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TESE DE DOUTORADO

INFLUENCE OF INTERNAL INDIVIDUAL CONSTRAINTS AND SHORT-TERM PRACTICAL INTERVENTIONS ON THE NEUROMECHANICS AND PERFORMANCE OF SOCCER KICKING IN YOUTH ACADEMY PLAYERS

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INFLUENCE OF INTERNAL INDIVIDUAL CONSTRAINTS AND SHORT-TERM PRACTICAL INTERVENTIONS ON THE NEUROMECHANICS AND PERFORMANCE OF SOCCER KICKING IN YOUTH ACADEMY PLAYERS

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“There is a driving force more powerful than steam, electricity and nuclear power: the will” (Albert Einstein)

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PALUCCI VIEIRA, L. H. **Influence of internal individual constraints and short-term practical interventions on the neuromechanics and performance of soccer kicking in youth academy players**. 2022. 333p. Thesis (Doctorate in Human Movement Sciences)- UNESP, Faculty of Sciences, Bauru, 2022.

ABSTRACT

Athletic performance is mutually dependent upon individual constraints and practical interventions. Regarding the former, it is recognised that brain activity and sleep indices can modulate movement planning and execution. Concerning the strategies used in practice, contemporary short-term prescriptions have been adopted by conditioning professionals and physiotherapists with the primary intention to acutely enhance musculoskeletal power output or accelerate post-exercise recovery processes. These includes postactivation performance enhancement (PAPE)-based plyometric warm-up and induced cooling (COOL) through ice packs, respectively. However, it remain unknown whether measures of brain dynamics and natural sleep patterns influence skill-related performance in soccer. To date, the literature does not show a consensus for PAPE effectiveness in young populations. Generally, COOL also negatively affects subsequent lower limb movements requiring high force-velocity levels. Based on these assumptions, the general aim of the current thesis was to investigate the influence of internal individual constraints (EEG and sleep-derived indices) and effects of short-term practical interventions (PAPE and COOL) on the movement kinematics and performance aspects of soccer kicking in youth academy players. A series of six studies is presented. These include a literature review, one technical note and four original experimental research articles (two observational and two interventions) in an attempt to answer the questions defined in the research programme. From the data gathered here, it was possible to provide evidence that a) kick testing in studies systematically lacked resemblance to competition environments; b) occipital brain waves during the preparatory phase determines ball placement while late frontal signalling control both ankle joint in impact phase and post-impact ball velocity; c) poor sleep quality and late chronotype preference are linked to subsequent impaired targeting ability; d) acute enhancements achieved via PAPE/plyometric conditioning are purely neuromuscular, being slightly converted into kicking mechanics or performance improvements; e) in a hot environment, repeated high-intensity running efforts impair both ball placement and velocity whilst a local 5-minutes COOL application assists recovery of overall kick parameters and f) a markerless deep learning-based kinematic system appear as reliable alternative in capturing on-field kicking motion patterns. To conclude, both internal individual constraints (EEG and sleep quality) and a short-term practical intervention (cooling quadriceps/hamstrings with ice packs) have an acute impact in kicking performance in youth soccer context. A model integrating evidence from all papers is presented alongside limitations and recommendations for future studies in this field.

Keywords: Technical skill; 3-dimensional kinematics; Accuracy; EEG; Human movement; Motor Control; Biomechanics.

PALUCCI VIEIRA, L. H. **Influência de restritores individuais e intervenções práticas de curto prazo na neuromecânica e desempenho do chute em jovens jogadores de futebol**. 2022. 333f. Tese (Doutorado em Ciências da Motricidade)- UNESP, Faculdade de Ciências, Bauru, 2022.

RESUMO

O desempenho esportivo depende mutuamente de restrições individuais e intervenções práticas. Em se tratando da primeira vertente, é reconhecido que a atividade cerebral e o sono podem modular o planejamento e execução de habilidades motoras. Com relação às estratégias da prática deliberada, prescrições contemporâneas de curto-prazo têm sido adotadas por profissionais de condicionamento e fisioterapeutas com a intenção primária de aprimorar agudamente a resposta de potência musculoesquelética ou acelerar o processo de recuperação após exercício, respectivamente. Estes incluem aquecimento via potencialização do desempenho pós-ativação (PAPE) pliométrico e resfriamento induzido (COOL) usando compressas de gelo, respectivamente. Entretanto, permanece desconhecido se medidas de dinâmica cerebral e padrões naturais de sono influenciam o subsequente desempenho de habilidades no futebol. Até a presente data, a literatura é conflitante sobre a efetividade de vários métodos para induzir PAPE em populações de jovens. Tradicionalmente, aplicar COOL também afeta negativamente movimentos dos membros inferiores dependentes de altos níveis de força e velocidade. Baseado nessas premissas, o objetivo geral da tese atual foi investigar a influência de restritores internos individuais (EEG e indicadores de sono) e efeitos de intervenções práticas de curto-prazo (PAPE e COOL) na cinemática de movimento e desempenho do chute em jovens jogadores de futebol. Para tanto, uma sequência de seis estudos é apresentada. Estes consistiram em uma revisão sistemática de literatura, uma nota técnica e quatro artigos originais de pesquisa experimentais (dois observacionais e dois intervenções) em uma tentativa de responder as questões definidas no programa de pesquisa da tese. A partir dos dados reunidos aqui, foi possível fornecer evidências de que a) testes de chute comumente usados na literatura falham em replicar o ambiente de competição; b) as ondas cerebrais occipitais durante a fase preparatória determinam a precisão do chute, enquanto a sinalização frontal tardia controla a articulação do tornozelo na fase de impacto e a velocidade da bola pós-impacto; c) má qualidade do sono e cronotipo com tendência noturna induzem a uma subsequente pior precisão do chute; d) melhorias agudas alcançadas via PAPE baseado em atividade condicionante de pliometria são puramente neuromusculares, sendo pouco transferidos para a mecânica e desempenho do chute em jovens; e) em um ambiente quente, esforços repetidos de alta intensidade prejudicam tanto a velocidade da bola quanto a precisão enquanto a aplicação local de COOL (região da musculatura do quadríceps femoral/isquiotibiais) durante 5 minutos ajuda na recuperação dos parâmetros de chute em termos globais e f) sistema de cinemática sem marcadores baseado em aprendizagem profunda surge como alternativa confiável para capturar os padrões de movimento de chute em campo. Conclui-se que restritores internos individuais (EEG e qualidade do sono) e intervenção prática de curto-prazo (resfriamento induzido com compressas de gelo) tem um impacto agudo no desempenho do chute em um contexto de futebol juvenil. Um modelo integrando as evidências a partir dos resultados de todos os artigos produzidos é apresentado, assim como suas limitações e recomendações para pesquisa futura nesta área.

Palavras-chave: Habilidade técnica; Cinemática 3-D; Acurácia; EEG; Movimento humano; Controle Motor; Biomecânica.

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3D	Three-dimensional
2D	Two-dimensional
APHV	Age of peak height velocity
AUC	Area under the curve
Avg	Average
BF	Biceps femoris
BVE	Bivariate variable error
BW	Bodyweight
CA	Conditioning activity
CI	Confidence interval
CM_{foot}	Foot centre-of-mass
CNN	Convolutional neural network
CNS	Central nervous system
COD	Change-of-direction
COOL	Cooling
CV	Coefficient of variation
DLT	Direct linear transformation
EEG	Electroencephalogram
ERD	Event-related desynchronisation
ERS	Event-related synchronisation
ERSP	Event-related spectral perturbation
ES	Effect size
F-MARC	FIFA Medical and Research Centre
fNIRS	Functional near-infrared spectroscopy
FOV	Field-of-view
GPU	Graphics processing unit
ICA	Independent component analysis
ICC	Intraclass correlation coefficient
ITC	Inter-trial coherence
MAE	Mean absolute error
MD	Mean percentage difference (PAPER 1), minimum difference (PAPER 3)
MRE	Mean radial error
NCAA	National Collegiate Athletic Association/USA

NSF	National Sleep Foundation
PAP	Postactivation potentiation
PAPE	Postactivation performance enhancement
PHV	Peak height velocity
PICO	Population, Intervention, Comparison, Outcome
PIM/TAT/ZCM	Proportional Integration Mode/Time Above Threshold/Zero Crossing Mode
RF	Rectus femoris
RHIR	Repeated high-intensity running
RLOA	Ratio limits of agreement
RM	Repetition maximum
RMS	Root-mean-square
RoB	Risk of bias
ROI	Region of interest
ROM	Range-of-motion
RPE	Ratings of perceived exertion
SEM	Structural equation modelling
SMD	Standardised mean difference
TE	Typical error
VL	Vastus lateralis

CHAPTER 1

INTRODUCTION

1. CONTEXT, RATIONALE AND AIM

Soccer is the most popular sport worldwide (ASKEN & RABINOVICI, 2021) and match results in this collective game are generally linked to successful executions of ball kicking (LIU et al., 2016). Enhancing kicking performance in soccer (i.e. fast ball velocity and targeting the goal accurately; LEES et al., 2010; YOUNG & RATH, 2011) requires high standards of information processing and cognitive planning (COLLINS; POWELL, & DAVIES, 1991; WOOD & WILSON, 2010; NOEL & VAN DER KAMP, 2012). Optimal coordination of movements in the lower limb segments are also necessary (e.g. proximal–distal sequence) (PUTNAM, 1991; DE WITT & HINRICHS, 2012). Roughly 80% of goal attempts in soccer are provided by shots made using the feet (WRIGHT et al., 2011). Furthermore, the number of shots and percentage of successful shots often discriminates winning as compared to drawing and losing games (CASTELLANO et al., 2012; MOURA et al., 2014; LIU et al., 2016). Identifying individual's characteristics and practical interventions that can modulate kick effectiveness is thereby warranted to inform practitioners about relevant internal/external constraints and also support day-to-day monitoring and prescription of practices in soccer.

A better understanding of kicking actions can be achieved when looking beyond measures that are of a "gross" nature (e.g. match-related statistics, percentage of kick on-target and horizontal distance reached by the ball following maximal kicks). These may cause a lack of sensitivity in detecting changes in movement features similar to those identified in controlled field studies, especially in research using ecologically valid measures (CARLING & DUPONT, 2011; RUSSELL & KINGSLEY, 2011). Even more advanced metrics such as lower limb and ball kinematics (i.e. velocity and accuracy) have notably been investigated during kick experiments without consideration of a number of potential confounders (ALI et al., 2007; BERJAN BACVAREVIC et al., 2012; VIEIRA et al., 2018a). A more holistic approach comprising variables commonly related to sports performance, including individual characteristics such as brain dynamics (BABILONI et al., 2008; THARAWADEEPIMUK & WONGSAWAT, 2017) and sleep quality/duration (BRANDT et al., 2017; STAUNTON et al., 2017; JULIFF et al., 2018; RUSSELL & KINGSLEY, 2011) may be useful. In addition, little is known about the role of short-term practical interventions that could directly impact muscle activity, mechanics and consequent kicking performance. Examples includes contemporary warm-up methods and popular post-exercise recovery strategies of which effects on the kicking parameters have not yet been determined (RUSSELL & KINGSLEY, 2011).

Sports performance mutually depends upon individual characteristics and deliberated practice contents (KISS et al., 2004). In reference to the former, poor sleep (e.g. ≥ 24 hours awake) can disrupt central nervous system (CNS) activity and thus impair visuospatial perception, decision-making ability, physical performance and motor skills (PILCHER & HUFFCUTT, 1996). Likewise, total sleep restriction worsened kicking performance in two previous studies (MEHRDAD et al., 2012; PALLESEN et al. 2017). A possible explanation for these declines in kick outputs is the negative effect that sleep deprivation has on brain functioning (THOMAS et al., 2000; KILLGORE, 2010; KILLGORE et al., 2006; GOEL et al., 2009; HALSON & JULIFF, 2017). However, full sleep restriction does not always adequately represent reality, as the most common issue in athletic populations consists in disrupted sleep patterns (sleep loss ranging from total, partial and fragmented deprivation) (LASTELLA et al., 2014). Currently, there is no empirical evidence about either the role of brain activity or the influence of habitual sleep-derived parameters on kicking performance in youth soccer (see systematic review by PALUCCI VIERA et al., 2021).

Notwithstanding, in reference to contextual factors, the quality of deliberated practice contents such as pre- and post-exercise prescriptions plays a critical role in athletic performance status in addition to individual characteristics influences. In this sense, it is possible to highlight two widespread methods adopted by strength and conditioning professionals and physiotherapy staffs in soccer, namely postactivation performance enhancement (PAPE) and cooling (COOL), whose effects on kicking ability were only partly explored. Respectively, these strategies primarily intend to promote an acute enhancement in musculoskeletal preparedness for ensuing activities (WILSON et al., 2013) and accelerate the recovery process owing to the deleterious effects of exercise-related fatigue (RUSSELL & KINGSLEY, 2011). In soccer, from a practical viewpoint, they could be implemented to aid pre-pitch entry (warming-up via PAPE-based methods), at half time (both PAPE and COOL) or following exercise cessation (COOL applying cryotherapy) (BLEAKLEY et al., 2012; SILVA et al., 2018). It is not uncommon that the governing body in various locations defines the format of youth tournaments as having unlimited number of substitutions (HARLEY et al., 2010; BELLISTRI et al., 2017; ATAN et al., 2016; PALUCCI VIEIRA et al., 2019a), thus allowing players to return to the field after being replaced. As a consequence, using PAPE and COOL strategies seems feasible even during the course of competitive games under such circumstances. The main problem identified among the empirical studies that have tested warm-ups preceding soccer kicks, is a predominance of only stretching (static, dynamic or ballistic) routines with no additional exercise stimuli or workload. According to the systematic and critical review presented in Chapter 2, this is the case in 8/10 publications found in the topic (PALUCCI VIERA et al., 2021). On the other hand, resistance/plyometric exercises are increasingly used within warm-up routines in team sports because they can facilitate PAPE state to a greater degree than traditional methods (ABADE et al., 2017; TILL & COOKE, 2009; TURKI et al., 2020; ZOIS et al., 2011; TILLIN & BISHOP, 2009; ZAGATTO et al., 2022a), whereas these were almost ignored in kicking research. Concerning the employment of COOL, it seems well justified to avoid cooling when the goal is to acutely recover athletic outputs dependent upon lower limb muscle power. However, the deleterious effects of extreme conditions such as the heat experienced in various regions in Brazil (see for instance NASSIS et al., 2015) could be transformed into benefits (BONGERS et al., 2015). Most importantly, the consequences of COOL in manipulative motor skills demanding both velocity and accuracy constraints are is still unclear (BLEAKLEY et al., 2012). Updated results in the literature review in Chapter 2 also support the latter premise, in particular the lack of studies evaluating the possible influence of COOL on kicking performance characteristics in soccer, and notably in youth categories (PALUCCI VIERA et al., 2021).

Regardless of whether individual characteristics or practical interventions can impact kicking performance, one key aspect in scientific investigations concerned to soccer skills consists in the definition of valid experimental configurations. Owing to the fact that testing procedures arguably need to attempt replicate or at least simulate the match constraints (ALI, 2011; RUSSELL & KINGSLEY, 2011), the preferably location to evaluate kicking biomechanics is the own soccer pitch (i.e. a naturally occurring environment) rather than an artificial/laboratory condition (see also GOEL, 2010). Currently, analysis of advanced soccer kicking technique features (e.g. joint positions) have been linked to labour-intensive work such as involving manual tracking when video-based kinematic systems are necessary (i.e. outside laboratory), of which applications could be limited only to research but not all practice contexts (DRAZAN et al., 2021; OTA et al., 2021; PALUCCI VIEIRA et al., 2022b). As a consequence, improving speed of kinematic processes related to kicking motion would benefit not only in expanding research in this area, but also delivering of results to athletes and coaches in a time-efficient manner (PAPIC et al., 2021).

