evaluate the test-retest reliability of these dynamics. Eleven healthy participants with no prior football experience participated in the experiment on two occasions, separated by a 1-week interval. The behavioral data elicited moderate reliability for the total range of motion in hip flexion, knee flexion and foot external rotation from Session I to II, suggesting a comparable kicking behavior across both trials.

From five identified cortical clusters, the right parieto-occipital and the mid-frontal cluster represented the same majority (at least 50%) of the cohort and were considered for reliability analysis. The kick-related activity observed in the parieto-occipital cluster was characterized by an alpha desynchronization emerging at kick-onset. The intraclass correlation coefficients (ICC) indicated moderate to excellent reliability, with higher estimates noted following ball contact **(Fig. 9)**.

The mid-frontal cluster depicted a theta synchronization from kick-onset to ball-contact, followed by an alpha desynchronization after ball-contact. The ICC estimates showed moderate to good, and moderate to excellent reliability for theta and alpha responses, respectively (**Fig. 10**).

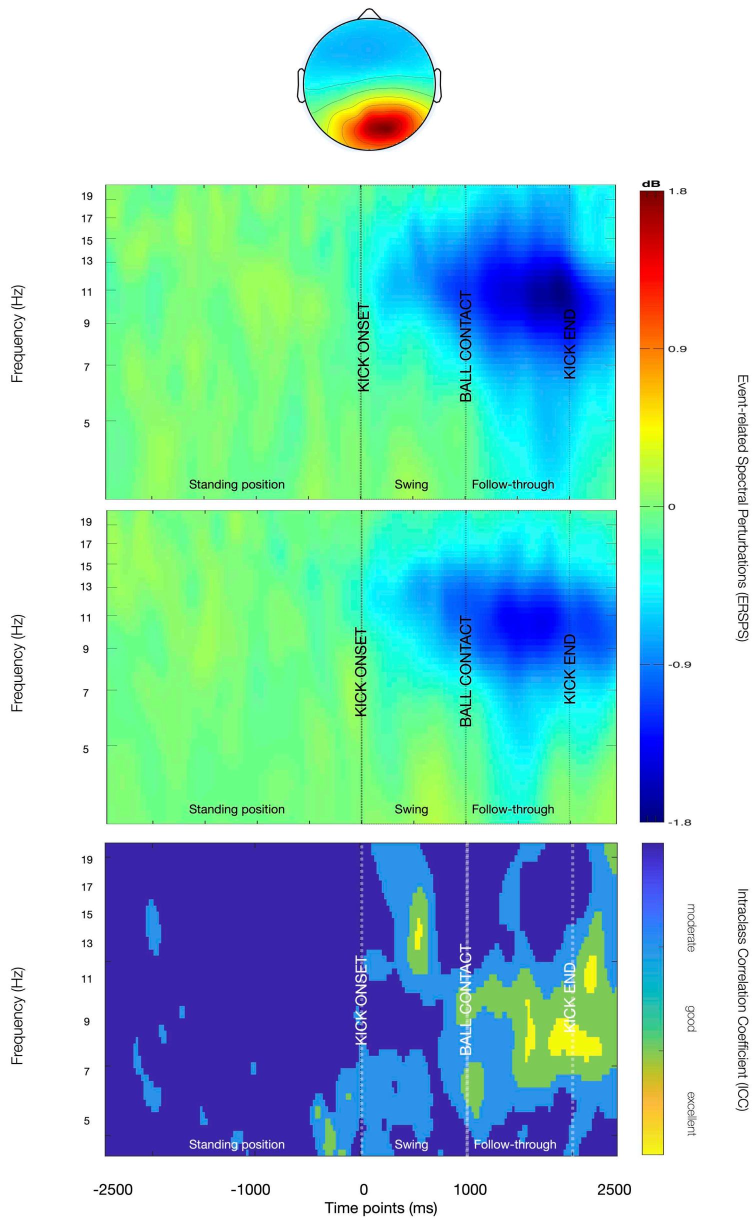

Fig. 9: The parieto-occipital ERSPs in session I (above) and session II (middle). The blue-colored pattern indicates desynchronization (negative values in dB) in the alpha frequency range starting with kick-onset. The below figure maps ICC estimates with the light blue color corresponding to moderate (ICC = 0.50 – 0.75), green color to good (ICC = 0.75 – 0.90) and yellow color to excellent (ICC >0.90) reliability. *(Reliable electrocortical dynamics of target-directed kicking by Piskin et al. (2024) is licensed under CC BY 4.0)*

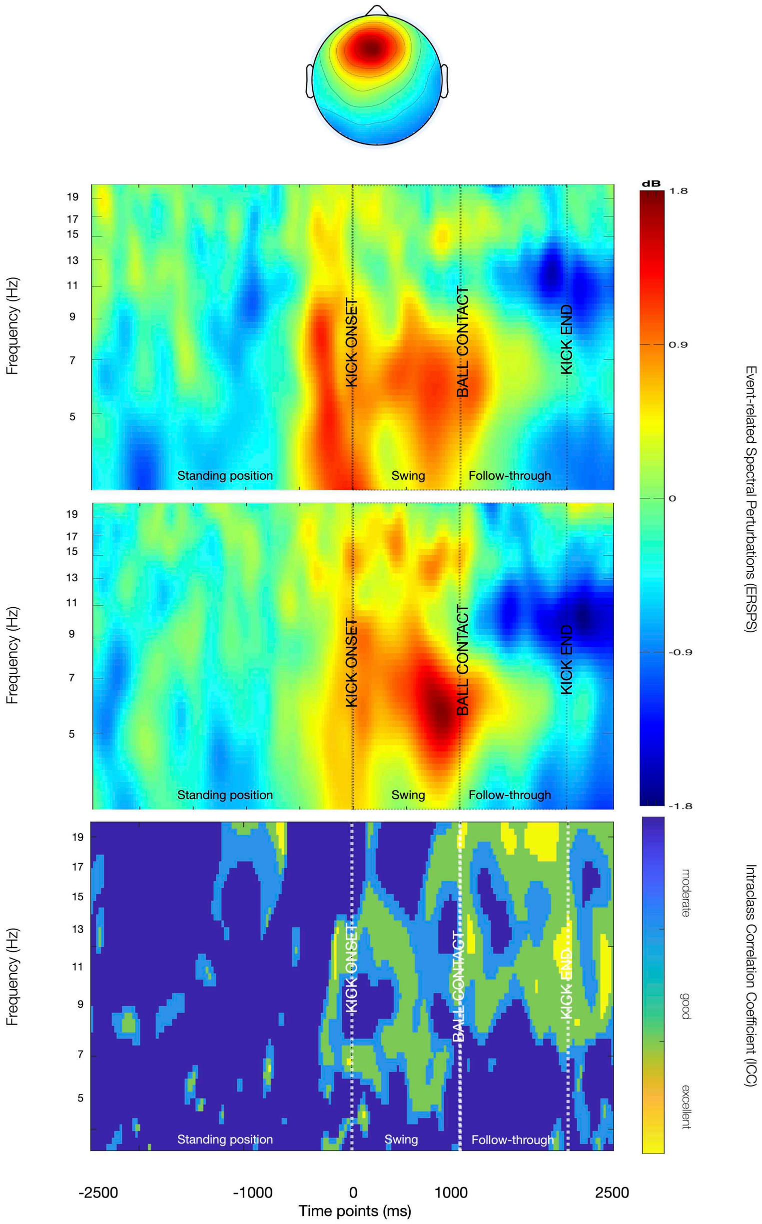

Fig. 10: The mid-frontal ERSPs in session I (above) and session II (middle). The red-colored pattern indicates synchronization (positive values in dB) in the theta frequency range starting with kick-onset, and the blue-colored pattern desynchronization in alpha frequency range following ball-contact. The below figure maps ICC estimates with the light blue color corresponding to moderate (ICC = 0.50 – 0.75), green color to good (ICC = 0.75 – 0.90) and yellow color to excellent (ICC >0.90) reliability. *(Reliable electrocortical dynamics of target-directed kicking by Piskin et al. (2024) is licensed under CC BY 4.0)*

3.3. Study II: Behavioral and cortical dynamics underlying superior accuracy in short-distance passes (Piskin et al., 2024b)

The objective of study II was to identify the skilled dynamics contributing to superior accuracy at both behavioral and cortical levels. Hereof, the ability to maintain a kicking behavior that yields higher accuracy in a stable setting along with its associated cortical underpinnings were compared between 15 healthy novices and 15 experienced football players. The behavioral data revealed significantly higher accuracy among experienced players. Entropy estimates computed on a trial-to-trial basis indicated that overall complexity was lower for foot acceleration, hip flexion, knee flexion, and foot external rotation in experienced players, with statistical significance observed specifically for hip flexion. Notably, differences became more pronounced at higher time scales **(Fig. 11)**.

To investigate how expertise modulates kick-related cortical dynamics identified in Study I, the ERSPs of the right parieto-occipital and frontal cluster were compared between the two groups. Experienced football players exhibited stronger alpha desynchronization in the right parieto-occipital cluster, occurring prior to ball contact. In contrast, novices showed weaker desynchronization that occurred after ball-contact, resulting in statistically significant differences **(Fig. 12)**.

Both groups demonstrated a theta synchronization in the frontal cluster. However, experienced players exhibited stronger synchronization, particularly at the moment of ball contact, which led to statistically significant differences **(Fig. 13)**.

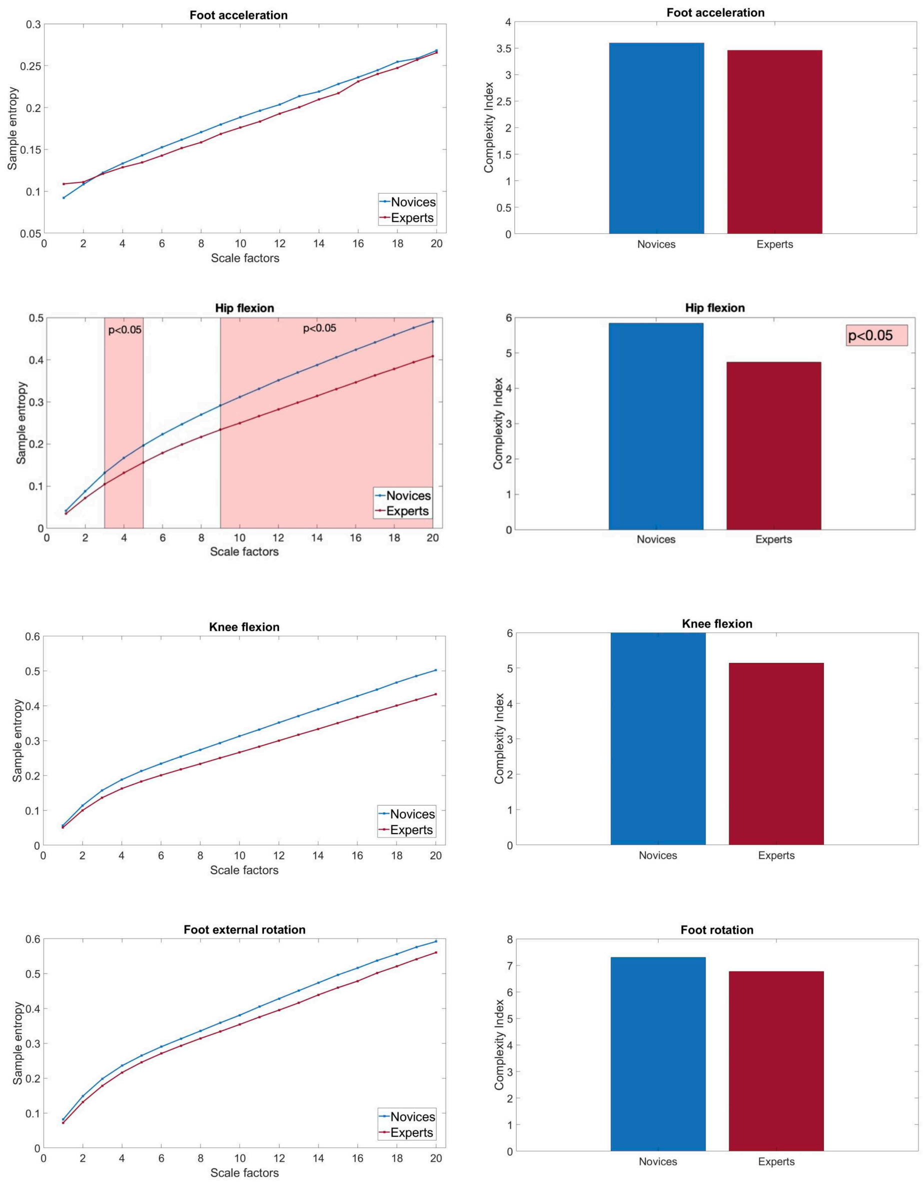

Fig. 11: Entropy estimates for foot acceleration, hip flexion, knee flexion and foot external rotation in novices and experienced football players (left column). The overall complexity index calculated as the area under the complexity curve shows lower variability in experts, reaching significance for hip flexion (right column). (*Behavioral and cortical dynamics underlying superior accuracy in short-distance passes* by Piskin et al. (2024) is licensed under *CC BY 4.0*)

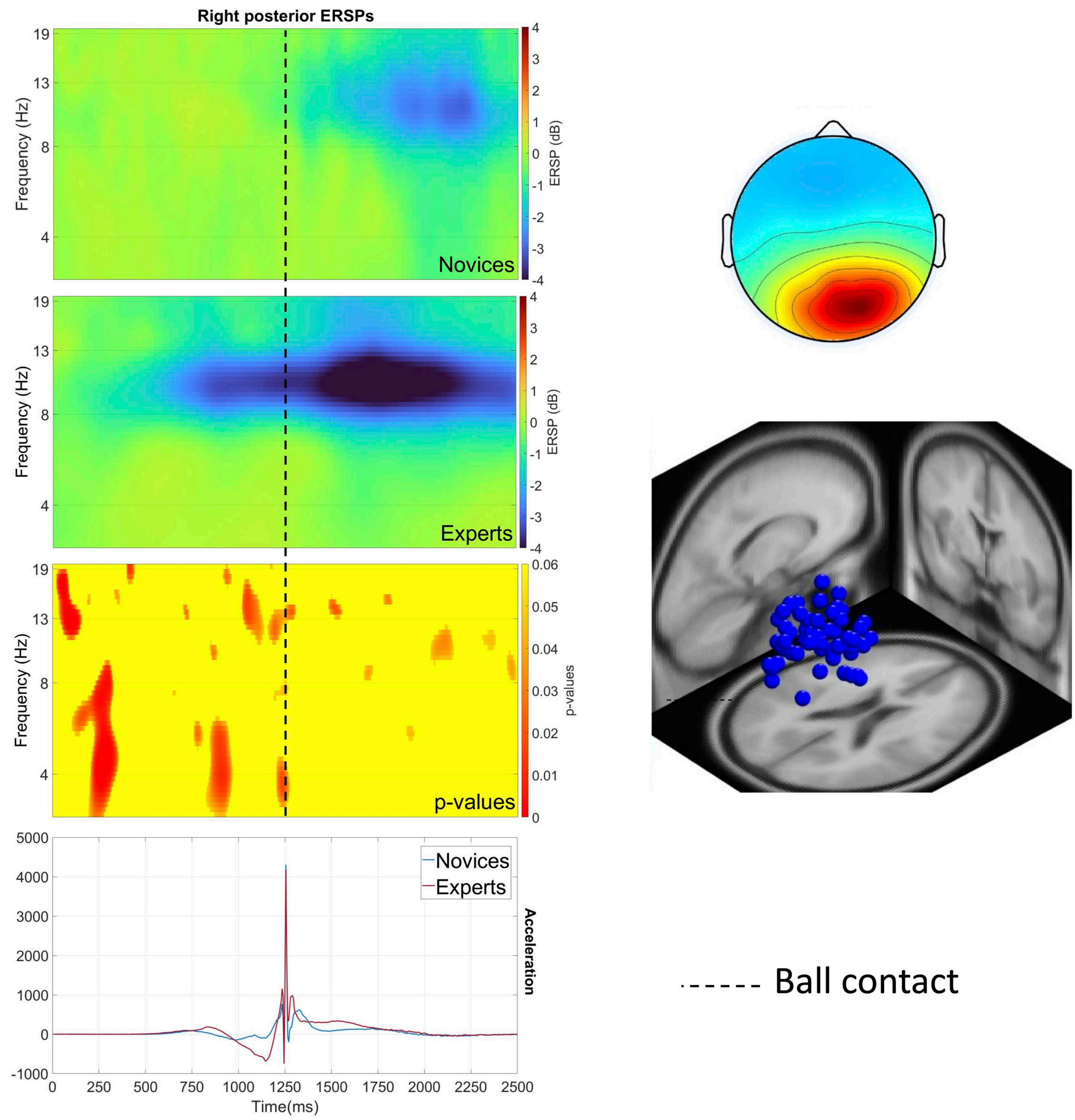

Fig. 12: The right parieto-occipital cluster shows a stronger alpha desynchronization (blue-colored pattern) in experienced players, starting prior to ball contact (the middle figure on the left column) and yielding statistically significant differences (the bottom figure on the left column). The right figure shows the distribution of ICs in the cluster. (*Behavioral and cortical dynamics underlying superior accuracy in short-distance passes by Piskin et al. (2024) is licensed under CC BY 4.0*)

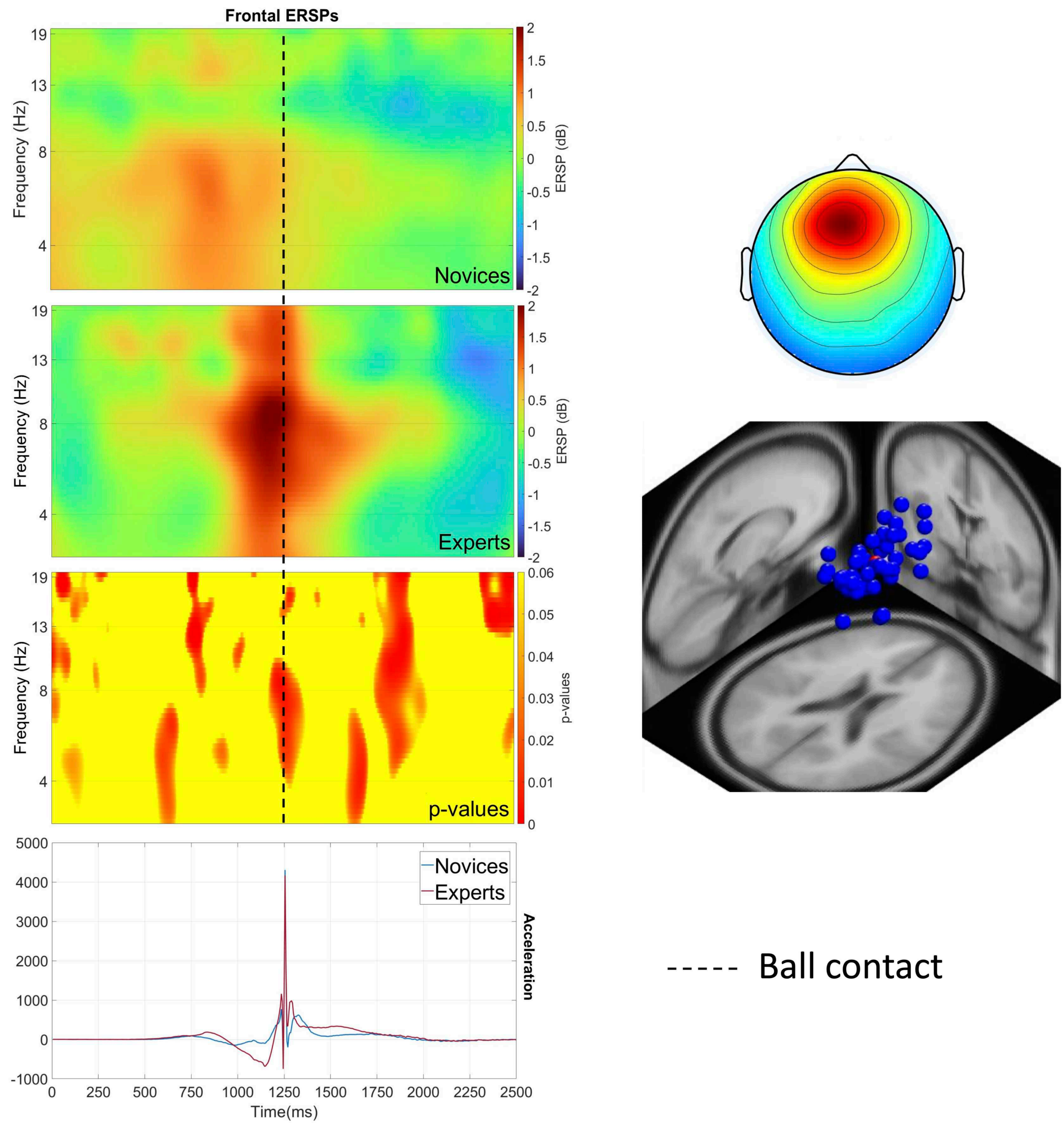

Fig. 13: The frontal cluster shows a stronger theta synchronization (red-colored pattern) in experienced players, particularly at ball contact (the middle figure on the left column) and yielding statistically significant differences (the bottom figure on the left column). The right figure shows the distribution of ICs in the cluster. (*Behavioral and cortical dynamics underlying superior accuracy in short-distance passes* *by Piskin et al. (2024) is licensed under CC BY 4.0*)

3.4. Cortical changes associated with an anterior cruciate ligament injury may retrograde skilled kicking in football: Preliminary EEG findings (submitted for publication)

Study III aimed to investigate the impact of an ACL injury on the behavioral and cortical correlates of skilled passing in football players. Building on the findings of Study II, entropy estimates of kicking motion in three joints - specifically hip flexion, knee flexion and foot external rotation - were compared between healthy players and those who have undergone an ACLR. While no significant differences were observed in accuracy rate or variability of hip and knee flexion between the groups, the entropy estimates for foot external rotation were significantly higher in injured players. This difference exhibited an incremental trend towards higher time scales **(Fig. 14)**.