Therefore, the main aim of the present thesis was to investigate the influence of internal individual constraints (EEG-derived brain activity and sleep quality/duration) and effects of short-term practical interventions (PAPE and COOL) on the movement kinematics and performance aspects of soccer kicking in youth academy players. The proposal aims to attempt fill some gaps in the literature while taking into account recent criticisms concerning the experimental approaches generally adopted for the research problems addressed here, whose suitability to the “real word” remains debatable (BUCHHEIT, 2017). More specifically, the work was designed to provide evidence to clarify issues of practical interest that have been unresolved. These include: Do players who show poor/short sleep patterns demonstrate impaired kicking performance? To what extent (positive, negligible or negative) does the use of contemporary warm-up techniques to induce PAPE and recovery with COOL influence subsequent movement kinematics and performance of youth soccer players in a critical technical action? The thesis also explored understudied underlying mechanisms likely responsible for motor adjustments during kicking in soccer (i.e. brain activity). A straightforward measurement technique to obtain on-field kicking kinematics was also experimentally tested later - deep learning-based markerless system - and compared to traditional supervised digitisation. By answering these questions, it would be possible to contribute to the decision-making process of training and competition contents/prescriptions, focused in optimise or preserve one of the most important motor skills of soccer as well as potentially offering a new methodological framework to kicking analysis. Taken together, a holistic approach is warranted when concomitantly considering individual constraints and manipulations of deliberated practice (ALI, 2011; CHERON et al., 2016; LEES et al., 2010; RUSSELL & KINGSLEY, 2011). For example, as the interest in the warm-up–recovery continuum occurs due to the influence of one sub phase on another, even though they are extreme moments interspersed by exercise (e.g. CHEN et al., 2018a, b). Before entering specifically into each of the topics raised above, it is also necessary to highlight a common sense (e.g. among practitioners working in elite standards) that construction of a thesis by sports scientist, as in soccer, may not always fit the ‘pragmatic’ backdrop that the research programme which usually comprises the bulk of a thesis was carried out. The ultimate goal is to provide useful information that can more broadly assist control of the various factors that may impact sports performance (ATKINSON & NEVILL, 2001; CARLING, 2012; BUCHHEIT, 2017) including a combination of both observational and intervention studies (ABT et al., 2022).

1.1. Cerebral signalling and sleep quality as individual constraints potentially regulating performance of soccer kicking

Sleep quality and duration indices should be monitored in the night prior to sporting events as these have been associated to reductions in performance (KENNEY; WILMORE, & COSTILL, 2015; BRANDT et al., 2017; JULIFF et al., 2018). Both athletes and coaches/instructors recognise that sleep is a critical component of sports performance and that the quality and quantity of sleep can directly impact training performance and results during competition (LASTELLA et al., 2014). However, it seems that measuring sleep-related indices has become a frequent conduct in research of team sports only over the last decade (see for a review: CLAUDINO et al., 2019). In footballers, sleep provides a number of psychological and physiological functions that can be important to the recovery process. Poor sleep quality and duration may cause adverse mechanisms, such as the inhibition of glycogen resynthesis, increased tissue damage markers and/or harmful consequences to the repair capacity of muscle structures, high mental fatigue, and worsening of cognitive aspects (NEDELEC et al., 2015). Accordingly, it is possible to find investigations relating sleep parameters and players status (e.g. physical performance-external loads) in professional senior (LASTELLA et al., 2015; FOWLER et al., 2015; THORPE et al., 2016) and notably in young players (BRINK et al., 2012; ROACH et al., 2013; SARGENT et al., 2013; ROBEY et al., 2014; FOWLER et al., 2017; WHITWORTH-TURNER et al., 2017, 2019). The latter generally depend on a gretaer amount of sleep than the former to avoid cognitive, physical and behavioral imppariments (HIRSHKOWITZ et al., 2015; PARUTHI et al., 2016).

Indeed, young football players may demonstrate sub-optimal sleep patterns. Fowler and co-workers (2017) using actigraphy (method objective, non-invasive and concurrently validated against polysomnography; DE SOUZA et al., 2003) found that young soccer players (16.2 ± 1.2 years-old) presented averages between 6 h and 33 min and 7 h and 29 min of total sleep duration, which is considered below the lower limit recommended by the National Sleep Foundation (14–17 years: 8–10 h; HIRSHKOWITZ et al., 2015), in addition to showing a high inter-individual variability, ranging from 4 h and 58 min to 10 h and 15 min. Whitworth-Turner and collaborators (2019) found similar results in players from England with an average of 18 years of age. The authors reported that one day after or on the third day preceding a match, the average total sleep duration of the youth players was 7 h and 3 min and 7 h and 14 min, respectively. For the first example, the values also correspond to the lower limit of the interval (7–9 h) typically recommended for individuals from this age on (HIRSHKOWITZ et al., 2015). Corroborating, age-matched Australian footballers also slept an amount of time (e.g. average 7 h and 13 min at home) very close to the aforementioned minimum threshold (ROBEY et al., 2014). In another key study, both Australian under-17 (7.0 ± 0.5 h) and Bolivian under-20 (6.4 ± 1 h) players failed to meet age-specific total sleep time recommendations, even in the environment they naturally dwell, i.e. respectively low and high altitude (ROACH et al., 2013).

It is generally accepted that reduced levels of sleep duration and quality negatively interfere with athletic performance as in global terms. In a large sample (576 athletes) including individual and team sports, those with worst perceived sleep quality were three times more likely to be defeated (BRANDT et al., 2017). In addition to a better subjective perception of sleep quality, a longer total time in bed and total time sleeping were also predictors of classification in a netball tournament (JULIFF et al., 2018). On the other hand, self-reported variables of sleep quality/duration and number of awakenings did not show correlations with performance in a population of 103 marathon runners (LASTELLA et al., 2014). Also, excessive sleep (10.55 ± 0.56 h) was reported in elite swimmers who finished below 4th place in a national competition when compared to better ranked peers (8.75 ± 1.14 h; CHENNAOUI et al., 2016).

To date, the impact sleep quality/duration may have on subsequent technical performance is unclear. Abegg (2015) reported absence of a significant difference in the percentage of successful passes during NCAA first division women's match performance after nights well (total sleep duration: 9 h 35 min; sleep efficiency: 91.90 ± 2.62%) or having poorly slept (total sleep duration: 6 h 56 min; sleep efficiency: 76.21 ± 12.06%). Fowler et al. (2015) reported similar findings in adult professional players. Domestic air travel induced fluctuations in the indicators of quantity and quality of sleep, but not in the number of kicks on-target. These investigations using game-related statistics could provide ideas, *a priori*, supporting the premise that sleep variations only generate small changes in subsequent technical performance in footballers. However, situational factors can influence the expression of match-play technical actions, such as the total number of shots and percentage of shots on-target (e.g. TAYLOR et al., 2008). Controlled field studies emerge as an alternative to help provide a better understanding of the factors that could hypothetically modulate kick performance (CARLING & DUPONT, 2011). Thus, empirical support is still limited to a potential association between sleep quality/duration with motor skills required in the soccer context, i.e. the movement features and performance outputs; key studies are only found in a range of other modalities.

According to results presented in a systematic review by Kirschen and collaborators (2020) who have collated, among competitive athletes–individual and team sports–the independent effects of individual sleep patterns/manipulations in sleep duration on ensuing technical and motor performance, i.e. whether derived from game-related statistics or tests in a controlled environment. Studies were identified in rugby, tennis and basketball players (six scientific articles in total). Clearly, the restriction or extension of sleep duration was associated with impaired and improved performance (e.g. accuracy), respectively. Likewise, total sleep deprivation impaired soccer kicking accuracy in two investigations (MEHRDAD et al., 2012; PALLESEN et al. 2017). In advance, it is important to note that the systematic review conducted here prior to designing the experiments (PALUCCI VIEIRA et al., 2021a) evidenced that only total sleep paradigm was used as an experimental condition, when searching for evidence on the effects of recovery-related methods–including sleep–upon soccer kicking performance indicators. Although studies adopting sleep deprivation have made important contributions to the understanding of player's responses face a manipulation of avoid sleeping, it is difficult to assume solely from these the existence of linear relationships between sleep and performance (ABEGG, 2015). This added to the real profile of sleep and the deprivation issues that are actually experienced by soccer players, both of which were introduced previously, it is still not possible to draw firm conclusions about the influence of sleep on subsequent kicking performance in soccer.

Sleep restriction has generally been notably associated with negative effects on CNS processes (see for a review: HALSON & JULIFF, 2017), resulting in a progressive loss of attention (DINGES et al., 1997), reaction time (GOEL et al., 2009) and visual function (RUSSO et al., 2003), and decision-making (KILLGORE, BALKIN & WESENSTEN, 2006). The effects of sleep deprivation on human performance are explained, at least in part, by reductions in the activity of brain regions responsible for acquiring pertinent environmental information including eye movements such as fixations, saccades and pupillary reactions (e.g. frontal field, parietal lobe of heteromodal cortex), and a decay in the metabolism of machinery involved in planning and execution of movements (e.g. pre-frontal, parietal, pre-motor and primary motor cortex) (KILLGORE et al., 2006; GOEL et al., 2009; WALKER et al., 2005).

Previously, the levels of cortical activity, in particular the spectral power in alpha rhythm (8–12 Hz) across various brain locations (e.g. Cz, C4, Fz and Oz), enabled prediction of accuracy in sports tasks primarily demanding on upper limb and trunk muscles. For example in air pistol shooting (LOZE et al., 2001), archery (SALAZAR et al., 1990; LANDERS et al., 1994) and golf putting (CREWS & LANDERS, 1993; BABILONI et al., 2008; BAUMESITER et al., 2008). Nonetheless, these findings have been contrasted by more recent research that did not report similar results in complex team sports skills, also controlled by the upper limbs (e.g. hockey shooting–CHRISTIE et al., 2017; baseball bating–PLUTA et al., 2018; basketball throw–CHUANG et al., 2013). For these three latter tasks, the cortical rhythms related to performance were frontal/midline theta (6–8 Hz; CHUANG et al., 2013) and frontal/posterior beta (13–30 Hz; PLUTA et al., 2018) in the preparatory phase. These results suggest caution in any attempt to extrapolate consistent findings about correlations between sports performance and cortical activity, related to simple voluntary movements in a static upright position (COOKE, 2013; HATFIELD et al., 2004; NAKATA et al., 2015) to possible implications as concerning skills requiring other types of more complex movement responses.

Scientific information reporting cortical activity related to manipulative motor skills using lower limbs is scarce. Taking into account that several literature reviews (e.g. COOKE, 2013; HATFIELD et al., 2004; NAKATA et al., 2015) collated cortical activity in manipulative tasks of individual sports, Table 1.1 contains a brief literature review (that did not constitute an exhaustive systematic review) from PubMed/NCBI, about brain dynamics in goal-directed motor tasks in team sports. Investigations with kick (imagined) movement and other evidence with soccer players (i.e. EEG-performance associations) potentially relevant to the current thesis were also included.

Recent evidence confirms that the motor cortex guides the muscles of the lower limbs during dynamic multi-joint tasks such as walking/running (GWIN et al., 2010; PETERSEN et al., 2012; PRESACCO et al., 2012). Preliminary studies in soccer highlighted that the levels of cortex activation may contribute to performance fluctuations, as there was a moderate correlation between competitive performance and brain connectivity, measured using EEG (THARAWADEEPIMUK & WONGSAWAT, 2017). Nevertheless, the latter determined EEG-derived variables only in a resting state and the performance was analysed using coaches' subjective scores. It is recognised that during kicking, the muscle activity and movement kinematics of the contact limb modulate both the ball velocity and accuracy (DICHIERA et al., 2006; DE WITT & HINRICHS, 2012; KATIS et al., 2013; CERRAH et al., 2018), which implies the probable participation of supra-spinal inputs on the variance of movement parameters and kicking performance. This is supported in only two preliminary works, which analysed the short pass ability in active subjects engaged in physical activity and sports programs using EEG (COLLINS; POWELL & DAVIES, 1991) and more recently penalty kick on a sample of university senior using fNIRS (SLUTTER, THAMMASAN & POEL, 2021).

Imagined kick has already been considered as a research topic (KITAHARA & KONDO, 2015; KITAHARA et al. 2017), but it is not fully accepted that the isolated imagination reliably reproduces the brain activity that occurs during the movement itself (HARDWICK et al., 2018). Also, although the publications addressing locomotion have demonstrated corticomuscular coupling in the legs similar to that of the upper extremities, it is generally assumed that there is a segregation at the cortical level regarding its movement-related activity (SALMELIN et al., 1995; NEUPER & PFURTSCHELLER, 2001; TINKHAUSER et al., 2019). At present, work by Slutter, Thammasan & Poel (2021) represent the experiment closest to describing the relationship between central signalling and kicking performance in soccer, especially considering its experimental approach testing players under field conditions. However, the low temporal resolution of the brain mapping technique used (LIU et al., 2021) and consideration only of the preparatory phase of the kick (SHAN & WESTERHOFF, 2005; KATIS & KELLIS, 2010; RABELLO et al., 2022) are fundamental limitations to its conclusions. Based on these assumptions, it seems still necessary to understand the underlying mechanisms likely responsible for motor adjustments (e.g. EEG metrics) in the execution of manipulative, ballistic and open circuit skills using lower limbs, as required in soccer. Technological advances make it possible to obtain EEG data during movement and outside a laboratory context (see for reviews in CHERON et al., 2016; PARK et al., 2015; PERREY et al., 2018), which also help justifies an in-deep exploratory analysis on the brain dynamics during soccer kicking. Arguably, this could assist in the proposal of new theoretical framework about ball kicking skill and possibly contribute to improve the performance of youth players identifying whether there exist specific brain states that are linked with optimal kick outputs.

To summarize, previous studies elucidated if sleep interruptions, sub-optimal patterns of sleep or total sleep deprivation could reduce performance, primarily in terms of physical capacity (e.g. REILLY & PIERCY, 1994; MENEY et al., 1998; LASTELLA et al., 2014). A simple extrapolation of the well-established findings regarding physical performance (FULLAGAR et al., 2015) for possible implications for technical performance remains debatable, due to a lack of association between these components (CARLING & DUPONT, 2011). Finally, the possible role of sleep-derived indices in subsequent performance of fundamental motor skills used in soccer has been much less explored in young players (NISHIDA & WALKER, 2007), in addition to a lack of empirical data illustrating brain activity-kicking outcome relationships (NAVARRO et al., 2018; PALUCCI VIEIRA et al., 2021b).

Table 1.1. Brain activity in movements pertaining to team sports, imagined kick and additional evidence in soccer potentially relevant to the current thesis[#].