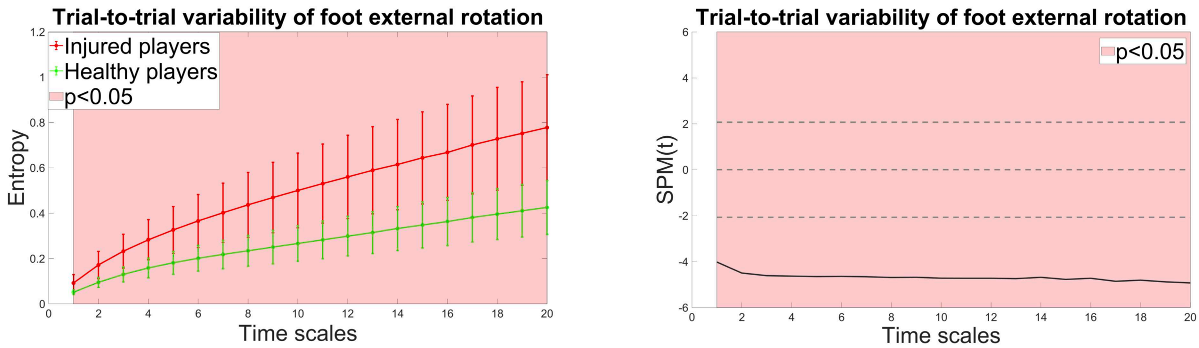

Fig. 14: Entropy estimates of foot external rotation in healthy and injured football players with significant differences in all 20 scales (left). The right figure exhibits the statistical parametric mapping (SPM) of observed differences.

The kick-related activity of two prominent cortical regions associated with skilled accuracy, namely the right parieto-occipital and frontal regions as identified in Study II, showed significant differences between the groups. Healthy players demonstrated stronger alpha desynchronization in the right parieto-occipital ERSPs, while injured players exhibited a stronger a theta synchronization subsequent to kick-onset **(Fig. 15)**. In the frontal cluster, both groups depicted a theta synchronization, which was notably stronger in injured players **(Fig. 16)**.

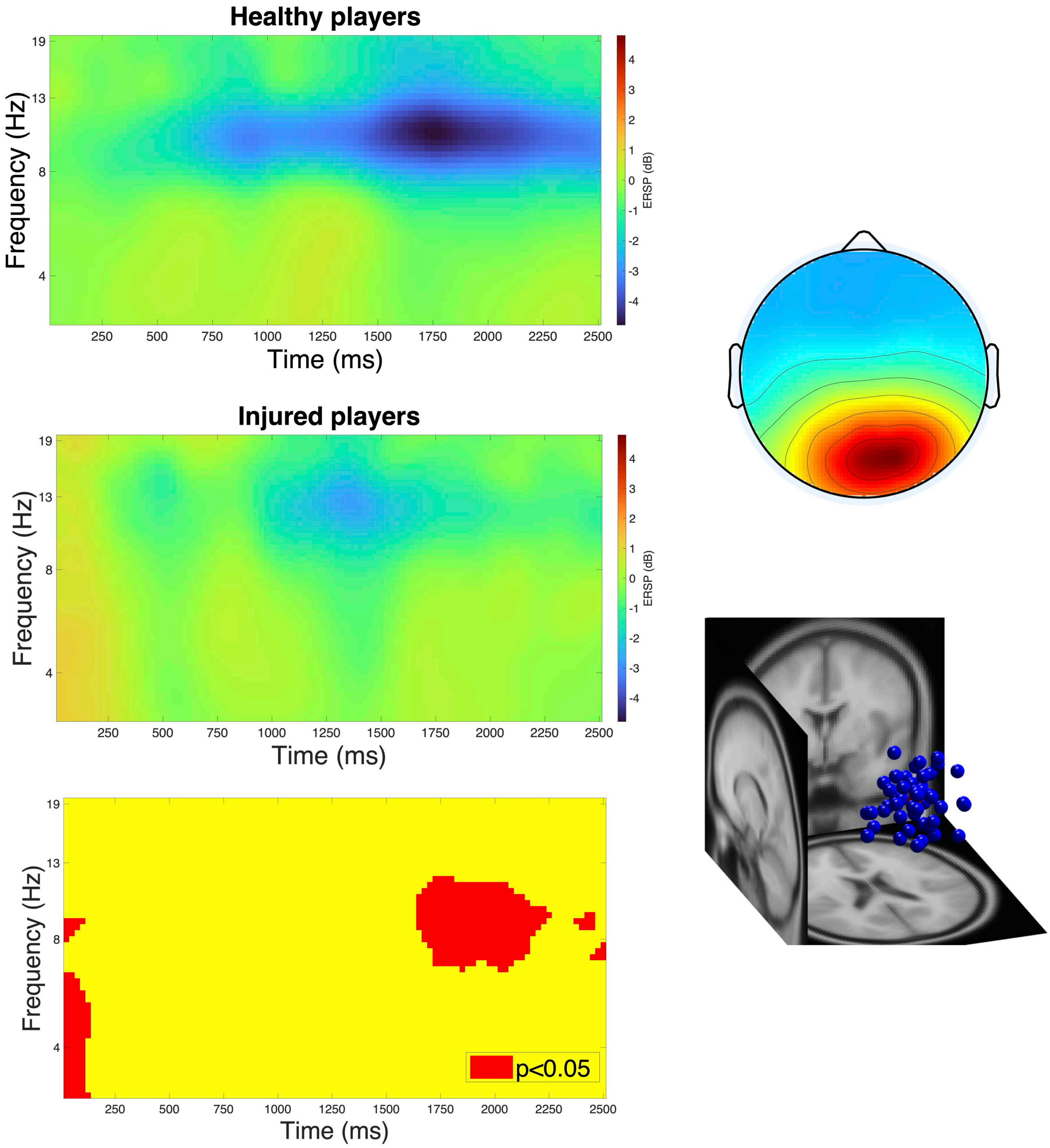

Fig. 15: Parieto-occipital ERSPs depicting a stronger alpha desynchronization (blue-colored pattern) in healthy players (left top). The left bottom figure maps significant *p*-values (shown in red). The top right figure shows the scalp map and the bottom right figure shows the distribution of ICs in the cluster.

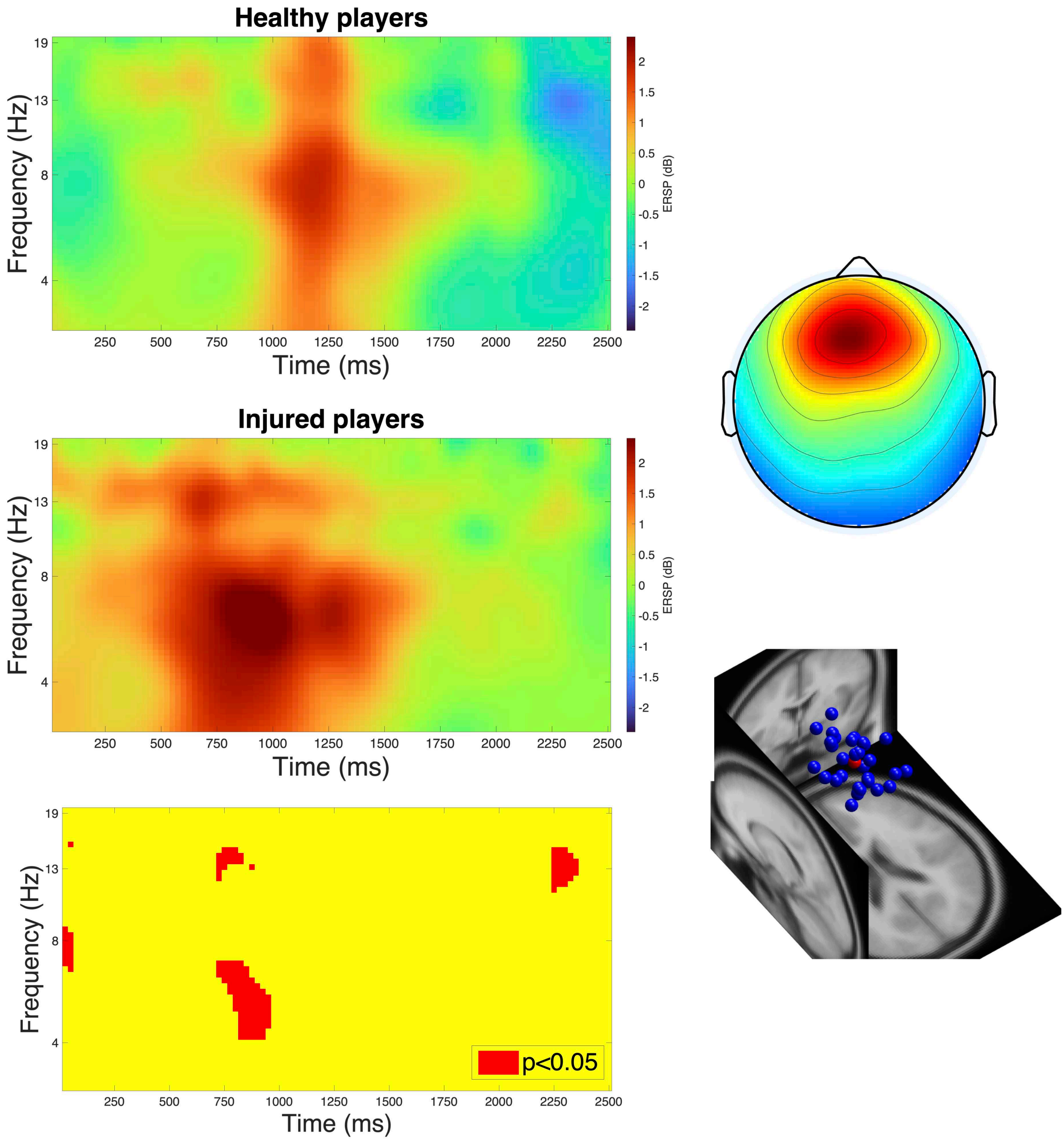

Fig. 16: Frontal ERSPs depicting a stronger theta synchronization (red-colored pattern) in injured players (left middle). The left bottom figure maps significant *p*-values (shown in red). The top right figure shows the scalp map and the bottom right figure shows the distribution of ICs in the cluster.