Reference	**Task**	**Technology**	**Channels/regions**	**Main findings**
Team sport skills				
COLLINS, POWELL & DAVIES, 1991	Soccer passing	EEG Biodata headboxes – 256 Hz	T3, T4, C3, C4, P3, P4 reference: Cz ground: thoracic vertebra 2	- success > failure α band power (8–13 Hz) in T3 and T4
SLUTTER, THAMMASAN & POEL, 2021	Soccer penalty kick	fNIRS Artinis Brite 24 (Artinis Medical Systems, Netherlands)	Left and right pre-frontal cortex, left temporal cortex, motor cortex, left and right dorsolateral pre-frontal cortex	adult university players - scoring > missing (inexperienced group) left temporal cortex activation - scoring = missing dorsolateral pre-frontal cortex-motor cortex connectivity - scoring < missing pre-frontal cortex asymmetry
CHUANG et al. 2013	Basketball free throw	EEG polygraph (NeuroScan SynAmps, USA)	F3, F4, Fz, P3, P4, Pz reference: Cz ground: Fpz	- successful throws = unsuccessful α1 (8–10 Hz), α2 (10–12 Hz) and θ1 (4–6 Hz) powers - successful throws > unsuccessful θ2 power (6–8 Hz) in Fz and F4 - non-significant correlations (r = -0.17 – -0.12) θ1 and θ2 powers at Fz vs. percentage of successful throws
CHRISTIE et al. 2017	Ice hockey shooting	eego™ sports 64 pro EEG system (Advanced Neuro Technology, Netherlands) – 500 Hz	F7, F3, Fz, F4, F8, M1, T7, C3, Cz, C4, T8, M2, P7, P3, Pz, P4, P8, O1, O2 reference: common ground: AFz	- top = moderate = bottom performance groups α peak frequency (7–14 Hz)

CHRISTIE et al. 2019	Idem previous	Idem previous	Idem previous, excepting reference: CPz	- successful = unsuccessful shots synchronization/desynchronization low (4–6 Hz) and high θ (6–8 Hz); low (8–12 Hz) and high α (10–12 Hz); SMR (12–15 Hz); β1 (15–18 Hz), 2 (19–22 Hz) and 3 (23–26 Hz) in all channels
CHRISTIE et al. 2020	Idem previous	Idem previous	Idem previous, excepting ground: AFz	- successful > unsuccessful shots β band power (12–15 Hz) in Fz - successful < unsuccessful shots β band power (12–15 Hz) in Pz
CHERON et al. 2016	Idem previous	128 electrodes cap (ANT)	Fz, C3, Cz, Pz, Oz	- α rhythm in the resting phase - θ rhythm previously to movement execution
PLUTA et al. 2018	Baseball batting	MUSE EEG headband (InteraXon, Canada) – 500 Hz	AF7, AF8, Fpz, TP9, TP10 reference: Fpz	- significant inverse correlations (r = -0.33 – -0.48) β power (13–30 Hz) vs. performance - non-significant correlations (r = -0.17–0.14) δ (1–3), θ (4–7), α (8–12 Hz) powers vs. performance
Motor imagery				
KITAHARA & KONDO, 2015	Imagined kick	EEG (g.LADYbird, g.tec, Austria) – 250 Hz	AFz, F1, Fz, F2, FC5, FC3, FC1, FCz, FC2, FC4, FC6, C5, C3, C1, Cz, C2, C4, C6, CP5, CP3, CP1, CPz, CP2, CP4, CP6, P1, Pz, P2, POz, O1, Oz, O2 reference: left earlobe ground: forehead	- seated leg extension with target/kicking a ball > leg extension event-related β desynchronization (14–26 Hz) - seated leg extension with target/kicking a ball = leg extension event-related α desynchronization (8–13 Hz) event-related β synchronization (14–26 Hz)
KITAHARA et al. 2017	Imagined kick	Idem previous	Idem previous	- Idem previous

NAITO & HIROSE, 2014	Ankle rotation	fMRI (Discovery MR750w 3.0T, General Electric, USA) – 3-tesla	Supplementary motor area, cingulate motor area, primary motor cortex, primary somatosensory cortex of the left hemisphere	- elite player < 3 second division players Medial-wall foot motor region activity
Additional evidence				
IWADATE et al. 2005	Oddball	EEG – 1kHz	Fz, Cz, Pz, C3, C4 reference: earlobes	- soccer players > non-athletes N140/P300 amplitude using lower limbs - soccer players < non-athletes P300 latency using lower limbs - soccer players = non-athletes P300 amplitude and latency using upper limbs
NAN et al. 2014	Peripheral visual performance	EEG Somnium system (Cognitron, Brazil) – 256 Hz	Cz, O1, O2 reference: average of mastoids ground: forehead	- significant correlations (r = 0.27–0.37) Dynamic peripheral visual performance vs. α amplitude (8–12 Hz) in all channels
THARAWADEEPIMUK & WONGSAWAT, 2017	Resting state	EEG Brain Master Discovery 24E – 256 Hz	Fp1, F3, C3, P3, O1, F7, T3, T5, Fz, Fp2, F4, C4, P4, O2, F8, T4, T6, Cz, Pz reference: A1—right ear ground: A2—left ear	- significant correlations (r = 0.54–0.58) Resting δ connectivity (0.1–3 Hz) vs. performance–coaches rating - non-significant correlations (r = 0.08) average α power (8–12 Hz) of posterior channels in resting vs. performance

FINK et al. 2018	Imagined decision-making	EEG amplifier (Brainvision actiCHamp Research Amplifier, Brain Products™) – 1000 Hz	Fp1/2, F7/8, F3/4, T7/8, C3/4, P7/8, P3/4, O1/2 reference: nose ground: forehead	- creative decision-making > control parietal and occipital α desynchronization (10–12 Hz)
DEL PERCIO et al. 2019	Estimate the distance between two given players	EEG (EB Neuro-Be-plus©, Italy) – 512 Hz	F3, Fz, F4, C3, Cz, C4, P3, Pz, P4, O1, O2 reference: between AFz - Fz ground: between Pz - Oz	- football players > matched non-players event-related parietal α desynchronization (8–12 Hz)

Note: δ delta; θ theta; α alpha; β beta; SMR sensorimotor rhythm. #Input arguments used in searches: (football OR soccer OR basketball OR handball OR volleyball OR field hockey OR curling OR ice hockey OR rugby OR water polo) AND (eeg* OR electroencephalography OR fNIRS OR nirs OR functional near-infra* OR near-infrared spectroscopy) AND (movement OR motor OR perform* OR kick* OR shoot* OR throw* OR accura* OR velocity OR speed OR target OR aim* OR skill OR goal-directed). The function text words was adopted "[tw]", which directs searches to paper titles, abstract, MeSH terms and other fields including keywords provided by authors. * = wildcard term.

1.2. Short-term practical interventions and their effects in enhancing/preserving soccer kick

A range of athletic tasks generally require movements that are highly dependent on both speed and muscle force, such as in the case of soccer kicking. One practical strategy that may allow maximising motor performance in humans–in particular speed and power outputs–was known for decades as postactivation potentiation (PAP) (SALE, 2002, 2004; CHIU et al., 2003; HODGSON et al., 2005). PAP is defined as the phenomenon by which there is an acute increase in muscle twitch and low frequency tetanic force following a contractile/conditioning activity (CA) (SALE, 2002). There are three primary mechanisms responsible for its occurrence: phosphorylation of the myosin regulatory light chains (HODGSON et al., 2005), increased recruitment of high-order motor units (TILLIN & BISHOP, 2009) or alterations in muscle architecture (e.g. reduction in pennation angle) properties (MAHLFELD et al., 2004) given a prior CA.

Recently, the use of widespread nomenclature PAP has been challenged in the context of sports sciences. This is due to the fact that the confirmation of PAP occurrence requires electrically evoked twitch contraction (TILLIN & BISHOP, 2009; BLAZEVICH & BABAULT, 2019; PRIESKE et al., 2020; BOULLOSA, 2021). Instead, it has been proposed the term 'postactivation performance enhancement' (PAPE) (BLAZEVICH & BABAULT, 2019) when referring to voluntary increase in muscle force and/or performance after a bout of prior CA. In the absence of such updated guidelines, most previous studies in soccer have used the former nomenclature PAP without including twitch assessment, i.e. these evaluated performance in criterion task(s) before and after applying a given CA (e.g. TILL & COOKE, 2009; MOLA; BRUCE-LOW, & BURNET, 2014; TITTON & FRANCHINI, 2017; DELLO IACONO & SEITZ, 2018; SANCHEZ-SANCHEZ et al., 2018). While PAP seems dependent almost upon only one internal musculoskeletal system mechanism (phosphorylation of myosin regulatory light chains) and its time-course is in the form of a negative exponential (maximal expression roughly immediately after CA cessation), PAPE on the contrary is influenced by muscle (temperature, water content and activation levels) and movement pattern factors and represents a “Gaussian”-like curve of observed responses across the time following CA (BLAZEVICH & BABAULT, 2019; PRIESKE et al., 2020). Following the above discussed call to rename PAP into PAPE where pertinent, soccer scientists then opted to use the latter when testing whether performance, but not twitch contraction enhancements, occurs as a function of CA (de KEIJZER et al., 2022; BRINK, & CONSTANTINOU; TORRES, 2021; IMPEY; BAHDUR, & KRAMER, 2022).

The PAP/PAPE methods have shown consistent positive effects on the performance of professional senior players. Increases in maximal locomotor speed and jumping ability have been identified in a range of studies (CHATZOPOULOS et al., 2007; NEEDHAM et al., 2009; TILL & COOKE, 2009; REQUENA et al., 2011; LOW et al., 2015; TITTON & FRANCHINI, 2017). However, most studies in soccer context refer only to the effects of PAPE on the final outcome of an action as measured by the total running time, jump height or power, in which the PAPE effects on movement mechanical factors and neuromuscular activity are less explored. As for example, Blazevich & Babault (2019) indicated that among non-phosphorylation-dependent processes impacting Ca2+ sensitivity (i.e. PAPE mechanism), neural drive estimated through muscle activation merits attention as it is unclear if increases in complex voluntary muscular performance do indeed result from an augmented neural discharge delivered to the muscle. It is also important to highlight that, although typically achieved by adopting a CA with high load or close to the maximal individual capacity (GOŁAŚ et al., 2016; SEITZ & HAFF, 2016), it is not infrequent to verify across research those publications supporting moderate intensity (WILSON et al., 2013) and most importantly the use of the own body weight (BISHOP et al., 2017) inducing subjects into a PAPE state. Such findings are of paramount importance from a practical point of view, taking into account the numerous barriers that can limit the number of coaches and players with access to sophisticated implements, external loads and structure (e.g. Olympic weightlifting platform, bar and squat rack) which in generally are expensive and dependent upon construction of facilities outside playing court/field context; these also demands optimal movement technique and mobility that are difficult to be seen apart from the professional senior standard (BISHOP et al., 2017; TURKI et al., 2020).

Furthermore, the benefits of PAPE in young populations seem not to be sustained in the same way as in adults (LOW et al., 2015), implying a necessity to deepen knowledge on the possible PAPE effects on the performance of youth categories (ZAGATTO et al., 2022b), as well as the theoretical better responsivenes to non-externally loaded CAs given its superior practical utilility.

PAPE can be found in soccer kicking action, resulting from prior dynamic or ballistic stretching routines. This is inferred by improvements in lower contact limbs kinematic characteristics alongside ball velocity and accuracy (GELEN, 2010; AMIRI-KHORASANI et al., 2010, 2011a, 2012; AMIRI-KHORASANI, 2013; AMIRI-KHORASANI & KELLIS, 2013; AMIRI-KHORASANI & FERDINANDS, 2014; FRIKHA et al., 2017) when using the aforementioned methods as compared to separate static stretching, which in turn can be detrimental to performance. Yet except for stretching strategies as in the various original articles above mentioned, the systematic critical review presented herein found that the consequences of other CAs (e.g. resistance, agility and plyometrics) on subsequent kicking ability in youth categories have not been sufficiently evaluated, despite its frequent usage in practice with academy players (ENRIGHT et al., 2018; READ et al., 2018). The absence of a closer resemblance between warm-up protocols employed in existing research and those used in practical contexts is also confirmed (PALUCCI VIEIRA et al., 2021a). In conjunction with stretching, warm-up routines applied to young soccer players increasingly take advantage of CAs more demanding/explosive in nature as compared to isolated stretches, based on the premise that they can facilitate a PAP/PAPE state to a greater extent as compared to traditional methods (TILLIN & BISHOP, 2009; ZOIS et al., 2011; TURKI et al., 2020). Of most importance, the Chapter 2 indicates that there is a fundamental question left unanswered at present, concerning the time-course of changes in kick parameters following warm-up (PALUCCI VIEIRA et al., 2021a). In advance, it is pertinent to state that the optimal time-window to possible obtain PAPE of kicking following CA cessation has not yet been determined.

While inducing players into an acute state of enhancement in performance is one of the main goals of pre-pitch entry strategies, prescriptions to aid maintaining/re-establish optimal athletic responses are equally important in order to prevent a reversal (e.g. declines) of previously achieved gains. In this sense, the use of COOL after high-intensity training sessions or official games is common among athletes to improve recovery (WILCOCK et al., 2006; ROWSELL et al., 2009). The practice of applying ice has become such an extensive attitude that it is frequent identifying COOL interventions in other various moments including those before, at half time or during matches (BLEAKLEY et al., 2012; MACEDO et al., 2016). The use of COOL could favour the process of re-establishing performance due to 1) facilitating rapid reduction in body temperature and consequently CNS-mediated fatigue; 2) the induction of peripheral vasoconstriction, which in turn stimulates increased venous return and greater removal of muscle by-products accumulated during exercise and 3) combined events 1 and 2 may cause a decrease in cardiovascular tension, ratings of perceived exertion, swelling and muscle pain; COOL has an important analgesic effect (BLEAKLEY & DAVISON, 2010; IHSAN et al., 2016), being able to facilitate the execution of subsequent movements (FISCHER et al., 2009). However, although asking players into COOL is a conduct capable of originating beneficial effects as above mentioned, mainly associated with well-being (ASCENSAO et al., 2011) and/or neuromuscular performance up to 24 h after sports events (HIGGINS et al., 2017), its effectiveness for acute recovery in athletic performance aspects is still controversial, specially relating to motor skills.

A systematic review found that approximately 75% of the available literature at the time of writing concluded that applying ice produced acute negative effects on the motor performance of athletes (BLEAKLEY et al., 2012). In other words, performing a COOL protocol and then a sport task again seems to result in a worse performance response compared to no intervention. Significant decreases in nerve conduction velocity (ALGAFLY & GEORGE, 2007) magnitude of muscle activation (MACEDO et al., 2016), and its delayed timing to reach peak values (OKSA et al., 1996) as well as lower muscle contraction (GARCIA-MANSO et al., 2011) can be highlighted as the likely mediators that trigger the decreases in muscle strength/power reported in young adults as a consequence of COOL (COMEAU et al., 2003; CROWE et al., 2007; PATTERSON et al., 2008; FISCHER et al., 2009; PEIFFER et al., 2009; DIXON et al., 2010; MACEDO et al., 2016). Cooling strategies have also been associated with changes in lower limb kinematics, affecting movements around hip and ankle joints during running (FUKUCHI et al., 2015). Yet the effects derived from the use of COOL have been much less documented in athletes aged under 20 years-old, who seem to be affected in a trivial/slight magnitude (MURRAY & CARDINALE, 2015). In addition, most of the literature used impractical treatment times; further studies using shorter periods of COOL are required, taking into account the reality of team sports where extended cooling periods are impractical (BUCHHEIT, 2017). Reducing the exposure time to COOL also possibly would not cause the same harmful effects generally observed in longer interventions (FISCHER et al., 2009). Importantly, environmental temperature across investigations which determined post-exercise recovery of soccer kicking through the use of ergogenic aids ranged from 18.2ºC (STEVENSON et al., 2017) to maximal 21ºC (ABT; ZHOU, & WEATHERBY, 1998; RUSSELL; BENTON, & KINGSLEY, 2012). Thus, it is unknown whether the common acute deleterious effects of COOL persists under very hot temperatures generally encountered in various tropical countries (NASSIS et al., 2015; COIMBRA et al., 2016). Two meta-analyses (TYLER; SUNDERLAND, & CHEUNG, 2015; BONGERS et al. 2015) indicated that when ice was applied in the heat circumstances (>26ºC and >30ºC, respectively) exercise performance and capacity improved rather than declined.