The complexity analysis of the right parieto-occipital region indicated lower entropy estimates in injured players at coarse and medium scales. Exceptionally, there were no significant differences for POz, while the estimates were higher for Pz also at fine scales in injured players **(Fig. 17, 18)**. In the frontal region, no significant differences were found for AF3, AF4, F3 and F1 electrodes. However, injured players showed lower entropy values in AFz, Fz, F2 and F4 at medium and coarse scales **(Fig. 19)**.

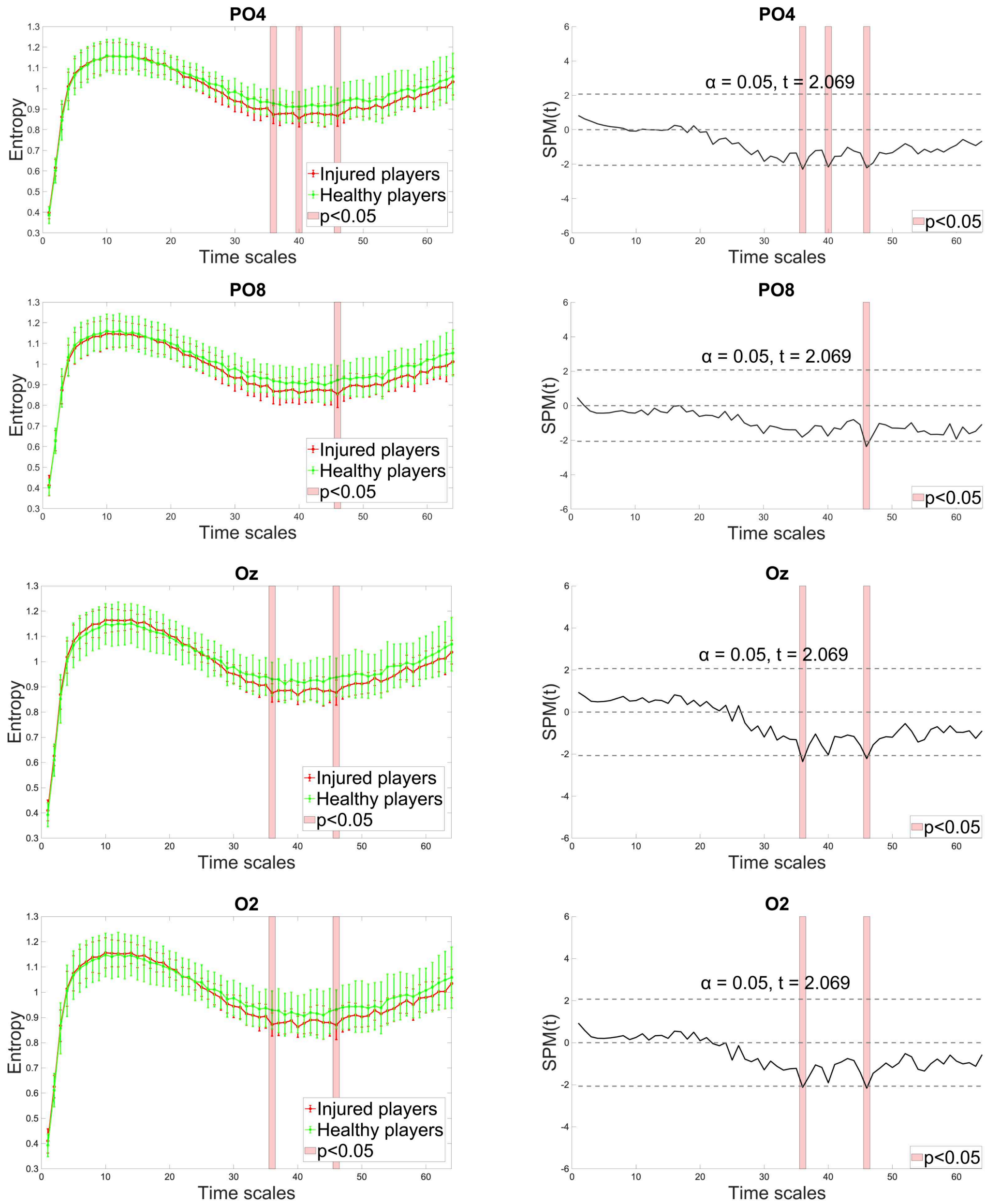

Fig. 17: Entropy estimates of channels in the parieto-occipital region along 64 scales with significant differences between the groups (left column). The right column shows the statistical parametric mapping of observed differences.

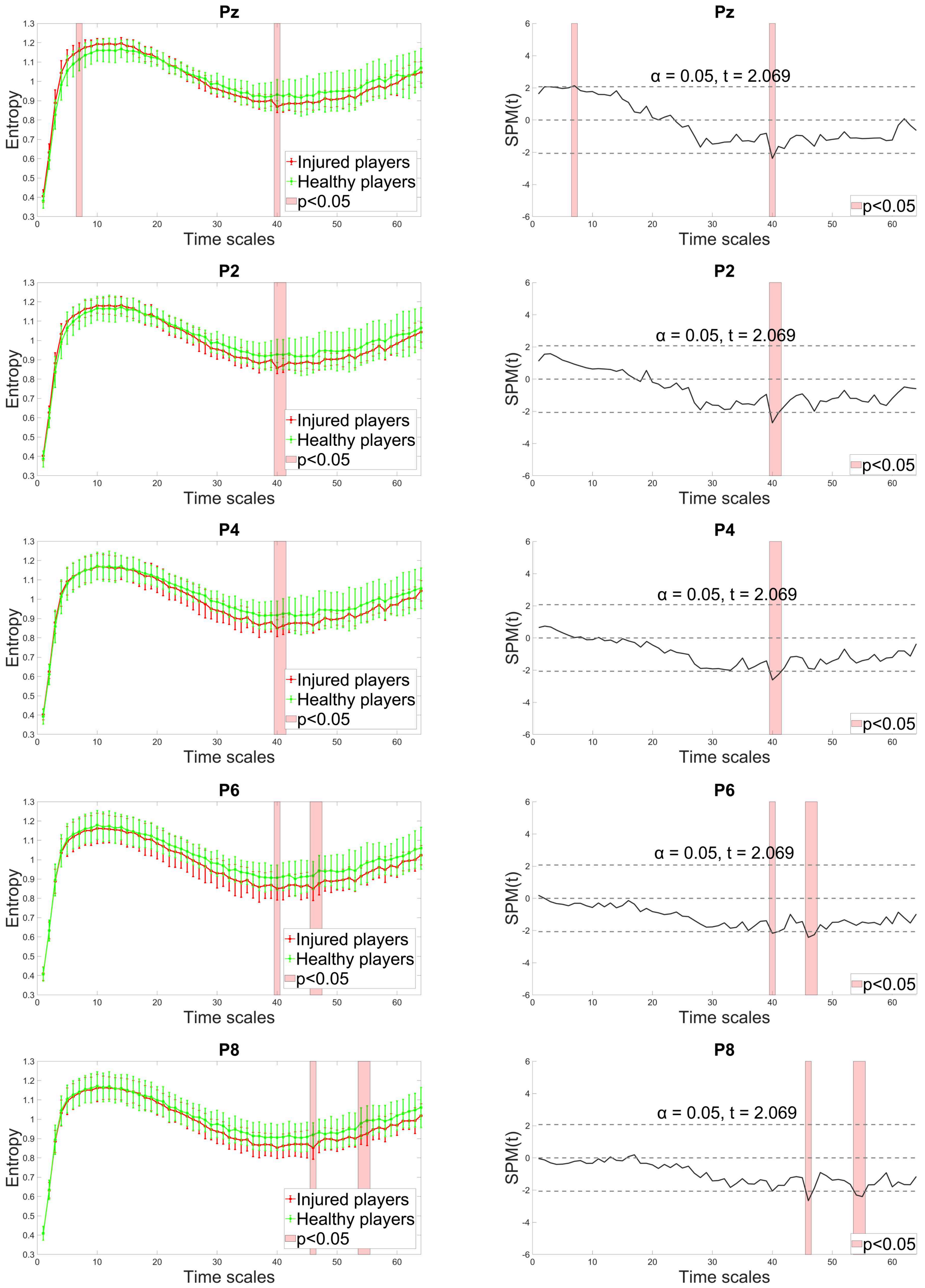

Fig. 18: Entropy estimates of channels in the parieto-occipital region along 64 time scales with significant differences between the groups (left column). The right column shows the statistical parametric mapping of observed differences.