Currently, the effectiveness of COOL to optimise motor skills has been systematically overlooked in scientific research (BLEAKLEY et al., 2012; PALUCCI VIEIRA et al., 2021a). The limited knowledge available refers to tasks that mainly demand the upper limbs. To be explicit, Lakie et al. (1995) found that applying COOL in the forearm 10 minutes at 10ºC improved pistol shooting performance (targeting) (+5–24%) when compared to control (20–23ºC) and heat (44ºC) conditions, and the authors related this to a reduction in tremor caused by the COOL application. Conversely, Wassinger et al. (2007) reported worsened accuracy in ball throwing against a wall (-7%), after 20 min of COOL application to the shoulder joint, with simultaneous impairment in proprioception measurements thereby suggesting cryotherapy confused the efferent, afferent path or central integration. Similar results to the latter study were reported in cricket players (ANU et al., 2014). Thus, in addition to the existing conflicting evidence, effects of COOL (if any) on the mechanics of movement and kick performance in soccer have not yet been established following intense exercise under environmental heat stress (PALUCCI VIEIRA et al., 2021a).

1.3. Methodological challenges to measure kicking kinematics and outcomes in the real world

Generally speaking, external or ecological validity is often a concern when designing testing routines in soccer, because experimental arrangements may constrain the actual performance of players, especially under laboratory conditions (THOMAS; NELSON, SILVERMAN, 2015). Also, athletic behaviour can be modified as a function of evaluator(s) attention paid to execution of their movements during a given assessment, potentially resulting in the so called Hawthorne effect (BROWN, 1954). In fact, results derived from tests of ball kicking have demonstrated poor concordance with outcomes observed in real competition (RÉ et al., 2014; SERPIELLO et al., 2017). On the other hand, there are various issues that make it difficult or or almost impossible to obtain advanced kicking kinematics data during official events. Examples includes large measurement areas, possible player occlusions and non-controllable variables occurring in match play (e.g. location of the action, distance to the defenders, and sight of the goal) (APRIANTONO et al., 2006; RUSSELL & KINGSLEY, 2011; VAN DER KRUK & REIJNE, 2018; SCHULZE et al., 2018). As a consequence, amongst the available options, field tests remain the most pertinent method to perform a detailed diagnosis of kicking ability in soccer. This is evident in particular when aiming to record time-series kinematics of player's movement as well as post-impact ball flight features (e.g. concomitant speed and placement in the goal plane).

Collation and critical evaluation of environmental constraints, technologies and data treatment approaches used to measure kicking performance across the scientific literature would help understanding of ecological validity, potential error issues (e.g. bias) and can ultimately aid provision of guidelines potentially useful for practical contexts and future research. Existing literature reviews that covered soccer kicking action were published in the years of 2007 (KELLIS & KATIS, 2007), 2010 (LEES et al., 2010) and most frequently 2011 (RUSSELL & KINGSLEY,

2011; ALI, 2011; SHAN & ZHANG, 2011; YOUNG & RATH, 2011). Thus, an update seems necessary to these publications in order to identify new trends in research ("hot topics") and strengths and weaknesses of current evidence. As for instance, notational-based metrics of kicking accuracy and ball velocity determined via radar equipment are widespread practices, in both applied contexts and scientific research. It is likely owing to the fact that they can provide real-time results, being easy tools to implement and record measures under field conditions and generally come at a lower cost as compared to gold-standard video kinematic systems (JAMES, 2006; PALUCCI VIEIRA et al., 2017; SOUSA et al., 2022). Meanwhile, throughout the literature review of the present thesis it is highlighted that some aspects of both methods (notational analysis and radar) still require careful interpretation. Simple criterion measures demonstrated a lack of sensitivity to intervention (warm-up) while information on whether radar and 3D video kinematic outputs have sufficient agreement to determine kicking velocity is not yet available (PALUCCI VIEIRA et al., 2021a).

Another prominent methodological barrier requiring urgent solution or improvement in existing procedures is the time-frame separating data collection and reporting of results derived from kicking kinematic analysis. This is given the common need to use manual frame-by-frame tracking in field studies interested in analysis of kicking motion. Sunlight and small perturbations to camera positioning are recognised to interfere with the use of infra-red or optoelectronic measurement systems, thereby limiting their preferred use to indoor environments (VAN DER KRUK & REIJNE, 2018). Consequently, assessing on-field kicking movement features have been linked to time-consuming processing of the (virtually unavoidable) video data. Here digitisation procedures in PAPER 2 and PAPER 3 exceeded four months, in which each kicking attempt required approximately between 30–40 minutes of manual work. In this sense, markerless motion analysis systems have been gaining popularity in recent years, probably given (i) their shorter time spent in both preparation of subjects and in offline post-collection processing of the data as compared to marker-based systems; (ii) this favours the implementation of field-based analysis rather than only laboratory observations (increased external validity) and (iii) this tool may also reduce experimental constraints (e.g. objects attached to the body) that potentially causes interference to the players habitual behaviour (see for a review COLYER et al., 2018). Aside from the practical value of this type of emerging technology to assist resolve one of the major problems related to kicking kinematics analysis (extremely labour-intensive work), reliability of contemporary markerless systems is yet to be determined in comparison to reference measures commonly used (i.e. manual tracking), in particular when evaluating ball kicking within a naturally occurring environment (PALUCCI VIEIRA et al., 2022b).

1.4. Aims and programme of research

Given the above, the general aim of the thesis was to investigate the influence of internal individual constraints (EEG and sleep quality/duration) and effects of short-term practical interventions (PAPE and COOL) on the movement kinematics and performance aspects of soccer kicking in youth academy players. For such purpose, a sequence of six studies was developed to answer the thesis' questions (Figure 1.1). The first study is a literature review titled "Acute Effects of Warm-Up, Exercise and Recovery-Related Strategies on Assessments of Soccer Kicking Performance: A Critical and Systematic Review" where the goal was to collate and provide a critical appraisal of published scientific studies specifically regarding soccer kicking performance related to three themes: warm-up, exercise and recovery. After reviewing the generalities of the relevant literature related to the thesis, firstly providing a logical/contextualised basis (Chapter 1) and then preparing the theoretical study presented in the Chapter 2, in other words, considering also the gaps in the literature confirmed through a published comprehensive systematic/critical review, one technical study and four experiments were proposed as follows.

From a micro to a macro perspective, in "Modelling the relationships between EEG signals, movement kinematics and outcome in soccer kicking" (Chapter 3) possible associations between cerebral activity at the cortical level, mechanics of movement of the contact lower limb and the consequent kicking outcomes in terms of ball velocity and accuracy were explored. It was hypothesized that high-frequency signals form the motor cortex would contribute to the development of ball velocity while the alpha occipital component modulate the magnitude of error in placing the ball in the goal. Remaining in the theme of internal/individual constraints, the study "Low sleep quality and morningness-eveningness scale score may impair ball placement but not kicking velocity in youth academy soccer players" (Chapter 4) aimed to analyse the inter-individual sleep quality/duration exhibited by young players and their impact on subsequent kicking skill. The hypothesis raised was that reduced sleep parameters are associated with worst kicking performance.

The two first original research studies were conducted through processing video kinematics via supervised tracking of markers of interest (anatomical points) in the case of kicking movement. With the advent of contemporary methods for automatic processing of image sequences based on neural networks, notably late in the 2010s (CRONIN, 2021), there was a unique opportunity to test the reliability of one available algorithm, which is reported as a technical note in "Automatic markerless motion detector method against traditional digitisation for 3-dimensional movement kinematic analysis of ball kicking in soccer field context" (Chapter 5). As a consequence, the remaining two field studies were conducted considering such a progressive approach to data processing.

Following on and specifically with reference to short-term practical interventions, Chapter 6 contains the study "Post-drop jumps kick potentiation in youth trained soccer players: temporal changes in EMG, kinematics and performance components" focused upon identifying whether a warm-up routine including a specific plyometric exercise was effective in causing neuromuscular postactivation and kicking performance enhancement. In this case, it was expected that muscle activity and kicking outcomes could benefit from the inclusion of a plyometric exercise prior to kicking, especially within five minutes after cessation of conditioning exercises included as a part of the warm-up. The work of the Chapter 7 "Recovery of kicking kinematics and performance following intermittent high-intensity running bouts in young soccer players: can a local cooling intervention help?" tested the application of cryotherapy as a candidate for recovery method of kicking parameters after performing repeated high-intensity running bouts. As a hypothesis, it was expected that intense locomotor efforts would promote acute declines in movement and kicking performance components, notably related to velocity features, and a short period of ice application would not interfere in movement/performance recovery while favouring the athletes' perceived well-being.

Finally, Chapter 8 is an Epilogue that collectively summarize the main evidence gathered in the series of studies, as well as containing a proposal of a theoretical model derived from results encountered in this thesis and how they can be potentially linked to each other. Conceptual advances, practical applications and directives for future investigations are also provided in addition to concluding remarks.

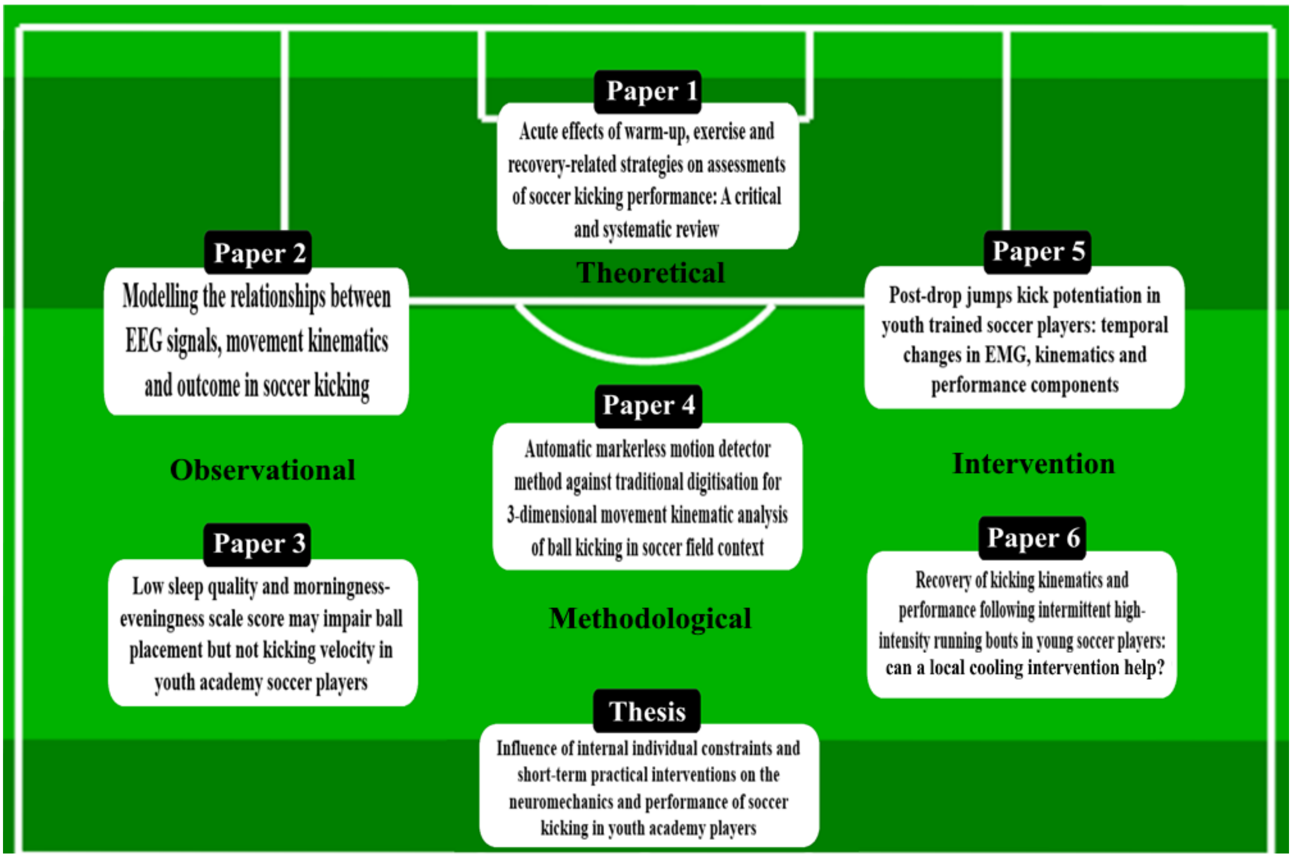

Figure 1.1. Overview of the present thesis document following a Scandinavian model for PhD theses.

CHAPTER 2

LITERATURE REVIEW

2. PAPER 1 – Acute effects of warm-up, exercise and recovery-related strategies on assessments of soccer kicking performance: a critical and systematic review [(2)]

Palucci Vieira, L.H., Santinelli, F.B., Carling, C., Kellis, E., Santiago, P., & Barbieri, F.A. (2021). Acute effects of warm-up, exercise and recovery-related strategies on assessments of soccer kicking performance: a critical and systematic review. *Sports Medicine*, *51*(4), 661–705. **https://doi.org/10.1007/s40279-020-01391-9**

[(2)] APPENDIX 2 - document obtained allowing reuse of this previously published study in the current thesis

2.1. Abstract

Background: A number of reviews have collated information on the impact of warming-up, physical exertion and recovery strategies on physical, subjective and physiological markers in soccer players yet none have solely analyzed their potential effects on components of kicking performance. *Objective*: To systematically analyse the influence of warm-up, exercise and/or recovery-related strategies on kicking performance in male soccer players and provide a critical appraisal on research paradigm related to kicking testing constraints and data acquisition methods. *Methods*: A systematic literature search was performed (until July 2020) in PubMed, Web of Science, SPORTDiscus, Scopus and ProQuest. Studies in male soccer populations, which included the effects of warm-up routines, physical exercise and/or recovery-related interventions, reported on comparisons pre-post or between experimental conditions and that computed at least one measure of kicking kinematics and/or performance were considered. Methodological quality and risk of bias were determined for the included studies. Constraints related to kicking testing and data acquisition methods were also summarized and discussed. *Results*: Altogether, 52 studies were included. Of these, 10 examined the respective effects of a warm-up, 34 physical exercise, and 21 recovery-related strategies. Results of eight studies showed that lower limb kinematics, kicking accuracy or ball velocity were improved following warm-ups involving dynamic but not static stretching. Declines in ball velocity occurred notably following intermittent endurance or graded until exhaustion exercise (three studies in both cases) without inclusion of any ball skills. In contrast, conflicting evidence in five studies was observed regarding ball velocity following intermittent endurance exercise interspersed with execution of ball skills. Kicking accuracy was less frequently affected by physical exercise (remained stable across 14 of 19 studies). One investigation indicated that consumption of a carbohydrate beverage pre- and mid-exercise demonstrated benefits in counteracting the potentially deleterious consequences of exercise on ball velocity while four studies reported conflicting results regarding kicking accuracy. Most evidence synthesized for the interventions demonstrated moderate level (77%) and unclear-to-high risk of bias in at least one item evaluated (98%). Main limitations identified across studies were kicks generally performed over short-distances (50%), in the absence of opposition (96%), and following experimental instructions which did not concomitantly consider velocity and accuracy (62%). Also, notational-based metrics were predominantly used to obtain accuracy outcomes (54%). *Conclusions*: The results from this review can help inform future research and practical interventions in an attempt to measure and optimise soccer kicking performance. However, given the risk of bias and a relatively lack of strong evidence, caution is required when applying some of the current findings in practice.