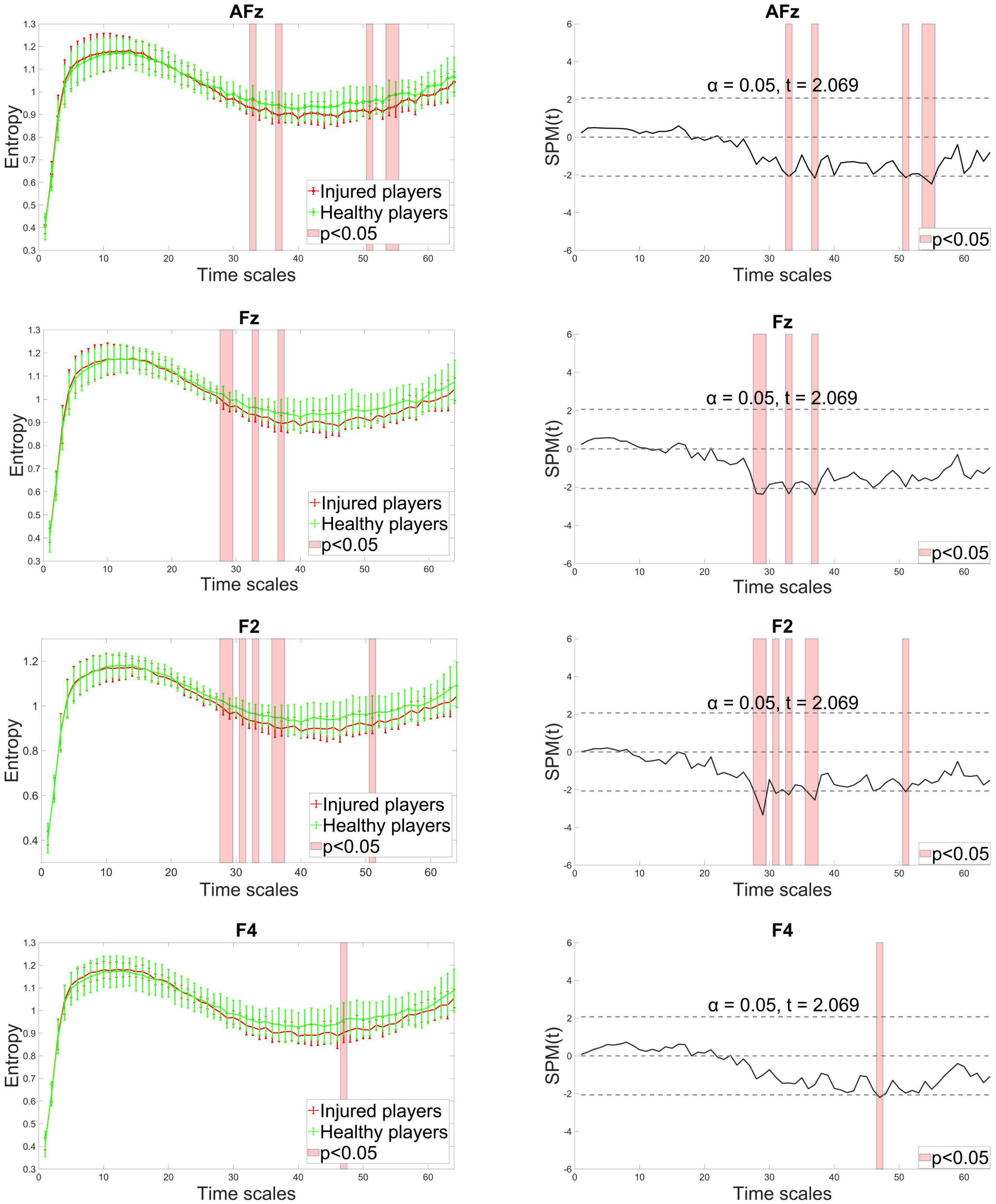

Fig. 19: Entropy estimates of channels in the frontal region along 64 time scales with significant differences between the groups (left column). The right column shows the statistical parametric mapping of observed differences.

4. DISCUSSION

The following section will present a synthesized discussion of the key findings derived from the conducted studies. A more comprehensive discussion of specific results can be found in the individual manuscripts. Subsequent sections will critically assess the strengths and limitations inherent in the methodological approaches employed and refer to their feasibility in achieving the objectives of the investigations. Furthermore, the implications of the findings will be discussed in terms of practical applications and prospective opportunities within the research landscape.

4.1. The main outcomes of the studies

The overall objective of the present dissertation was to comprehend the consequences of an ACL injury on skilled pass accuracy in football from a neurophysiological perspective. To establish a theoretical foundation for the empirical investigations, an initial literature review was conducted with a binary focus, bridging neurophysiological and neurocognitive alterations observed subsequent to injury. The collated findings of included studies highlighted the extension of altered CNS activity into neurocognitive functioning in injured athletes. Diverse neuroimaging and neurophysiological methods employed in investigations uncovered injury-related functional and structural adaptations operating within varying domains of the CNS. Reported changes in cortical excitability and inhibition (Lepley et al., 2019, 2020; Scheurer et al., 2020; Tang et al., 2020; Zarzycki et al., 2018, 2021), reduced corticomyographic potentials (Needle et al., 2017; Lepley et al., 2019) and white matter volume (Lepley et al., 2020) evidenced sensorimotor deficits in injured athletes as a consequence of altered afference and learned non-use of the injured or painful limb as a protective strategy (Hopkins & Ingersoll, 2000). Augmented activity in posterior regions and enhanced connectivity between cortical regions involved in attentional control and motor coordination suggested the compensation of these deficits through reweighting visuospatial and attentional information during motor tasks (Criss et al., 2020). Together with the decline reported for reaction time, processing speed and dual task performance (Ahmadi et al., 2020; Mohammadi-Rad et al., 2016; Negahban et al., 2013; Swanik et al., 2007), the literature review hinted at constrained neurocognitive capacity as a potential consequence of injury-related cortical strategies. However, despite critical findings providing a neurophysiological basis for post-injury performance declines in athletes, the utilization of simple tasks with poor ecological validity hindered the inference of sport-specific conclusions.

Building on this, the empirical studies intended to explore cortical dynamics associated with skilled performance in a football-specific task and whether these dynamics differ in injured athletes compared to their healthy counterparts using mobile EEG. Study I described kick-related dynamics by means of ERSPs detected in reproducible source-derived clusters and established their reliability across two different sessions to provide a task-specific physiological measure with high internal consistency for subsequent experiments (Lopez et al., 2023). Among five identified cortical clusters, the right parieto-occipital and mid-frontal clusters consistently represented the same majority of participants at both sessions. Since reoccurring ICs with comparable spatial distributions are seen as a potential cortical marker for a given task in source-level analysis (Grandchamp et al., 2012), the consistent activity of IC-derived clusters observed across two different sessions were highlighted as reliable cortical dynamics associated with target-directed kicking. The robust posterior alpha and frontal theta oscillations with substantial reliability depicted prominent visuospatial and attentional processes occurring upon the execution of a kick (Baumeister et al., 2008; Doppelmayr et al., 2008; Erickson et al., 2019; Worden et al., 2000). Furthermore, Study I also established ERSP as a reliable EEG measure to explore cortical dynamics associated with the developed kicking task in subsequent studies.

Replicating the experimental setting, Study II followed a comparative approach to unravel expertise-specific cortical modulations which contribute to skilled kicking behavior and examined differences in ERSP patterns addressed in Study I between novices and experienced football players. As expected, experienced football players achieved significantly higher pass accuracy which was associated with an overall lower complexity of kicking biomechanics reaching significance for hip flexion. This indicated their ability to predict and maintain a spatial pattern in the x-axis across trials that yielded higher accuracy (Davids et al., 2003; Schmidt, 2003; Stergiou & Decker, 2011). Furthermore, the negative correlation found between SE estimates of hip flexion and accuracy rate in both cohorts introduced improved control of hip flexion as a distinctive marker of superior pass accuracy, potentially facilitating optimal speed for optimal accuracy (Shan & Westerhoff, 2005; van den Tillaar & Fuglstad, 2017). Incremental differences in SE towards higher time scales indicated that variability of kicking as a gross motor behavior differed to a larger extent between the groups relative to fast biomechanical dynamics (Busa & van Emmerik, 2016). EEG findings provided a neurophysiological perspective to these differences by revealing expertise-specific modulations in kick-related cortical dynamics. Aligning with Study I, spatially comparable parieto-occipital and frontal clusters represented the majority of cohorts. Differences in parieto-occipital alpha suppression and frontal theta synchronization were interpreted as the improved ability of football players to process visual information and focus their attention at a higher extent during a kick (Clayton et al., 2015; Gevins, 1997). In the light of other supporting findings (Baumeister et al., 2008; Brenton & Müller, 2018; Chuang et al., 2013; Simonet et al., 2019; Voss et al., 2010), Study I and II collectively introduced visual and attentional resources critical while kicking and their effective use as a skilled strategy employed by experienced football players to promote an accurate kicking behavior.

Grounding on the overlap of visual and attentional processes contributing to skilled pass accuracy and their compensatory exploitation for injury-related deficits collated in the literature review, Study III explored whether ACL injuries have an influence on behavioral and cortical underpinnings elicited by Study II. As a novel add-on, MSE analysis was conducted also on EEG data to understand if injury constrains information processing capacity within right posterior and frontal regions. Although no significant difference was found in accuracy rate between healthy and injured players, entropy estimates of foot external rotation were significantly higher among injured players showing increased variability. This was attributed to a noisier spatial pattern potentially resulting from reduced proprioceptive acuity (Muaidi et al., 2009). Incremental group differences at coarser scales elicited that spatial noise became more evident upon integrating fast motion dynamics into a gross kicking behavior (Busa & van Emmerik, 2016). At the cortical level, these differences were associated with divergent responses of posterior alpha and frontal theta activity, indicating that healthy players processed visuospatial information during the execution of kicks more intensely, while injured players required a higher level of attention, which is a previously reported phenomenon following ACLR (Baumeister et al., 2008; 2011; Miao et al., 2017). Furthermore, MSE analysis revealed a decreased level of complexity in injured players specifically at coarser scales within these two regions and expanded the interpretation of EEG findings. As also compiled in the literature review, the compensation of sensory deficits during motor tasks imposes increased cortical load in injured individuals (Burcal et al., 2019; Needle et al., 2017;), may potentially constrain the integration of task-related information into long-range networks (Liu et al., 2023; McIntosh et al., 2014), and be detrimental to complex adaptive behaviors (Shine et al., 2016; van den Heuvel et al., 2016; Yue et al., 2017). The scarcity of comparable studies employing MSE analysis - particularly those involving motor tasks – limited context-specific interpretation of the results to hypothetical conclusions. Nonetheless, focusing on target dynamics provided by Study I and II and enriching its context with an innovative add-on, Study III provided preliminary insights into potential implications of an ACL injury for kicking performance from a neurophysiological perspective and underscored the potential for future research.

4.2. Methodological considerations

The current dissertation comprises one literature-based and three empirical studies, each with its own specific objectives and corresponding methodological frameworks. While these studies collectively advance the understanding of ACL research by presenting neurophysiological findings within a sport-specific context, it is important to acknowledge that each study has its own methodological strengths and limitations. Recognizing these pros and cons is crucial for accurately interpreting the findings and guiding future research by identifying areas for potential improvement. Hence, the following sections will address the strengths and limitations inherent in the data collection and analytical methods employed in these studies.

4.2.1. Strengths and limitations of the literature review

The literature review aimed to bridge neurophysiological alterations with their implications for the neurocognitive functioning of athletes. Due to the variety of methodologies employed and domains explored, a scoping review approach was adopted (Arksey & O'Malley, 2005). Scoping reviews are particularly valuable for evaluating the breadth and focus of existing literature on a specific topic, offering a comprehensive overview of the volume and characteristics of available studies. They are especially beneficial in emerging fields where precise research questions have yet to be established, aiding in the identification of evidence types that guide practice and the research methodologies utilized (Armstrong et al., 2011). Munn et al. (2018) describe scoping reviews as precursors to systematic reviews as they identify existing evidence types, summarize concepts, definitions and methods used in the field, and highlight knowledge gaps. In this context, the scoping literature review in the present dissertation provided insights into injury-related changes detectable across various domains of the CNS and their potential impact on cognitive functioning. By acknowledging sport-specific cognitive responses (Yongtawee et al., 2021), it focused on athletes participating in interceptive sports and identified potential domains where deficits may manifest. The review also revealed methodological heterogeneity and the diversity in explored domains while underscoring challenges in systematically presenting findings and quantifying their effects. The overview of methods can guide future research by identifying gaps in existing literature regarding tests and tasks, paving the way for developing settings that may better reveal the neurophysiological consequences of injuries on sport-specific performance (Chang et al., 2022).

However, several limitation were noted. The cohort under consideration included elite and recreational athletes engaged in team sports, emphasizing the relevance of neurocognitive functions within dynamic competitive environments (Vestberg et al., 2012; Voss et al., 2010). Nonetheless, the variability in scales used and reported characteristics to define participants' athletic or activity levels resulted in a broader description of "athletes" without concrete inclusion criteria, leading to a more heterogenous participant group overall. Additionally, some studies were excluded due to either participant heterogeneity (Baumeister et al., 2008) or lack of information regarding athletic levels (Miao et al., 2017), potentially omitting valuable findings from this review. Moreover, despite presenting a substantial body of evidence, the simplicity and unidimensionality of the tasks employed raise questions about the transferability of observed changes to sport-specific performance (Chang et al., 2022). Neurophysiological studies primarily measured CNS activity at rest, during isometric contractions or simple knee -hip flexion-extension movements. Neurocognitive assessments consisted of computerized or pencil-and-paper tests, while dual-tasking paradigms combined cognitive tasks with single- or double-leg stance. However, real sporting scenarios involve complex motor actions intertwined with cognitive processes aimed at achieving specific goals (Herold et al., 2018). As methodological advancements continue to evolve, transitioning to more complex and sport-specific tasks may enhance the practical relevance of scientific findings.

Another limitation is the broad time span between injury occurrence and measurement - ranging from 2 weeks to 70 months – which complicates inferences regarding chronicity of deficits. Coupled with insufficient evidence concerning sport-specific performance post-injury, this variability raises critical questions for RTS protocols in terms of "what" and "when" needs to be measured to clear injured athletes safely for RTS (Meredith et al., 2021). Finally, longitudinal studies with prospective follow-ups suggest that altered CNS activity may predispose individuals to injury (Diekfuss et al., 2019, 2020; Grooms et al., 2015). To ascertain the extent to which these differences exist among athletes who subsequently sustain injuries, further prospective studies with extended follow-up periods are necessary to accumulate evidence distinguishing predisposing changes from neurophysiological consequence resulting from injuries.

4.2.2. Strengths and limitations of the short-distance passing task

The short-distance passing task developed and used in the empirical studies was designed to simulate short-distance passes on the field. Short-distance passes are critical in football when accuracy is paramount, as they facilitate ball possession, create scoring opportunities, and increase the likelihood of shots on target (Adams et al., 2013; Lago-Peñas et al., 2011; Redwood-Brown, 2008). While there is substantial evidence in the literature regarding the biomechanical underpinnings of accurate kicking, no studies have yet explored short-distance passes from a neurophysiological perspective. The findings of the empirical studies offer valuable insights into cortical dynamics associated with short-distance passing and elucidate how expertise and injury can modulate these dynamics. These insights can improve interventions aimed at enhancing pass accuracy in diverse scenarios by grounding them in neurophysiological principles.

The standardized positioning employed in this task reduced both intra- and inter-individual variability in motor behavior, thereby enhancing the reliability of findings (Haar et al., 2017). Significant behavioral variance can obscure consistent neural signatures associated with specific motor actions. When cortical responses vary widely across trials and individuals, identifying clear patterns or trends becomes challenging. This noise can mask the signal of interest, making it difficult to draw reliable conclusions about the relationship between motor performance and cortical activity (Cohen, 2015; Henry, 2006). By providing insights into cortical dynamics during standardized side-foot kicks executed from a stable position, these findings establish a baseline for future investigations of how various factors - such as target distance, kicking techniques (with and without stepping), and whether targets are fixed or moving – affect described dynamics. Another methodological strength of this task is that its execution minimizes large explosive movements, resulting in manageable artifacts that enhance data quality. Both IMU and EEG signals are known to be adversely affected by movement and soft-tissue artifacts (Cuesta-Vargas et al., 2010; Gorjan et al., 2022; Lebel et al., 2017).

Despite its strengths, the employed passing task has limitations that should be considered when translating findings into practical applications. For instance, while the target was placed three meters away to promote a standardized motor behavior, this setup reflects real-game passing situations only partially. Some studies have found no significant effects of pass length on scoring success (Amatria et al., 2019; Bostanci et al., 2018; Cotta et al., 2013), while others indicate that longer passes may enhance scoring probability. One study reported that goals were most frequently scored with passes exceeding 10 meters – achieving an 18.4% success rate – compared to a reduced rate of 17.1% for passes shorter than 10 meters (Michailidis et al., 2013). Another investigation found a scoring probability of 22.2 for passes ranging from 10 to 24 meters (Michailidis, 2014). As another point, to standardize motor behavior and increase the accuracy demands of kicking, a smaller target was used. However, on-field scenarios often involve vertical accuracy as another variable influencing success, that may bring different demands for players (Cordón-Carmona et al., 2023; Hunter et al., 2018). Moreover, although standing passes are feasible on the field, many scenarios require players to execute kicks while running or approaching a moving ball within a dynamic environment. In such cases, players must track a moving ball and anticipate its trajectory for successful subsequent actions (Kellis & Katis, 2007; Lees & Nolan, 1998). The current task may not adequately address these demands, and may therefore have limited ecological validity. The simplicity and predictability of the task may also account for insignificant differences or small effects observed in the present results. As an extension of its strengths, future research could utilize these findings as a baseline to investigate whether increasing task demands – such as variations in distance and height of passes or unpredictable targets – affect the cortical correlates associated with short-distance passing.

4.2.3. Strengths and limitations of MSE analysis on behavioral data

MSE analysis has established itself as a powerful non-linear metric for analyzing the complexity of biological signals since its introduction in 2002 (Costa et al., 2002). MSE extends SE by measuring irregularity or variability within time series data. Traditional linear metrics often discard or fail to capture the full spectrum of this variability, treating it as noise or reducing complex interactions to simple correlations or averages based on the assumption of linearity. However, many biological processes exhibit time-dependent behaviors characterized by fluctuations and cycles that have functional significance. Non-linear metrics like MSE can effectively model this complexity by accounting for temporal irregularities, thereby providing insights into the intricate interactions among different physiological levels within a system (Decker et al., 2011; Stergiou et al., 2006).

Conventional entropy-based algorithms are typically single-scaled, which limits their ability to capture how these interactions evolve across various temporal scales. In contrast, MSE offers a comprehensive framework that assesses both short-term fluctuations and long-term trends within the same dataset. Notably, MSE maintains its sensitivity even in the presence of noise in the data (Costa et al., 2005). While the complexity of the original time series may not reveal significant differences, its derivatives can be more sensitive to variations in complexity at specific scales, thus uncover pathology-, cohort- or condition-specific changes (Busa & van Emmerik, 2016; Costa et al., 2002; Zhai et al., 2022). The multiscale structure allows for scale-wise statistical analyses, enabling researchers to determine complexity profiles based on the number of scales exhibiting increased or decreased complexity (Costa et al., 2005). Additionally, an overall complexity index can be derived from calculating the area under the complexity curve (Busa & van Emmerik, 2016).

MSE has been successfully applied to various physiological signals such as electrocardiogram, EEG and EMG (Costa et al., 2002; McIntosh et al., 2014; Zhang et al., 2013), as well as behavioral data (Bisi & Stagni, 2016; Busa et al., 2016; Liau et al., 2019; Moras et al., 2018). Given that movement patterns can vary significantly depending on the time frame considered, analyzing complexity across multiple scales is particularly relevant in movement analysis. Fine scales capture complexities associated with rapid movement dynamics, while coarser scales reflect the intricacies of gross motor behaviors. This approach measures integrated information related to movement across lower and higher physiological systems (Reed, 1982). Study II and III demonstrated that while fast dynamics of kicking captured in small time windows exhibited greater regularity from trial to trial, the overall behavior became increasingly complex towards higher scales. Specifically, Study II revealed significant differences between novices and experienced players regarding coarse motor behavior, which would have remained undetected using a single-scaled SE analysis. By scaling the data, the level of underlying systems operating differently between the groups could be uncovered.

Despite its strengths, MSE is a probabilistic approach that involves multiple statistical steps and has inherent limitations that needs to be considered. One critical factor influencing the robustness of MSE analysis is the length of the analyzed time series. A minimum number of data points is necessary to enhance the accuracy of estimated matching probabilities. Recommendations for minimum lengths vary based on theoretical calculations, for instance Gow et al. (2015) suggest a range of 14^m – 23^m data points for the highest scale due to large confidence intervals reported by Richman & Moorman for a length of 10^m (2000). The required length may also depend on the frequency range of interest relative to the sampling rate. For example, if data are recorded at a sampling rate of 100 Hz over a duration of 100 seconds, scale 10 would analyze fluctuations observed at 10 Hz after coarse-graining (100 Hz * 100 seconds / 10 (scale) * 100 Hz). Therefore, if frequencies over 10 Hz are to be analyzed, a higher data length should be considered. The acquisition of data with a sufficient length can pose challenges for participants particularly in continuous tasks. To address this issue, Grandy et al. (2016) have proposed conducting MSE on sparse datasets, a solution applicable in trial-based setting such as those in Study II and III. Their findings indicated substantial reliability for entropy estimates computed on concatenated series (Grandy et al., 2016; Puglia et al., 2022).

Another limitation inherent to behavioral data lies in ambiguities regarding physiological processes underlying temporal scales. While certain frequencies in EEG or electrocardiographic signals hold particular physiological significance, fluctuations in behavioral measures, such as center of pressure or acceleration, are often task-dependent. Consequently, the number of scales to be analyzed are determined without physiological considerations. One potential solution is to identify sensitive scales that reveal differences between conditions and cohorts, and base subsequent analysis on these parameters (Gow et al., 2015).