PROSPERO ID: CRD42018096942

2.2. Introduction

The ability to kick the ball is evidently an essential skill in the sport of soccer notably when attempting to score goals [1]. High standards of shooting performance are associated with increased odds of winning [2–4]. Monitoring kicking performance and identifying factors affecting this component of play are therefore important. Individual characteristics such as the maturity, skill level and gender of players can notably influence kicking ability [1]. Another key factor frequently reported to impact kicking is physical exertion (e.g. external load). Prolonged aerobic exercise [5, 6] and repeated high-intensity running bouts interspersed with short recovery intervals [7, 8] are shown to impair central buffer [9] and lower limb mechanical functioning [10]. However, authors reviewing the effect of physical exertion on technical aspects of play using controlled field tests have presented contrasting findings. In 2011, Russell and Kingsley [11] reported that exercise-induced fatigue significantly impaired shooting performance, although only three studies all conducted in male soccer populations were available at the time of writing. In comparison, a more recent meta-analysis of acute and residual match-related fatigue in soccer, including two additional studies, reported trivial-to-small declines in shooting outputs linked to exercise [12]. A range of protocols to induce fatigue and measure its impact on kicking performance have been employed in investigations in male soccer players [13] (e.g. intermittent endurance with [14–16] or without inclusion of ball skills [17–19] or intermittent high-intensity bouts [20, 21]) yet their effects have not been systematically reviewed.

In general, the capture of advanced information on kicking movement and ball kinematics in real-world competition settings lacks feasibility [11, 22, 23]. As such, research investigations typically employ controlled field or laboratory experiments to assess kicking performance (e.g. exercise-induced effects [11, 24]). However, the results obtained using controlled testing is questionable [25, 26], notably due to poor criterion validity and the task constraints commonly utilised across studies. Examples of constraints include kicking targets positioned in the goal centre and instructions not concomitantly indicating the need for ball velocity and accuracy [27, 28]. In addition, the inclusion of opponents [29, 30] and kicks performed using a rolling and not only a stationary ball are frequently not considered [11, 31]. Low sampling measurement frequencies also possibly produce distorted limb kinematics data [32] and simple notational-based outcome metrics for quantifying accuracy can lack reliability and sensitivity [11, 24]. While previous reports have critically appraised kick assessment methodologies, these were generally published approximately one decade ago [1, 11, 33–36]. Arguably, an up-to-date collation and critical evaluation of procedures utilised in studies examining key variables related to soccer kicking performance, would help identify good practice for current research while generating practical applications [11].

Ensuring player readiness to respond to kicking demands in soccer can be enhanced by warm-up routines [37] while recovery prescriptions [38] or ergogenic aids [17, 18, 39] are commonly used in an attempt to counter fatigue elicited from exercise. A plethora of reviews have examined the impact of intervention strategies such as warm-ups [40–42] or recovery-related modalities during and following exercise [12, 43–46] on physical, physiological and perceptual performance markers in team sport athletes. Yet, to our knowledge, none have specifically collated and critically appraised the current evidence on the effects of these factors on components of kicking performance such as accuracy and ball velocity. For example, standard warm-up programs including only submaximal running followed by stretching and sport-specific drills are generally shown to be suboptimal and may even impair preparedness for physical tasks that are explosive in nature [41]. Again, the impact of such warm-up practices on goal-directed soccer skills such as kicking have not been examined collectively despite several original research papers comparing performance following different stretching routines in male soccer players [47–51]. Finally, research investigating the effects on kicking outputs of rest periods (e.g., breaks in play such as the half-time) [52], commonly prescribed ergogenic (e.g. hydro-nutritional) interventions [53] or the time-course of changes in performance following exercise cessation has yet to be synthesised. This would help determine the role of recovery processes and their effectiveness in counteracting potential exercise-induced declines in kick outputs [11]. Therefore, to examine the acute effects of warm-up, exercise and/or recovery-related strategies on kicking performance, we systematically reviewed the current body of original research articles in soccer players and critically appraised the testing constraints and data acquisition methods.

2.3. Methods

Permission for this study was granted by the Institutional Human Research Ethics Committee of the São Paulo State University (#2650204). The work was conducted following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) statement [54]. The protocol was registered (updated record pending publication) at PROSPERO (ID = CRD42018096942).

2.3.1. Search strategy

Searches for relevant scientific studies on the influence of (#1) prior warm-up, (#2) physical exercise demands and (#3) recovery-related strategies on players' movement kinematics and performance during soccer kicking were conducted using five electronic databases (from inception to July 2020), namely PubMed/NCBI (United States National Library of Medicine), Web of Science Core Collection (Clarivate™), SPORTDiscus (EBSCO Industries Inc.), SCOPUS® (Elsevier B.V) and ProQuest® (ProQuest LLC). Additional searches were performed in Google Scholar (Google LLC) when the full-text was not available, allowing for inclusion of studies found on ResearchGate™. In all databases, pertinent descriptors were combined (Table 2.1) through a Boolean strategy, using operators 'OR' between terms of the same column, and 'AND' inserted between columns. Full description of input arguments used in each database is also provided

(Electronic Supplementary Material Table S1). A dedicated computer software (EndNote X7.0.1, Thomson Reuters©, USA) enabled management of references.

Table 2.1. PICO descriptors combined in the search strategy.

Population	Intervention			Comparison	Outcome
Soccer	Warm-up*	Exercise*	Recover*	N/A	Kick*
Football*	Heat*	Fatigue*	Rest*		Shoot*
Association football	Stretch*	Match demands	Supplementation		Skill
11-a-side	Strength	Match-related fatigue	Cold water immersion		Technical
	Postactivation potentiation	Effort	Compression garments		
		Running	Massage		
	Pre-match		Electrical stimulation		
			Sleep		
			Post-match		

N/A not applicable, * wildcard term.

2.3.2. Selection criteria

*Inclusion criteria***.** Studies were included if they unrestrictedly met all the following criteria: i) original article; ii) with full-text and abstract available for screening; iii) published/ahead of print up to and including the 30th July 2020; iv) written in English; v) published in an indexed peer-reviewed scientific journal. Conference proceedings, literature reviews, meta-analysis, books, thesis, and dissertations were not considered. In addition, following a PICO (Population, Intervention, Comparison, Outcome) eligibility criteria [55], studies were included if they vi) (P) referred to male footballers; vii) (I) examined the effects of a warm-up (≤ 25 minutes) [42], exercise (i.e. when there was previous warm-up in addition to a given exercise protocol), and/or recovery-related strategies (i.e. resting and/or ergogenic aids) [12, 43]; viii) (C) reported comparisons pre vs post intervention or among experimental conditions and ix) (O) included at least one outcome measure regarding biomechanical variables of kicking performance [ball velocity, accuracy (any quantitative metric indicating proficiency in ball placement in the goal/target)] and/or lower kicking limb movement kinematics [e.g. joint angular displacement, foot velocity], x) obtained in a controlled experimental setup.

Exclusion criteria. The qualitative synthesis was not performed for studies i) including athletes from other football codes; ii) special populations (players with cerebral palsy, amputees); iii) without mention of the warm-up, exercise and/or recovery-related protocols used; iv) providing match-related statistics to determine kicking performance; v) examining validity of tests; vi) where a ball was not kicked; vii) assessing skills which required ball manipulation other than shooting actions; viii) studying exercise consisting solely of cognitive/mental efforts, ix) using measurements performed > 48 h following a recovery-related strategy intervention [56] and, x) in studies including female players while in those including male and female players only information pertaining to the male group was retained.

2.3.3. Methodological quality assessment and risk of bias

Risk of bias (RoB) of results or inferences were determined for each study using Cochrane Collaboration's Tool [57], taking into account the criteria of random sequence generation, allocation concealment, blinding of participants, personnel and outcomes, incomplete outcome data, selective outcome reporting and other source of bias. Each item was deemed as low, high or unclear risk. Review Manager software (RevMan, v5.3.5, The Cochrane Collaboration, Denmark) [58] was used to obtain the graphs of RoB. Methodological quality of included studies was assessed using twelve questions (Q1–12) modified from the checklist presented in Palucci Vieira et al. [59] in addition to three key components obtained from RoB analysis (random sequence generation, concealment of allocation and blinding of outcome assessors) [60]. For the criteria, a three-point scale was used (Electronic Supplementary Material Table S2). A sum of scores from all questions was subsequently computed ($\sum = 0–24$) and the values were then converted into percentages (0–100%). Studies were classified as having high (≥75%), moderate (50–74%) and low (< 50%)

methodological quality [61]. Two evaluators (LV, FS) performed independent assessments. If discrepancies occurred, these were resolved in a consensus discussion with a third evaluator (EK). Methodological quality was not an inclusion/exclusion criteria.

2.3.4. Data extraction and codification

In the first screening stage, record titles, abstracts, and keywords were examined independently by two evaluators, according to the inclusion and exclusion criteria established while a third senior researcher was asked to solve any disagreement that occurred between the two evaluators (same authors as described in Section 2.3.3). Inter-evaluator agreement for the current review was assessed using Cohen's kappa coefficient (k_{mean} = 0.95). After examination of the included full-text studies, data extraction was subsequently performed by one author (LV) following a structured script which included the following items [1,28,29,32,33,62–77]: sample characteristics (number of participants, age, competitive level and playing position), environment where the data collection took place, type of ball used, software/equipment which measured outcome variables, acquisition frequency and instructions given to the participants on how to complete the kicking task. More specifically regarding the kicking task, the following constraints were also considered: trials, kick type, approach run parameters, target, goal size and whether opponents (defender and/or goalkeeper) were present. The extraction sheets were created and adjusted following pilot checking across 10 studies randomly selected amongst those included in the current review.

Where mean and standard deviation values were reported, these were used to calculate mean percentage difference (MD) and standardised mean difference (SMD) [78]. When possible, associated 95% confidence intervals (95%CI) were also estimated for individual studies using the RevMan software [58]. When results were presented as figure(s), we implemented a custom-built algorithm in MATLAB® environment (The MathWorks Inc., USA) to estimate the real data [59]. In the absence of pertinent data on full-texts, the corresponding authors were contacted. If available, *p*-values were presented for the instances where it was not possible to compute SMD (e.g. due to insufficient information and lack of reply to our request). The treatment effects obtained (i.e. MD or SMD) refer to between-groups (e.g. intervention vs. control) and/or within group comparisons (e.g. pre- vs. post-intervention) [79]. The symbols > (greater than), < (lower than) and = (no difference) were used to summarize main findings [41]. When inferences about null-hypothesis significance test were omitted, the acronym "vs." (versus) was employed. Subgroup analyses were performed considering the type of intervention protocol, player age [youth adolescent (13–17 years-old) or adult senior (≥ 18 years-old)] [80] and competitive standard [elite (professional players, competing at national/international levels) or sub-elite] [81, 82].

2.3.5. Evidence synthesis

To summarize the main results according to the level of scientific evidence provided, we used a classification adapted from van Tulder et al. [83]. Therefore, findings were deemed to represent 'strong evidence' (consistent findings observed among multiple high-quality studies), 'moderate evidence' (consistent findings observed among multiple moderate-quality studies and/or one high-quality study), 'limited evidence' (findings provided by one moderate-quality study and/or only low-quality studies), 'conflicting evidence' (when inconsistent findings were observed) or 'no evidence' (when there was no available studies). Consistencies and inconsistencies were determined respectively by ≥ 75% and < 75% of studies reporting results showing the same direction [84].

2.4. Results

2.4.1. Search results

The entire search process resulted in 10777 studies, plus 3 additional studies manually entered. Figure 2.1 presents a flow chart with all steps from initial search until inclusion. After duplicates were removed, 4397 studies remained on reference manager. Following on, non-relevant content was immediately excluded (e.g. non sport performance specific). After verification of the title, abstract and keywords, of the 2091 studies assessed for screening, 73 were deemed eligible. Additional reading of full-texts determined 52 studies [13–21, 23, 37–39, 47–51, 64, 85–115] that were suitable for inclusion in the systematic review. Of these, 10 examined the effects of a warm-up (19%) [37, 47–51, 88, 90, 105, 108], 34 exercise (65%) [13–21, 23, 38, 39, 85–87, 89, 91, 93-97, 100–104, 107, 110, 112–114, 116] and 21 recovery-related strategies (40%) [14, 16–18, 38, 39, 64, 85, 86, 91–93, 97-99, 106, 107, 109, 111, 115, 117].

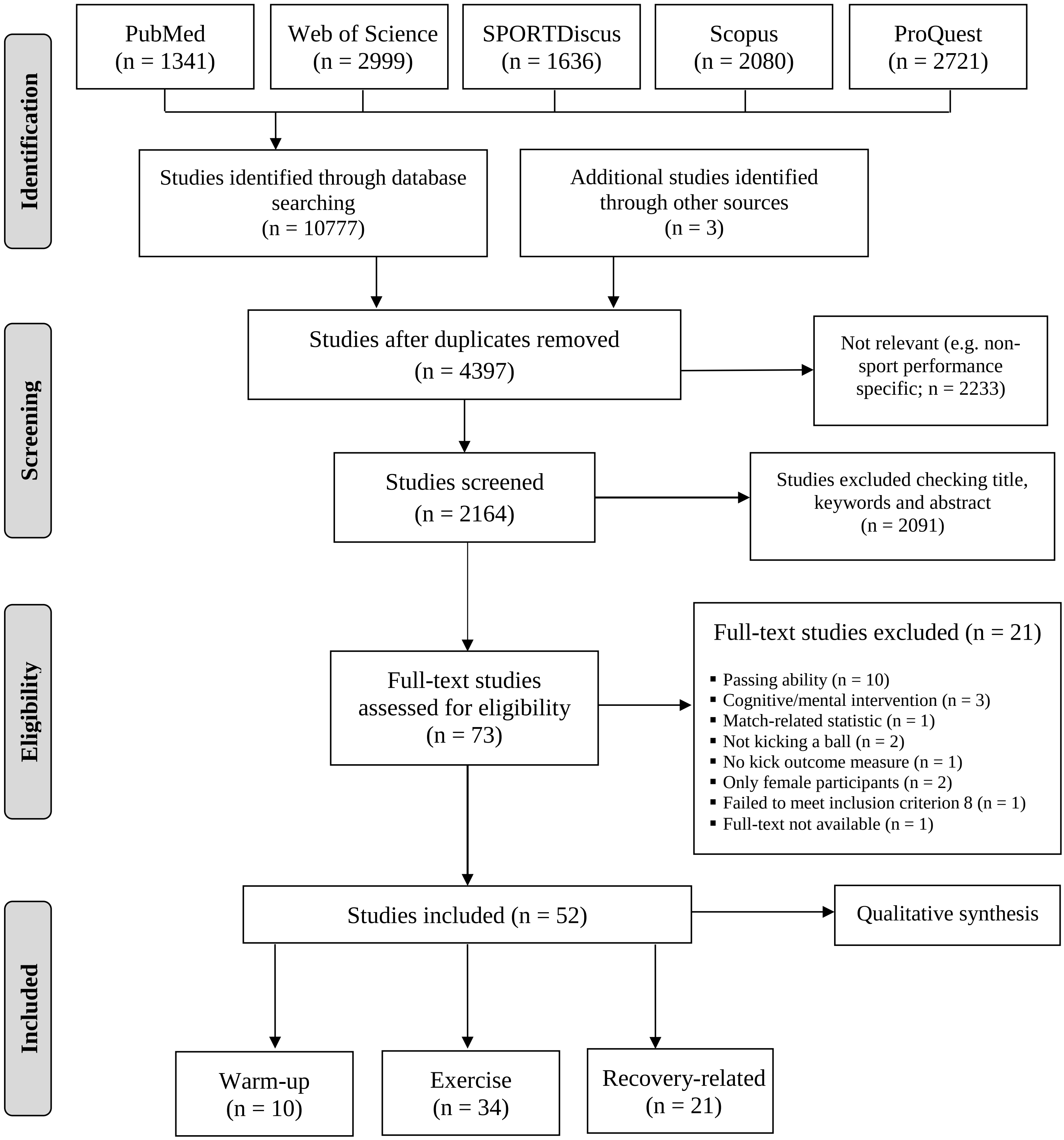

Figure 2.1. Flow chart including literature search and selection steps following PRISMA statement.