Moreover, two critical parameters used in SE computation, the embedding dimension (*m*) *and* tolerance margin (*r*), significantly influence entropy estimates. Lower values of *m* combined with higher values of *r* tend to increase detection rates for matches and improve the accuracy of estimates (Kirchner et al., 2012). However, as *m* refers to the length over which new information is generated, selecting an appropriate value is crucial to ensure sufficient information content within patterns being analyzed. Numerous studies have employed empirical approaches to investigate how varying *m* values affect estimates (Costa et al., 2003; Duarte & Sternad, 2008; Jiang et al., 2013; Pincus et al., 1994), alongside methods such as autoregressive models (Lake et al., 2002), mutual information methods and false nearest neighbor techniques (Chen et al., 2005). Regarding *r* values, research indicates that ranges between 0.10 – 0.30 yield consistent results (Duarte & Sternad, 2008; Pincus et al., 1994). Grandy et al. (2016) explored *r* values ranging from 0.10 – 0.50 and found no significant differences. However, it is important to note that as the SD of time series decreases due to coarse-graining procedure, a fixed *r* x SD value may inflate entropy values towards higher scales offering a broader range for matching data points. Therefore, recalculating SD at each scale is recommended to enhance the accuracy of entropy estimates (Kosciessa et al., 2020).

4.2.4. Strengths and limitations of EEG source-level time-frequency analysis

Source-level analysis has emerged as a strong tool to cope with the inverse problem in EEG analysis, which refers to the challenge of determining cortical sources with respect to electrical potentials that are recorded on the scalp and mix as a result of volume conduction (Grech et al., 2008; van den Broek et al., 1998). While channel-level analysis ignores spatial mixing, source-level analysis identifies functional sources in a more sterile manner. Algorithms such as ICA decompose summed signal into mathematically independent components and produces stable brain and non-brain components across sessions (Grandchamp et al., 2012). Besides being a commonly used tool to clean artifacts (Winkler et al., 2011), the construction of regions of interest based on detected brain sources is becoming a gold standard in mobile EEG studies (Gwin et al., 2010; Peterson & Ferris, 2018; Protzak & Gramann, 2021; Visser et al., 2022). Through incorporating simple, approximate, 3-D complex or volumetric head models and using high-density EEG, the spatial resolution and precision of source estimations can be enhanced (Hallez et al., 2007; Michel & He, 2009; Stoyell et al., 2021; Valdés-Hernández et al., 2009).

Despite these advancements improving spatial resolution in EEG analysis, limitations particularly regarding spatial accuracy still exist. Pitfalls with the electrodes and EEG cap underscore the need to be careful against these limitations already while recording the data. Electrodes are placed on the head typically with respect to anatomical landmarks such as nasion, inion and pre-auricular joints (Klem et al., 1999). After placing fixed caps, investigators measure the distances between nasion and inion, and the right and left pre-auricular joints, and check the accuracy of cap placement by making sure that Cz is aligned with the vertex and is placed centrally. However, variations are reported even with fixed caps and despite such measures, which may cause shifts in the estimates of source localization (Atcherson et al., 2007; Scrivener & Reader, 2022). Although not used in the current studies due to the expenditure of time, ultrasonic, electromagnetic or camera-based scanning systems exist to check the accuracy of the electrode positions and account for errors (Reis & Lochmann, 2015).

Another pitfall may be due to the application of the electrolyte-gel or solution, used to establish electrode contact with the scalp and enhance conductivity. The excessive application of these can cause low-impedance electrical bridges between two or more electrodes (Tenke & Kayser, 2001), influence metrics calculated under electrodes where electrical bridging was evidenced or increase variability of each recording site. Such bridges may potentially deform or smooth the topography of waveforms and time-locked parameters of interest by deteriorating source localization estimates (Greischar et al., 2004; Tenke & Kayser, 2001). Alschuler et al. (2014) have conducted an analysis on publicly-available EEG datasets and reported that 54 % of EEG recording sessions had an electrode bridge. They have emphasized that the prevalence of this methodological issue may be more common than believed and underlined the need for establishing systematic screenings as a standard part of EEG analysis. With methods such as pairwise comparisons of channels by superimposing waveforms or algorithms based on the characteristics of electrical distance frequency distributions, bridged electrodes can be detected and removed from the data (Alschuler et al., 2001; Tenke & Kayser, 2001).

At the analytical level, it is important to note that despite advanced algorithms and head models, source localization may still not be completely precise. Several studies have evidenced errors in a range of 10 – 20 mm for superficial cortical sources (Akalın Acar & Makeig, 2013; Barborica et al., 2021; Klamer et al., 2015; Lascano et al., 2014; Seeber et al., 2019). Sohrabpour et al. (2015) have reported an improvement of 4 mm when the number of electrodes was increased from 32 to 64, which was implemented in the empirical studies. In the same study, using 128 electrodes was shown to increase the accuracy totally 2.3 mm. Still, the interpretation of findings based on estimated sources relative to anatomical regions should be done by caution due to these spatial limitations.

The length of the data is another point which may influence the reliability of decomposed sources. Having a statistical fundament, ICA decomposition may not be able to accurately separate sources, if the independence of functionally distinct processes is not represented adequately by the data. A reliable estimation of the data length is calculated as the size of the weight matrix being the square of number of channels, or as a number of time points minimally a few times the square of the number of channels (Delorme & Makeig, 2004).

Moreover, unequal number of participants across cortical clusters or unequal distribution of ICs within a cluster should also be mentioned as an important but unsolved limitation of source-level analysis. Regarding the former, most studies analyze clusters which represent the majority of the cohort (Gebel et al., 2020; Solis-Escalante et al., 2019; Peterson & Ferris, 2018), or focus on a specific cluster of interest with respect to research focus (Protzak & Gramann, 2021; Visser et al., 2022). Relating to the latter issue, there are currently no conclusive guidelines.

Regarding the limitations of time-frequency analysis, the sensitivity to baseline selection should be mentioned as one significant limitation of ERSPs. The computation of spectral perturbations typically involves comparing post-stimulus spectral power to a pre-stimulus baseline period. Variability in baseline activity can lead to inconsistent results, as fluctuations in background oscillatory activity may skew the interpretation of event-related changes (Grandchamp & Delorme, 2011).

Another challenge associated with ERSP analysis is the potential for spurious effects due to multiple comparisons across time and frequency dimensions. Given that ERSP generates a large number of data points, statistical corrections are often necessary to control for type I errors. However, applying these corrections can reduce statistical power and complicate the interpretation of significant findings. Researchers must carefully balance the need for rigorous statistical control with the risk of overlooking meaningful effects (Morales & Bowers, 2022).

Finally, the choice of parameters used in the time-frequency decomposition process—such as window length, overlap, and frequency resolution—can significantly influence ERSP outcomes. For instance, shorter time windows may provide better temporal resolution but can lead to increased spectral leakage and reduced frequency specificity (Roach & Mathalon, 2008). Conversely, longer windows may smooth out rapid changes in brain activity and obscure transient effects. The subjective nature of parameter selection introduces variability across studies and can hinder comparability between findings (Delorme & Makeig, 2004; Grandchamp & Delorme, 2011).

4.2.5. Strengths and limitations of MSE analysis on mobile EEG data

In section 4.2.5., the application of MSE analysis to behavioral time series was discussed. The current section will address the strengths and limitations intrinsic to MSE analysis on mobile EEG data.

In recent years, numerous studies have increasingly utilized nonlinear methods to investigate the complexity of various brain signals, which underpins cognitive functions, emotional regulation, and behavioral responses (Angsuwatanakul et al., 2020; Lau et al., 2022; Parbat & Chakraborty, 2021; Sun et al., 2022; Yao et al., 2021). MSE analysis has provided valuable insights in EEG research by elucidating the confounding roles of excessive or insufficient complexity in various contexts (Catarino et al., 2011; Liu et al., 2023; McBride et al., 2014; Zuo et al., 2022). While linear EEG metrics yield substantial information regarding regional and temporal activation within different brain areas, MSE highlights the brain's information processing capacity, which is shown to be sensitive to various conditions such as diseases (Azami et al., 2017; Catarino et al., 2011; Chu et al., 2017; Chung et al., 2013), gender-related differences (Lewandowska et al., 2023), physical activity levels (Wang et al., 2014) and cognitive states (Ahammed & Ahmed, 2023; Zhai et al., 2022; Zou et al., 2020). One of the most important strengths of MSE analysis is its ability to profile the complexity of EEG signals across multiple temporal scales. This multiscale approach allows for the interpretation of findings in the context of local or distributed entropy, or with respect to frequencies. Entropy at fine scales is understood to represent information processed locally, while coarser scales reflect the integration of information into long-range networks. Profiling the EEG entropy of younger and older individuals across multiple scales, McIntosh et al. (2014) could show that the developmental changes characterized by the establishment of new connections between widely distributed neuronal populations reverse with aging and regresses into higher modularity observed in infants. Furthermore, by finding significant differences between physically active and inactive elderlies at higher scales, Wang et al. (2014) showed that being active may be protective for this age-related regression and restore the information processing capacity of the brain across long-range networks. Besides uncovering physiological processes operating at specific scales, it should also be mentioned as a strength of the multiscale structure that decreasing random noise at higher scales as a result of coarse-graining may make them more sensitive to differences that remain undetected at finer scales (Costa et al., 2005).

With regard to the latter aspect, time scales in MSE can also be interpreted as descriptors of fast-to-slow dynamics quantified by high-to-low frequencies in conventional Fourier Analysis. The algorithm down-samples the data to derive coarser scales, assigning each a specific frequency based on the sampling rate of the series. For instance, for a dataset sampled at 250 Hz, scale 1 corresponds to dynamics operating at 250Hz, scale 2 at 125, scale 3 at 62.5, and so forth (Kosciessa et al., 2022). This scaling allows for an examination of complexity within specific frequency bands and enables a more nuanced interpretation of findings (Puglia et al., 2022).

However, alongside general limitations applicable to any time series analysis, such as those discussed in section 4.2.3. regarding embedding dimension and tolerance margin used in the algorithm, there are specific challenges associated with computing entropy across multiple temporal scales in EEG data. Primarily, preprocessing procedures required for EEG analysis can significantly influence entropy estimates. The frequency characteristics of non-brain artifacts, such as drifts and eye blinks concentrated in lower frequencies, and muscle activity in higher frequencies, contaminate brain signals at specific scales. Data recorded at mobile settings necessitate tailored bandpass filter cutoffs and additional procedures such as ICA decomposition to mitigate movement artifacts effectively. While some researchers advocate for minimal preprocessing prior to MSE computation (Okazaki et al., 2015), others recommend the removal of non-brain sources (Miskovic et al., 2016). Puglia et al. (2022) assessed the reliability of entropy estimates derived from data with varying sampling rates, bandpass filter cutoffs, and with or without artifact correction, and evidenced the impact of preprocessing parameters on entropy estimates. The validation of pipelines for specific data may be helpful to determine and employ parameters yielding most accurate results (Puglia et al., 2022).