2.4.2. Research quality and risk of bias

Evaluation of the 52 studies selected showed a mean ± standard deviation rating of methodological quality equal to 63 ± 11% (Electronic Supplementary Material Table S3). With the exception of RoB items which were also used to evaluate methodological quality (described in details below), the questions with the lowest and highest mean scores reached were Q4 (1.02 ± 0.64 points) and Q2 (1.96 ± 0.19 points), respectively. Risk of bias according to each key criteria are provided as percentages across literature studies (Figure 2.2) and on an individual basis (Figure 2.3). The largest RoB (23% of studies with 'high' RoB) [37,38,48,49,87,88,90,97,99,104,105,109] was observed in 'selective reporting (reporting bias)' item and lowest RoB (100% of studies with 'low' RoB) was found regarding 'incomplete outcome data (attrition bias)'. The 'blinding of outcome assessment (detection bias)' entry demonstrated the greatest amount of uncertainty across studies (98% of studies with 'unclear' RoB), except for one study showing 'low' RoB [115]. Items also showing few studies with 'low' RoB were 'blinding of participants (performance bias)' (19%) [14,17,39,85,86,92,94,106,115, 117] and 'allocation concealment (selection bias)' (13%) [14, 39, 50, 51, 106, 115, 117].

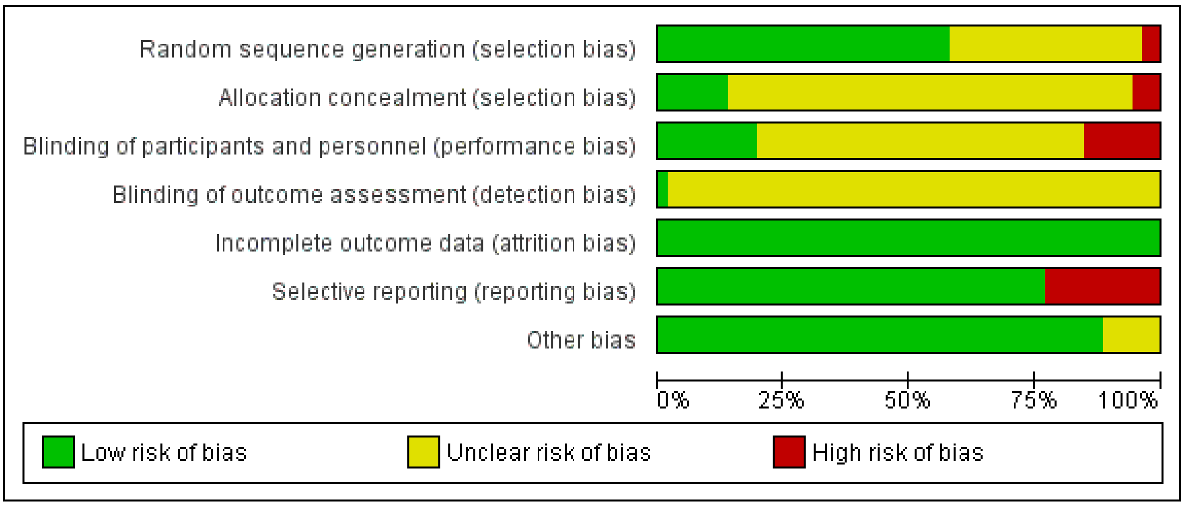

Figure 2.2. Risk of bias graph considering all studies pooled.

Figure 2.3. Risk of bias for individual studies and according to the different criteria assessed. (+) = low risk; (?) = unclear risk; (-) = high risk.

2.4.2. Research paradigm

2.4.2.1. General information

A total of 947 players were evaluated in the included studies (320 youth), representing an average of 18 participants per study (range: five to 174 players). Nearly half of the studies were published on or after 2015 and the majority dated from the last decade (Figure 2.4). Details on demographic characteristics, the location where experiments took place and apparatus used in data acquisition are presented in Table 2.2. Investigations were conducted primarily on the football pitch (25%), in a laboratory setting (19%) or indoor/court (15%) while several (40%) did not specify the experimental location.

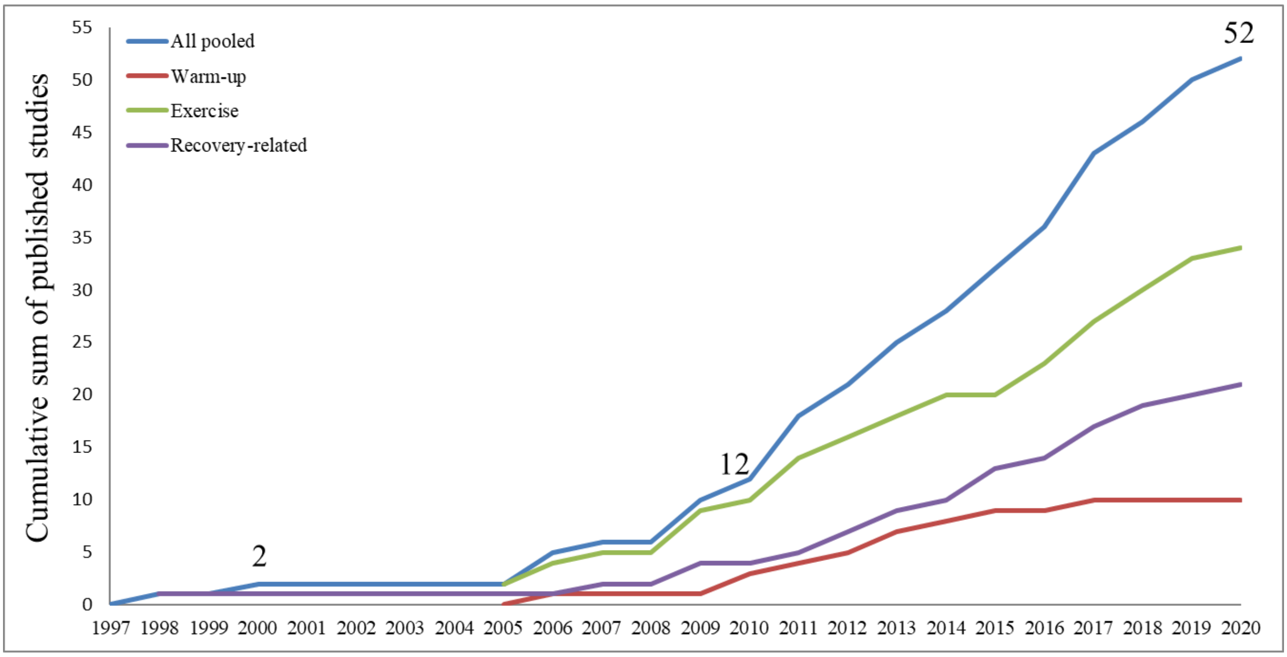

Figure 2.4. Cumulative sum showing (per year up to July 2020) the number of published articles that addressed the acute effects of warm-up, exercise and/or recovery-related strategies on soccer kicking ability.

Table 2.2. Demographic characteristics, location of the experiment, apparatus for data collection, and instructions given to the participants in studies included in the review.

Study	Participants				Location (surface)	Ball		Technology and key variables	Instruction/Aim
	n	Age (mean)	Level	Position		FIFA-approved	Size (Mass and pressure)		
Abbey and Rankin [85]	12	22.5	1st div NCAA	--	Laboratory (artificial grass)	--	--	ACCUR–Notational analysis	Attempting to hit a goal
Abt et al. [86]	6	18	Recreational	Midfielders	--	--	--	ACCUR–Notational analysis	Shoot at a target goal
Ali et al. [17]	16	21.3	Semi-PRO	Outfield (various)	Laboratory	--	--	ACCUR–Notational analysis V_{BALL}–Radar–The SpeedCheck sports, UK	Shoot across the goalkeeper towards the open space of the goal
Amiri-Khorasani et al. [87]	5	25.6	Experienced	--	Laboratory	Yes	5 (435 g, 0.69 atm)	$KINEMATICS_{LIMB}$–Video 3D–Vicon MX-F20, UK (200 Hz)	Strike the ball as hard as possible
Amiri-Khorasani and Kellis [47]	12	19.2	Collegiate	--	Laboratory	Yes	5 (435 g, 0.69 atm)	$KINEMATICS_{LIMB}$ and V_{FOOT}–Video 3D–Vicon MX-F20, UK (200 Hz) V_{BALL}–estimated using V_{FOOT}	Kick as hard as possible
Amiri-Khorasani et al. [88]	6	19.2	Collegiate	--	--	Yes	5 (435 g, 0.69)	$KINEMATICS_{LIMB}$–Video–Vicon MX-F20, UK (200 Hz) V_{BALL}–estimated using V_{FOOT}	Maximal velocity place kick
Amiri-Khorasani et al. [89]	5	25.6	Experienced		Laboratory	Yes	5	$KINEMATICS_{LIMB}$–Video 3D–Vicon MX-F20, UK (200 Hz) V_{BALL}–estimated using V_{FOOT}	Hit the ball as hard as possible
Amiri-Khorasani et al. [48]	18	19.2	PRO	--	--	Yes	5 (435 g, 0.69 atm)	$KINEMATICS_{LIMB}$–Video 3D–manual digitisation–Vicon Motion Systems, USA (50 Hz)	Maximal velocity place kick
Amiri-Khorasani [49]	15	21.2	PRO	--	--	Yes	5 (435 g, 0.69 atm)	$KINEMATICS_{LIMB}$–Video 3D–Eagle Motion Analysis Corp., USA (200 Hz)	Kick the ball as hard as possible
Amiri-Khorasani and Ferdinands [37]	24	19.4	PRO	--	--	--	(435 g, 0.69 atm)	$KINEMATICS_{LIMB}$ and V_{BALL}–Video 3D–manual digitisation–Peak Performance, USA (50 Hz)	Maximal velocity kick
Amiri-Khorasani et al. [90]	18	19.2	PRO	--	--	Yes	5 (435 g, 0.69 atm)	$KINEMATICS_{LIMB}$–Video 3D–manual digitisation–Peak Performance, USA (50 Hz)	Maximal velocity place kick
Apriantono et al.	7	20	Univ	--	--	Yes	5 (435 g,	$KINEMATICS_{LIMB}$, V_{FOOT} and V_{BALL}–	Maximal kick toward a goal

[23]							0.69 atm)	Video 3D–manual digitisation–DKH Inc., Japan (500 Hz)	
Beliard et al. [38]	22	13.5	Highly trained	Defenders/ midfielders	Pitch (artificial grass)	--	--	V_{BALL}–Radar–Stalker ATSII Applied concept, USA	To target the radar behind the net
Cariolo et al. [91]	12	21.1	Semi-PRO	--	--	--	--	ACCUR–Video 2D–Kinovea, France	Kick the ball to score
Currell et al. [18]	11	21.4	≥Recreational	--	Pitch (artificial grass)	--	--	ACCUR–Notational analysis	--
Deutschmann et al. [92]	40	23.1	Regional	All pooled	Court	--	--	V_{BALL}–Radar–SpeedTrac Speed Sport, USA	Kick performed at maximum power
Draganidis et al. [93]	10	20	Elite	--	Pitch (natural grass)	--	--	ACCUR–Notational analysis	Shot into the goal by aiming at different segments
Ferraz et al. [94]	12	19.7	Semi-PRO	--	--	--	70 Ø (430 g)	V_{BALL}–Radar – Sports Eletronics Inc., USA ACCUR–Video 2D	Kick with maximum force and attempt to hit a target
Ferraz et al. [15]	10	27.3	Amateur	--	--	--	70 Ø (430 g)	V_{BALL}–Radar – Sports Eletronics Inc., USA	Kick with maximum force and attempt to hit a target
Ferraz et al. [95]	9	19 – 35	Experienced	--	--	--	68–70 Ø (410–50 g)	V_{BALL}–Radar – Sports Eletronics Inc., USA	Shoot as hard as possible
Ferraz et al. [96]	24	19.7	Semi-PRO	--	--	--	70 Ø (430 g)	V_{BALL}–Radar –Applied Concepts Inc., USA ACCUR–Video 2D	Kick with maximum force and attempt to hit a target
Frikha et al. [51]	20	13.4	Regional	--	Court	Yes	5 (430 g, 0.79 atm)	ACCUR–Manual direct measurement	Kick to a target
Gaspar et al. [114]	20	13.8	Regional	All pooled	Pitch (artificial grass)	--	5	ACCUR–notational analysis V_{BALL}–Radar–Stalker Sports, USA (34.2–35.2 GHz)	1-Maximal effort kick 2-Kick into a goal that was divided into zones, to achieve as high a score as possible
Gelen [50]	26	23.3	3rd div PRO	--	--	--	--	V_{BALL}–Radar – Sports Radar, Astro Products, USA	Maximal speed shoot by targeting the middle of the goal without requiring a hit
Gharbi et al. [20]	10	14.6	--	--	Pitch (artificial grass)	--	--	ACCUR–Video	--
Greig [97]	10	20.8	PRO	--	--	--	--	V_{FOOT}–Video 3D–Qualisys, Sweden (200 Hz)	Maximal velocity kick with no accuracy constraint
Hasan et al. [99]	12	15.7	Local Recreational	--	--	Yes	5	$KINEMATICS_{LIMB}$–Video 3D–C-Motion, USA (200 Hz) and 2D–Kinovea, France	Kick as hard as possible
Hasan et al. [98]	12	15.4	Local Recreational	--	Laboratory (synthetic surface)	Yes	5	$KINEMATICS_{LIMB}$, V_{FOOT} and V_{BALL}–Video 3D–C-Motion, USA (200 Hz)	Kick to generating maximum velocity
Izquierdo et al.	174	17.6	National	All	Pitch	--	--	V_{BALL}–Radar–Stalker Professional Radar,	Maximal ball velocity when aiming at goal

[116]				(separate)	(natural grass)			USA	
Juarez et al. [100]	21	16.1	1st div National junior	--	Laboratory	Yes	--	KINEMATICS$_{LIMB}$, V$_{FOOT}$ and V$_{BALL}$–Video 3D–VICON Motion Systems, UK (250 Hz)	Maximal kick
Katis et al. [64]	10	26.3	Amateur	--	Laboratory	--	--	KINEMATICS$_{LIMB}$ and V$_{BALL}$–Video 3D–Vicon motion analysis systems, UK (120 Hz)	Kick the ball as fast and hard as possible aiming at the centre of the goalpost
Katis et al. [101]	10	24.5	Amateur	--	Laboratory	Yes	5 (430 g, 0.88 atm)	KINEMATICS$_{LIMB}$ and V$_{BALL}$–Video 3D–Vicon motion analysis systems, UK (120 Hz)	Kick the ball as fast and hard as possible aiming at the centre of the goalpost
Kaviani et al. [117]	8	30	Recreational	--	Laboratory	--	--	ACCUR–Notational analysis	--
Kellis et al. [102]	10	22.6	Amateur	--	--	--	--	KINEMATICS$_{LIMB}$, V$_{FOOT}$ and V$_{BALL}$–Video 3D–Kwon 3-D Visol Inc., Korea (120 Hz)	Kick as powerful as the participants could
Maly et al. [19]	20	22.4	Elite PRO	Goalkeeper excluded	Pitch (artificial grass)	Yes	5	ACCUR–Video 2D–TEMA Biomechanica 2.3, Australia (50 Hz) V$_{BALL}$–Radar–Stalker Plano, USA (33,4–36 GHz)	Kick to the centre of the goal with maximum effort
Masmoudi et al. [103]	10	14.6	--	--	Pitch (artificial grass)	--	--	--	--
McMorris et al. [104]	12	20	Collegiate	--	--	--	-- (0.41–0.48 atm)	ACCUR–Notational analysis	Aim for the center of the target
McMorris et al. [105]	12	21	Recreational	--	--	--	55 Ø	ACCUR–Notational analysis KINEMATICS$_{LIMB}$–Video 2D–Peak Motus Software 32 version 2000 (100 Hz)	Kick as hard as possible at a target
Muller and Brandes [106]	26	23.9	Amateur	--	Indoor	--	--	V$_{BALL}$–Radar – SpeedTrac XTM, USA ACCUR–Video 2D– VirtualDub, Avery Lee	Objective to strike the target with maximum velocity
Otten et al. [115]	34	25	Amateur	--	Pitch	Yes	5	V$_{BALL}$–Radar–WG 54, D&L, The Netherlands	Maximal effort shots
Owen et al. [107]	13	22.2	Semi-PRO	--	Indoor	--	--	ACCUR–Notational analysis V$_{BALL}$–Radar–SpeedCheck, UK	Shoot the ball at targets in a full-sized goal
Ozturk and Gelen [108]	21	19.7	Amateur	--	--	--	--	V$_{BALL}$–Radar– Sports Radar 3600, Astro Products, USA	Kick at a maximal speed and aim at a plastic figure
Pallesen et al. [109]	19	16.5	Local	--	Indoor pitch	--	--	ACCUR–Notational analysis	Kick the ball to a target
Radman et al.	28	22.9	Semi-PRO	--	Pitch	Yes	5	ACCUR–Notational analysis/Video	Accurately hit the most distant scoring

[110]					(artificial grass)			V_{BALL}–Radar–Applied Concept Marketing, USA	zones of the leg-opposite side of the goal while keeping realistic (match-specific) kicking velocity.
Russell et al. [39]	15	18	Academy PRO	--	Indoor (rubberized surface)	--	--	ACCUR–Video–Vicon, USA V_{BALL}–Video–Quintic, UK	Kick the ball as accurately as possible at the target
Russell et al. [16]	15	18.1	Academy PRO	--	Indoor (synthetic track)	Yes	5	ACCUR–Video–Sony Ltd, UK (50 Hz) V_{BALL}–Video–Quintic Consultancy Ltd, UK (50 Hz)	Kick the ball toward one of shooting targets
Sánchez-Sánchez et al. [21]	18	22.4	Amateur	Outfield excluding goalkeeper	Pitch (artificial grass)	Yes	--	V_{BALL}–Radar–Radar Sales, USA	Kick at the fastest speed possible
Sasadai et al. [111]	11	20.8	Experienced	--	--	Yes	5 (430 g, 0.87 atm)	$KINEMATICS_{LIMB}$, V_{FOOT} and V_{BALL}–Video 3D–DIPP-Motion XD, Japan (200 Hz)	Maximal kick
Stevenson et al. [14]	22	20	Univ	--	Indoor	--	5	ACCUR and V_{BALL}–Video–Kinovea Org., France (50 Hz)	Kick toward one of four randomly illuminating targets
Stone and Oliver [112]	9	20.7	Semi-PRO	Outfield (various)	Pitch (artificial grass)	--	--	ACCUR–Notational analysis	--
Torreblanca-Martinez et al. [13]	15	U18	Top	--	--	--	--	V_{FOOT}–Video 3D–CLIMA system/3D Soccer Analyzer STT®, Spain (50 Hz)	Maximal kick
Zemková and Hamar [113]	10	21.8	Elite	--	--	--	--	V_{BALL}–Analogic velocity sensor–FiTRO Dyne Premium, Slovakia (100 Hz)	Kick as fast as possible

PRO professional, *Univ* university, *div* division, *Video* videogrammetry, V_{BALL} ball velocity, V_{FOOT} foot velocity, *ACCUR* accuracy; *n* number of participants, -- = information not reported or unclear.

2.4.2.2. Experimental approaches

Regarding the kicking task constraints adopted, 35% of studies examined players kicking a stationary ball, 15% a rolling ball, one used both [114], while the remainder (46%) did not provide any detail. The instep kick was predominantly analyzed (44%) while half of the studies did not indicate the region of the foot used to kick the ball. Regarding the approach run, approximately 37% of studies mentioned at least one characteristic of the run, 58% did not, or this was self-selected in several studies (Table 2.3). Instructions given to the participants were: to kick at maximal velocity without accuracy constraints (37%), hit the target without velocity constraints (25%), kick at maximal velocity and hit a target (13%), hit a target with maximal velocity (6%), maximal velocity and try to hit a target (8%), hit a target with realistic velocity (match specific) in one study [110] or instructions were omitted in 10%. The location at which players aimed their kicks included the entire goal (15%), only in its centre (25%), targets with multiple locations in the goal (15%) or only in the four corners (8%). No information on kicking target configuration was available in 37% of studies.

Table 2.3. Task constraints adopted in each study included in the review.

	Trials		Kick type			Approach run	Target			Goal size (m)	Opponent
Study	Number	Interval (s)	Limb	Foot region	Ball condition		Location	Distance (m)	Dimensions (m)		
Abbey and Rankin [85]	5 x 8	6	--	--	Rolling	7,6 m	Entire goal	13.7	--	1.8 x 1.2	--
Abt et al. [86]	4 x 8	--	Dominant	Inside	--	--	Entire goal	15.6	--	1.5–width	--
Ali et al. [17]	3 x 10	60	Both	--	Rolling	--	Various–entire goal	~16.5 – 25	1.2 x 0.8–upper corners	2.44 x 7.32	Yes (GK)
Amiri-Khorasani et al. [87]	10	--	Dominant	Instep	Stationary	3 m, 0º	--	3	1 x 1	--	--
Amiri-Khorasani and Kellis [47]	2 x 2 x 5	--	Dominant	Instep	--	3 m, 0º	--	3	1 x 1	--	--
Amiri-Khorasani et al. [88]	2 x 2 x 5	--	Dominant	Instep	Stationary	3 m, 0º	--	3	1 x 1	--	--
Amiri-Khorasani et al. [89]	10	--	--	Instep	Stationary	3 m, 0º	--	3	1 x 1	--	--
Amiri-Khorasani et al. [48]	3 x 5	--	Dominant	Instep	Stationary	3 m, 0º	Goal centre	11	2 x 2	--	--
Amiri-Khorasani [49]	3 x 5	--	Dominant	Instep	Stationary	3 m, 0º	--	3	1 x 1	--	--
Amiri-Khorasani and Ferdinands [37]	3 x 5	--	Dominant	Instep	Stationary	3 m, 0º	Goal centre	11	2 x 2	--	--
Amiri-Khorasani et al. [90]	3 x 5	None	Dominant	Instep	Stationary	3 m, 0º	Goal centre	11	2 x 2	--	--
Apriantono et al. [23]	2 x 5	--	--	Instep	--	--	Goal centre	11	--	3 x 2	--
Beliard et al. [38]	2 x 8 x 2	--	--	--	--	--	--	10	--	--	No
Cariolo et al. [91]	2 x 8	--	--	--	--	--	Lower/upper corners	--	--	--	--
Currell et al. [18]	3 x 6 x 10	None	Dominant	--	Stationary	--	Various–entire goal	16.46	--	--	--
Deutschmann et al. [92]	2 x 3	--	Dominant	Instep	--	3 m	--	--	--	--	--
Draganidis et al. [93]	3 x 5 x 6	--	--	--	Stationary	--	Various–entire goal	16	--	--	--
Ferraz et al. [94]	7 x 3	--	--	Instep	--	--	Goal centre	11	1 x 1– circle	7.32 x 2.44	--
Ferraz et al. [15]	6 x 3	--	--	Instep	--	--	Goal centre	7	1 x 1– circle	3 x 2	--
Ferraz et al. [95]	2 x 2	None	--	Instep	--	--	--	11	--	--	--
Ferraz et al. [96]	6 x 3	--	--	Instep	--	--	Goal centre	11	1 x 1– circle	7.32 x 2.44	--
Frikha et al. [51]	4 x 2 x 10	SS 15 [a]	Dominant	Inner	Stationary	SS angle and distance	Entire goal	6.10	--	2.435 x 2.44	--
Gaspar et al. [114]	6 x 3 6 x 12	60 --	Dominant Dominant	-- --	Stationary Rolling	5 m 5 m	-- Various–entire goal	11 --	-- 0.7 x 0.7–upper corners	7.32 x 2.44 --	-- No

Gelen [50]	4 x 3	--	--	--	--	--	Goal centre	11	--	--	--
Gharbi et al. [20]	2 x 2 x 10	--	--	--	--	--	Entire goal	6.1	--	2.435 x 1.22	--
Greig [97]	8 x 1	--	--	--	Stationary	SS	--	--	--	--	--
Hasan et al. [98]	4 x 5	--	--	Instep	Stationary	--	--	6.1	--	--	No
Hasan et al. [99]	20	--	--	Instep	Stationary	--	--	6.1	--	3 x 2	No
Izquierdo et al. [116]	3	60	--	Instep	--	2 steps	--	5	--	--	--
Juarez et al. [100]	3	30	Dominant	Instep	--	4 – 5 m	--	5	--	--	--
Katis et al. [64]	2 x 3	30	--	Instep	Stationary	45º, 1 step	Goal centre	7	--	--	--
Katis et al. [101]	2 x 2	15	Both	Instep	Stationary	45º, 1 step	Goal centre	7	--	--	--
Kaviani et al. [117]	--	--	--	--	Stationary	--	Various–entire goal	16.46	--	--	--
Kellis et al. [102]	3 x 3	30	--	Instep	--	2 steps	Entire goal	11	--	2.5 x 7.5	--
Maly et al. [19]	2 x 3	--	Dominant	--	--	--	Goal centre	--	--	--	--
Masmoudi et al. [103]	3 x 2 x 10	--	--	--	--	--	--	6.1	--	--	--
McMorris et al. [104]	3 x 3	--	--	--	--	1 m	Various–entire goal	7	Width 0.3–goal centre	0.24 x 3.3	--
McMorris et al. [105]	2 x 4 x 9	--	--	--	--	--	Various–entire goal	8.5	Width 0.075–goal centre	0.24 x 3.3	--
Muller and Brandes [106]	2 x 7	--	--	--	--	0º, 2 m	Goal centre	8	0.3 x 0.3	3 x 2	--
Otten et al. [115]	3 x 3	30	Dominant	--	--	SS	--	5	--	--	--
Owen et al. [107]	3 x 2 x 10	60	Both	--	Rolling	--	Various–entire goal	~16.5	1.2 x 0.8–upper corners	--	Yes (GK)
Ozturk and Gelen [108]	4 x 3	--	--	--	--	--	Goal centre	11	--	--	--
Pallesen et al. [109]	2 x 3 x SS	60 [a]	--	--	Stationary and rolling	--	Entire goal	5	--	1 x 1	--
Radman et al. [110]	2 x 6 x 10	6	Dominant	--	Stationary	2 steps	Various–entire goal	16.5	0.488 x 0.488–upper corners	3 x 2	--
Russell et al. [39]	4 x 8	30	--	--	Rolling	--	Lower/upper corners	15	1 x 0.5	7.33 x 2.44	--
Russell et al. [16]	4 x 4	--	SS	--	Rolling	--	Lower/upper corners	15	1 x 0.5	7.33 x 2.44	--
Sánchez-Sánchez et al. [21]	4 x 2 x 2	60	--	--	Stationary	--	--	11	--	--	--
Sasadai et al. [111]	4 x 5	--	--	Instep	--	--	--	--	--	--	--
Stevenson et al. [14]	3 x 5 x 4	--	Dominant	--	Rolling	--	Lower/upper corners	--	--	7.33 x 2.44	--
Stone and Oliver [112]	2 x 10	30	Both	--	Rolling	--	Various–entire goal	~16.5	1.2 x 0.8–upper corners	2.44 x 7.32	--
Torreblanca-Martinez et al. [13]	3 x 1	--	--	Instep	--	--	--	--	--	--	--

Zemková and Hamar [113]	3 x 3	--	Dominant	--	--	--	--	--	--	--	--

Note: When the number of trials was expressed by two numbers, these are in reference to series/time moment/experimental conditions x number of trials performed; when the number of trials was expressed by three numbers, these are in reference to experimental conditions x time moment x number of trials performed. *SS* self-selected, *GK* goalkeeper; [a] = total time to complete the required number of trials. -- = information not reported or unclear.

2.4.2.3. Data acquisition

Ball velocity was determined in 65% of included studies, using a radar (50%), or a three-dimensional (3D) video kinematic system (41%; sampling frequency ranging from 50 Hz [14, 16, 37] to 500 Hz [23]) using trajectories derived from one [37] to eight markers [98] positioned on the ball's surface or equation estimates using foot velocity data as input argument were also utilized [47, 88, 89]. Accuracy measures were reported in 46% of studies (Table 2.2). Of these, notational analysis was performed in approximately half (54%) and included factors such as number of goals [86], success percentage [85, 91]; points obtained determined by 1) targets with associated score [18, 110, 114, 117], 2) F-MARC battery of tests [93] and 3) Loughborough soccer shooting test [17, 107, 112]; number of kicks hitting the target [109] and constant/variable error [104, 105]. Manual direct measurement [51], two-dimensional (2D) video kinematic systems [19, 94, 96, 106] or unclear methods [14, 16, 20, 39, 91, 103] enabled calculation of the ball deviation for a given target in 42% of studies. Foot velocity was addressed in 17% of the studies through 3D video kinematic systems (operating at 50 Hz [13] to 500 Hz [23]), taken as the velocity of various segmental locations including the fifth (5thmet) [23] or fourth [100] metatarsal head; 5thmet base [111]; center-of-mass of markers positioned at the ankle and 5thmet head [47]; calcaneus and 5thmet head [102]; 5thmet head and base [97]; lateral and medial malleolus and 5thmet head [98] or the foot segment with lowest y-axis position value [13]. Other parameters derived from lower limb kinematics–not restricted to foot velocity–in reference to hip, knee and ankle joints (e.g. range-of-motion, linear velocity, angular joint displacement and velocity) were computed in 33% of the selected studies [23, 37, 47–49, 64, 87–90, 98–102, 104, 111].