Furthermore, when entropy of a certain frequency range is of particular interest, two critical considerations arise: First, bandpass filtering the data to isolate specific frequency ranges may obscure significant differences that would otherwise be detectable across broader ranges. Azami et al. (2017) reported significant findings that align with existing evidence only when analyzing broadband signals. Second, the conventional MSE algorithm inherently applies low-pass filters through coarse-graining processes to derive coarser time scales. This results in a tendency towards slow fluctuations dominating coarse scales. While fine scales capture the entire broadband signal spectrum, low-pass filtering removes high-frequency components and insulates lower frequencies at coarse scales. Implementing scale-wise filters could enhance the frequency-specificity of analyzed scales (Kosciessa et al., 2020).

Lastly, the current lack of evidence elucidating the relationship between cortical complexity and human movement constrains the interpretation of mobile EEG entropy by reducing comparable findings to those of studies conducted under stationary conditions. This highlights the necessity for further research exploring complexity dynamics in motor tasks for a detailed and reliable comprehension of entropy in movement context. Additionally, integrating linear metrics into analyses can enhance the interpretation of entropic dynamics since evidence suggests that MSE captures both non-linear and linear autocorrelations while relating to power spectral density characteristics such as peak amplitude and slope (Courtiol et al., 2016).

4.3. Practical implications and prospects

Recent advancements in the field of exercise neuroscience and MoBI research have enabled the examination of cortical activity during sports-specific tasks. The promising findings have underscored the value of a neuroscientific perspective in understanding athletic skills and developing interventions to enhance them (Nakata et al., 2010; Yarrow et al., 2009). Given that accuracy in short-distance passes is a fundamental skill significantly influencing match outcomes, it has recently become the focus of numerous studies investigating various interventions to improve it (Asrul et al., 2021; Dunton et al., 2020; Robin et al., 2020). Based on a mobile EEG approach, the findings of the present dissertation reveal the critical role of cortical dynamics in achieving a higher level of pass accuracy. Insights into how its associated cortical dynamics are modulated in particular contexts such as expertise and injury offer valuable applications for sports science, coaching, and rehabilitation.

Study I established that visuospatial and attentional processes are prominent demands during target-directed passing, as evidenced by the reliable activity of posterior and frontal regions. Study II further enlightened that experienced football players achieve higher accuracy compared to novices by employing these cortical processes more effectively. Coaches, trainers and sports scientists can develop intervention paradigms that are specifically designed to challenge and enhance visuospatial and attentional capabilities during passing. Improving the ability to process visual information efficiently while maintaining focused attention may contribute to the automaticity of spatial kicking patterns and ultimately improve accuracy (Dunton et al., 2020; Otte et al., 2021).

Moreover, converging neurophysiological deficits described in the literature review towards a football-specific task, Study III revealed potential consequences of an ACL injury on pass accuracy. Preliminary findings indicated enhanced attention but reduced visuospatial processing among injured players, suggesting a potential constraint on task demands due to compensatory of biomechanical and sensory deficits during kicking. This introduces pass accuracy as a critical domain for further investigation in injured players. Increased variability in foot external rotation may reflect spatial errors during kicking and highlight the necessity for proprioceptive acuity assessments (Muaidi et al., 2009). With growing evidence emphasizing the neurophysiological consequences of ACL ruptures, conventional therapeutic and rehabilitative approaches - primarily focused on peripheral measures such as range of motion, muscle strength and joint stability – are increasingly gaining a trend towards neuroscience principles (Gokeler et al., 2019; Machan et al., 2021; Onate et al., 2019). In light of emerging evidence indicating diminished pass accuracy post-injury, these approaches could be expanded to include strategies aimed at restoring visuospatial and attentional processes during passing under various game scenarios. The feasibility and cost-effectiveness of modern EEG systems (He et al., 2023) may prospectively enable the established measurement of neurophysiological markers of sport-specific tasks and their responses to tailored training programs. Integrating assessments of pass accuracy into post-injury protocols and studying it prospectively from a neurophysiological perspective could expand the understanding of how ACL injuries impact this substantial skill and may bring an explanation to decreased passing statistics reported for post-injury seasons (Barth et al., 2019; Niederer et al., 2018).

While the present dissertation provides foundational insights into the cortical dynamics associated with passing, several avenues remain unexplored. Future research should aim to build upon these findings by incorporating more complex and ecologically valid experimental designs. The current studies utilized a relatively simple, stable passing task and proposed a methodology to investigate its associated cortical dynamics using a mobile EEG approach. However, football is inherently dynamic and players often execute kicks under varying conditions, such as different speeds, distances, and angles (Kellis & Katis, 2007; Lisenchuk et al., 2021). Future studies can explore how the modification of these variables affect described cortical patterns and whether certain variables are more sensitive in detecting differences between cohorts.

The predictability of the target is another crucial variable regarding the practical relevance of passing. In real football situations, passes occur also within unpredictable environments driven by rapid decision-making processes (Cardin et al., 2013). Future studies should investigate how different levels of predictability modulate cortical dynamics during passing. Particularly among injured players, increasing task demands may reveal deficits more extensively and provide insights into performance declines observed on the field with greater ecological validity (Smeets et al., 2021).

Additionally, functional outcomes following ACLR may depend on the type of graft used (Hardy et al., 2017; Yunes et al., 2001). Differences between graft types have been reported in motor tasks in which knee muscle forces are particularly relevant (Schroeder et al., 2022). The homogeneity of graft types in the investigated cohort or the comparison of different graft types could yield more specific insights into the consequences of deficits. Furthermore, although neurophysiological deficits have been reported even after extended periods up to 10 years, a chronic progression of knee functions is also recognized (Kaarre et al., 2023). Therefore, more longitudinal studies are necessary to track the persistence of identified deficits over time.

Gender-specific differences in football performance - including pass accuracy - have also been reported by studies (Bradley et al., 2014; Pappalardo et al., 2021). Given the notably high incidence rates and differing predisposition factors among female players (Bisciotti et al., 2016; Cheung et al., 2015; Walden et al., 2011), homogenous investigations across genders may illuminate gender-specific differences related to ACL injuries.

Lastly, while Study I focused on analyzing cortical activity within posterior and frontal regions – highlighted as prominent task-related markers due to consistent reoccurrence of ICs - differences in other cortical regions have also been previously documented (Baumeister et al., 2008; Lehmann et al., 2021, Sherman et al., 2023). Future investigations should consider exploring additional cortical regions to deepen the understanding of neurophysiological deficits associated with ACL injuries.

5. CONLUSION

The present cumulative dissertation aimed to investigate dynamics that promote pass accuracy, an essential determinant of success in football, and to assess how these dynamics are affected by an ACL injury in football players from a neurophysiological perspective. Employing a mobile EEG approach and a repeated-measures design, cortical correlates of short-distance passing showing substantial test-retest reliability were characterized. ERSP patterns observed consistently in the posterior and frontal regions across two distinct sessions highlighted the prominence of visuospatial and attentional processes engaged during the execution of a kick. Compared to novice players, experienced football players exhibited enhanced capabilities in processing visuospatial information and maintaining focused attention, which was associated with improved pass accuracy. In injured players, although the accuracy performance was not different, notable behavioral and cortical changes were evident. The higher variability observed for foot external rotation indicated reduced spatial consistency. Differences in the posterior and frontal ERSP patterns implied reduced visuospatial processing and an increased level of attention demand. Furthermore, the task-related complexity within these regions was diminished, suggesting a limitation on the amount of information processed. The current findings may indicate a conflict between compensation mechanisms for sensory deficits and the cortical processes that facilitate accuracy in short-distance passing, and underscore the potential for prospective research in this topic. Further evidence is required to explore and acknowledge these deficits through enriched experimental designs that incorporate various passing distances, angles, unpredictable targets and distractors. Describing the extent of post-injury deficits within ecologically more valid real game scenarios can bring a physiological explanation to performance declines observed after an ACLR in football players. Such insights could guide practical implementations aiming to restore athletic skills and inspire future studies to transition into ecologically more valid settings, thereby enhancing the transferability of findings to real-world situations.

6. SCIENTIFIC DISSEMINATION

6.1. Peer-reviewed publications

Piskin, D., Benjaminse, A., Dimitrakis, P., & Gokeler, A. (2022). Neurocognitive and Neurophysiological Functions Related to ACL Injury: A Framework for Neurocognitive Approaches in Rehabilitation and Return-to-Sports Tests. Sports Health: A Multidisciplinary Approach, 14(4), 549–555. https://doi.org/10.1177/19417381211029265

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Piskin, D., Müller, R., Büchel, D., Lehmann, T., & Baumeister, J. (2024). Behavioral and cortical dynamics underlying superior accuracy in short-distance passes. Behavioural Brain Research, 471, 115120. https://doi.org/10.1016/j.bbr.2024.115120

Piskin, D., Gokeler, A., Chen, Y.-H., & Baumeister, J. (2024). Development of an Effector-Specific Stop Signal Task with Higher Complexity: A Proof-of-Concept Study. Journal of Motor Behavior, 1–10. https://doi.org/10.1080/00222895.2024.2400126

6.2. Oral presentations

Piskin, D., Büchel, D., Lehmann, T., & Baumeister, J. (2023, July 4-7). Reliability of event-related spectral perturbations in target-directed kicking in soccer [Oral presentation]. 28th Annual Congress of European College of Sports Science, Paris, France. https://www.ecss.mobi/DATA/CONGRESSES/PARIS_2023/DOCUMENTS/BOA_Paris_2023_Web.pdf

6.3. Poster presentations

Piskin, D., Cobani, G., Lehmann, T., Büchel, D., & Baumeister, J. (2024, June 2-5). Multiscale Entropy Analysis in Mobile EEG: Could It Have a Potential Use in Real-World Settings? [Poster presentation]. 5th International Mobile Brain/Body Imaging Conference. https://sites.google.com/view/mobi-2024/program/conference-schedule

6.4. Awarded video abstract presentations

Piskin, D., Cobani, G., Lehmann, T., Büchel, D., & Baumeister, J. (2024, June 2-5). Multiscale Entropy Analysis in Mobile EEG: Could It Have a Potential Use in Real-World Settings? [Video abstract presentation]. 5th International Mobile Brain/Body Imaging Conference. https://sites.google.com/view/mobi-2024/program/conference-schedule

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