2.4.3. Warm-up methods and their influence on soccer kicking

2.4.3.1. Overview

Of a total of 10 studies (Table 2.4), six aimed to verify whether warm-up routines consisting of running plus static or dynamic stretching routines impacted upon subsequent kicking features [37, 47–49, 88, 90]. Two studies combined both aforementioned stretching methods (limited evidence) [50] or included ballistic stretching as an additional condition [51]. Taken together, these eight works [37, 47–51, 88, 90] indicated greater effectiveness of dynamic/ballistic stretching (in lower limb kinematics [37, 47–49, 90], ball velocity [37, 47, 50, 88] and accuracy [51]) compared to static stretching, which on the other hand tended to impair kicking parameters when applied separately. Standalone studies tested the effects of additional warm-up strategies [50, 105, 108]. Below, results are depicted according to variables, subgroups and level of scientific evidence.

2.4.3.2. Stretching routines

In senior players, a moderate evidence for greater ball velocity following dynamic stretching compared to static stretching (SMD = 0.99–2.44) [37, 47, 88] was observed. When participants of these studies are divided according to playing standard, there was also a moderate evidence of greater ball velocity after dynamic versus static stretching in sub-elite (SMD = 0.99–2.44) [47, 88] and in elite players (SMD = 2.40) [37]. Similarly, moderate evidence of the benefits of dynamic stretching as compared to static stretching routine (SMD = 0.75) was found regarding kicking accuracy in sub-elite youth players [51]. Limited evidence existed showing a positive influence of dynamic stretching effects on foot velocity (i.e. in sub-elite senior players; SMD = 1.00) [47].

2.4.3.3. Additional methods

Three studies in senior soccer players provided limited evidence on the effects of additional distinct warm-up routines other than only running plus stretching protocols. Warm-ups consisting of running followed by the execution of unloaded squat, kicking movement simulation with elastic band or whole-body vibration increased ball velocity more than running alone in sub-elite players (MD = 4.84–6.03%) [108]. In elite players, running plus dynamic warm-up movements (e.g. straight leg kick, skipping, high knee) [50] produced improvements in ball velocity compared to solely a running warm-up (SMD = 1.21). Finally, accuracy (SMD = 0.03–0.78) or ankle velocity of the kick (SMD = 0.59–1.07) did not significantly differ after a warm-up on a cycle ergometer, ball juggling/kicking against a wall or a combination of these two methods in sub-elite players [105].

Table 2.4. Effects of warm-up methods on soccer kicking performance reported in studies included in the review.

Study (*N* = 10)	Design	Warm-up method (WU)	Transition		Main results			
			Min	Type	**Foot velocity**	**Ball velocity**	**Accuracy**	**Additional kinematics**
Stretching routines								
Amiri-Khorasani and Kellis [47]	Pre-post Randomized Balanced	WU_1: 4´ jog + 5 kicks + 30´´ rep ss WU_2: 4´ jog + 5 kicks + 5 x 1´´ rep x 3 vel (slow, moderate, max) ds	2	Rest	Post-WU_2 vs. pre-WU_2 SMD = 1.00 [0.14; 1.86] MD = 11.52%	$\Delta WU_1 < \Delta WU_2$ SMD ≥ -0.99 MD = -17.33%		$\Delta WU_1 < \Delta WU_2$ Knee and ankle max ang vel SMD ≥ -0.96 MD = -13.41– -11.1%
Amiri-Khorasani et al. [88]	Pre-post Randomized Balanced	WU_1: 4´ jog + 5 kicks + ss WU_2: 4´ jog + 5 kicks + ds	2	Rest		$\Delta WU_1 < \Delta WU_2$ SMD = -2.44 [0.80; 4.09] MD = -132.67%		
Amiri-Khorasani et al. [48]	Post-only Counterbalanced Randomized RM	WU_1: 4´ jog + no stretching WU_2: 4´ jog + ss WU_3: 4´ jog + ds	2	Rest				Post-WU_2 < post-WU_3 Ang disp max knee flex and ang vel knee SMD = -2.40– -0.95 MD = -176.40%
Amiri-Khorasani and Ferdinands [37]	Post-only Randomized Balanced RM	WU_1: 4´ jog + no stretching WU_2: 4´ jog + ss WU_3: 4´ jog + ds	2	Rest		$WU_1 > WU_2$ SMD = -0.48 [-1.05; 0.09] MD = 4.62% $WU_2 < WU_3$ SMD = 2.40 [1.65; 3.16] MD = -24.87% $WU_1 < WU_3$ SMD = 2.05 [1.34; 2.76] MD = -19.10%		Hip and knee ang vel $WU_3 > WU_1 > WU_2$ SMD = 0.61–1.90 MD = 17.11–147.88%
Amiri-Khorasani [49]	Post-only Balanced RM	WU_1: 4´ jog + no stretching WU_2: 4´ jog + ss WU_3: 4´ jog + ds	2	Rest				$\Delta WU_2 < \Delta WU_3$ Hip, knee and ankle DROM SMD = 0.25–0.80 MD = 103.04–228.89%
Amiri-Khorasani et al. [90]	Post-only RM	WU_1: 4´ jog + no stretching WU_2: 4´ jog + 4´ ss WU_3: 4´ jog + 4´ ds	2	Rest				Hip DROM Post-WU_2 < post-WU_3 SMD = 1.12 [0.41; 1.82] MD = 601.80%
Frikha et al. [51]	Post-only Randomized Partially balanced	WU_1: 5´ jog 70% MAS + 10´ resting WU_2: 5´ jog 70% MAS + 10´ ss + 6 VJ WU_3: 5´ jog 70% MAS + 10´ ds + 6 VJ WU_4: 5´ jog 70% MAS + 10´ bs + 6 VJ	1	Rest			$WU_1 < WU_3$ SMD = -0.53 [-0.10; 1.17] MD = -10.33%	

							$WU_2 < WU_3$ SMD = -0.58 [-1.22; 0.05] MD = -13.79% $WU_2 < WU_4$ SMD = -0.75 [0.10; 1.39] MD = -11.59%	
Additional methods								
Gelen [50]	Post-only Randomized Balanced RM	WU_1: 5´ jog + 2´ walking + 5´ jog 140 bpm WU_2: 5´ jog + 2´ walking + 5´ jog 140 bpm + 10´ ss WU_3: 5´ jog + 2´ walking + 5´ jog 140 bpm + 10´ de WU_4: 5´ jog + 2´ walking + WU_2 + WU_3	4–5	Seated		$WU_3 > WU_1$ SMD = 1.21 [0.62; 1.81] MD = 3.25% $WU_2 < WU_1$ SMD = -0.72 [-1.28; -0.16] MD = -2.16%		
McMorris et al. [105]	Post-only Randomized RM	WU_1: 12´ sitting WU_2: 15´ cycling (3´ 60 rpm/50 W + 12´ T_{LA}) WU_3: 12´ ball juggling + wall volley test WU_4: 6´ WU_3 + 6´ cycling at T_{LA}	20 s	--			$WU_1 = WU_{2–4}$ SMD = 0.03–0.78 MD = -24.43–55.17%	Vertical ankle vel WU_4 vs. $WU_{2,3}$ SMD = 0.89–1.07 MD = -26.92– -27.62%
Ozturk and Gelen [108]	Post-only Randomized Balanced RM	WU_1: 10´ jog 140 bpm + 2´ walking WU_2: WU_1 + 3 x 10 rep unloaded squat WU_3: WU_1 + 3 x 10 rep kick with elastic band WU_4: WU_1 + 6 x 30´´ whole-body vibration (30Hz)	3–4	Seated		$WU_1 < WU_{2–4}$ *P* = 0.01 MD = -4.84– -6.03%		

SMD = standardised mean difference [upper; lower confidence limits or range], *MD* = mean percentage difference, *vel* velocity, *rep* repetitions, *jog* jogging, *ss* static stretching, *ds* dynamic stretching, *bs* ballistic stretching, *de* dynamic exercises, *max* maximal, *ang* angular, *VJ* vertical jump, *bpm* beats per minute, *RM* repeated measures, *TLA* lactate threshold, *disp* displacement, *DROM* dynamic range-of-motion, *MAS* maximal aerobic speed estimated using the Yo-Yo intermittent recovery test Level 1 [117].

2.4.4. Exercise-induced effects on soccer kicking

2.4.4.1. Overview

Given the variety of exercise protocols reported in the included studies (Table 2.5), these were classified primarily according to the fatigue intended to elicit (local or general) [126], degree of load (submaximal fixed-intensity, graded until exhaustion, intermittent or all-out) [123, 124] and duration (explosive, high-intensity or endurance) [123, 125]. As such, the majority of the physical exercises found (56%) were designed as general intermittent endurance exercise protocols [14–19, 38, 39, 85, 86, 94, 96, 97, 102, 107, 112–114, 116]. There was also groups of studies examining the impact of general intermittent high-intensity exercise [20, 21, 103], general graded until exhaustion endurance exercise [64, 101, 110], local all-out high-intensity exercise [13, 87, 89] and local submaximal fixed-intensity endurance exercise [23, 93]. These latter protocols (except general graded until exhaustion endurance) provided only limited evidence of their effects on kicking kinematics or performance. Single studies (also providing limited evidence), verified the effects linked to general all-out endurance exercise [95], general submaximal fixed-intensity endurance exercise [100], local graded until exhaustion endurance exercise [104] and a soccer practice session [91]. Collectively, physical exercise negatively impacted upon ball velocity in 65% of the studies. In contrast, accuracy remained stable across exercise protocols in 74% of studies. No reports showed a significant increase, post-exercise, in any kicking performance variables. The following section includes descriptions of exercise-induced effects according to the level of evidence provided per variable of kicking and within subgroups.

2.4.4.2. General intermittent endurance exercise

In accordance with findings from a previous review [12], exercise protocols requiring general intermittent endurance efforts were also sub grouped according to format: 11 vs. 11 soccer match-play [113, 114, 116], simulated soccer demands with [14–16, 39, 94, 96] or without [17–19, 38, 85, 102, 107, 112] ball skills or laboratory-based protocols (limited evidence) [86, 97].

Simulated soccer demands with ball skills. Conflicting evidence existed regarding the effects on ball velocity of simulated soccer demands interspersed with execution of ball skills in senior players, when all playing standards were pooled (SMD = 0.19–1.50) [14–16, 39, 96]. Sub-elite senior players exhibited moderate evidence pointing to no significant changes (SMD = 0.19–0.45) [14, 15, 96], while evidence was conflicting in elite senior peers (SMD = 0.45–1.50) [16, 39]. Irrespective of playing standard, strong evidence [14, 16, 39, 94, 96] indicated kick accuracy was not modified following simulations of soccer demands when ball skills were included (SMD = 0.07–0.53). Strong evidence for no significant changes was also observed in sub-elite senior players (SMD = 0.07–0.44) [14, 94, 96] while this evidence was moderate in elite (SMD = 0.10–0.53) [16, 39].

Simulated soccer demands without ball skills. Moderate evidence for declines in ball velocity were exhibited in senior players (SMD = 0.50–1.37) following simulated soccer demands without ball skills (irrespective of standard) [19, 102, 107]. In sub-elite players, the evidence was conflicting (SMD = 0.02–1.37) [17, 102, 107] while evidence was limited in elite peers (SMD = 1.03) [19]. Limited evidence of impairments was also observed regarding foot velocity (SMD = 1.03) in sub-elite senior players [102]. The same trend occurred regarding ball velocity in sub-elite youth players (SMD = 0.47) [38]. Conflicting results were observed regarding the effects of simulated soccer demands without ball skills on accuracy (SMD = 0.19–2.94) irrespective of playing standard [17–19, 85, 107, 112]. In sub-elite populations, this conflicting evidence persisted (SMD = 0.27–2.94) [17, 18, 85, 107, 112] while there was limited evidence showing no changes in elite senior players (SMD = 0.19) [19].

Match-play demands. Limited evidence was available regarding the effects of match-play demands on kicking performance according to subgroups/variables of kicking. Two studies, one in sub-elite youth (SMD = 0.12) [114] and the other in elite senior (SMD = 0.39–0.55) [113] indicated no significant changes in ball velocity following match-play (match simulation used in the former).

Declines in ball velocity were observed in a study in elite youth (SMD = 0.57–1.04) [116] while accuracy was not altered in sub-elite youth players (SMD = 0.04) [114] respectively following competition and simulated matches.

2.4.4.3. General intermittent high-intensity exercise

Two studies provided limited evidence of the effects of general intermittent high-intensity exercise on kicking accuracy in sub-elite youth players (SMD = 0.09–0.92) [20, 103] while one (also representing limited evidence) reported declines in ball velocity in sub-elite senior players (SMD = 1.06) [21].

2.4.4.4. General graded until exhaustion endurance exercise

Moderate evidence indicated that, in sub-elite senior players, significant declines of ball velocity (SMD = 0.58–1.19) occurred following general graded until exhaustion endurance exercise protocols [64, 101, 110].

Table 2.5. Exercise-induced effects on soccer kicking performance reported in studies included in the review.

Study (*N* = 34)	Design	Exercise protocol (EX)	HT (min)	Main results			
				Foot velocity	**Ball velocity**	**Accuracy**	**Additional kinematics**
General intermittent endurance EX							
Simulated soccer demands (no ball skills)							
Abbey and Rankin [85]	Mid-post	5 x 3 rep 15´ (jog 55% VO_{2max} + running at 120% VO_{2max} + walking + jog at 55% VO_{2max} + sprint max)	10			Mid = post SMD = 0.58–2.94 MD = 3.10–16.26%	
Ali et al. [17]	Pre-post	6 x 15´ x 10–12 rep (walking + running at 95% VO_{2max} + jog at 55% VO_{2max} + sprint + 3´ resting) – LIST [118]	--		Pre = post SMD = -0.02 [-0.71; 0.68] MD = 0.14%	Pre > post SMD = -0.30 [-0.99; 0.40] MD = 12.62%	
Beliard et al. [38]	Pre-mid-post	2 x 36´ (3 bouts x 12´) locomotor exercise (including standing, walking, jogging, running, sprinting) – SAFT[90] [119]	15		Pre > post SMD = -0.47 [-1.07; 0.13] MD = 3.51%		
Currell et al. [18]	Pre-mid-post	10 x 6´ [4 rep 90´´: 10´´ walking + 2 x (10´´ jog at 50% max vel + 10´´ at 95% max vel) + 15´´ walking + 5´´ sprint + 15´´ jog at 50% max vel + 5´´ sprint]	10			Pre > post *P* < 0.001 MD = 12.4%	
Kellis et al. [102]	Pre-mid-post	9600 m [4 x 12 x 200 m: 60 m walking + 15 m sprint (5 m dacc + 5 m walking) + 60 m jog + 60 m running]	15	Pre > post SMD = -1.03 [-1.98; -0.09] MD = 14.11%	Pre > post SMD = -1.37 [-2.37; -0.38] MD = 16%		Pre > post Ankle ang, shank max ang vel SMD = -0.38– -0.88 MD = -8.81– -10.76%
Maly et al. [19]	Pre-post	4 bouts at 10–13 km/h (0–160 m) + 7 at 13.5–14 km/h (160–440 m) + 0.5 km/h increments per 8 bouts, with 10 s active recovery between bouts – Yo-Yo IRT1 [120]	--		Pre > post SMD = -1.03 [-1.70; -0.37] MD = 5.82%	Pre = post SMD = -0.19 [-0.81; 0.44] MD = -10%	
Owen et al. [107]	Pre-post	6 blocks x 15´ x 11 rep (20 m walking, sprint, running at 95% VO_{2max} + jog at 55% VO_{2max}), with 3´ interval between blocks – LIST [118]	--		Pre > post SMD = -0.50– -0.73 MD = -2.92– -4.64%	Pre = post SMD = -0.27 [-1.04; 0.51] MD = 14.29%	
Stone and Oliver [112]	Pre-post	3 x 15´: 10 x 90´´ [3 x 20 m walking at 5 km/h + 1 x 15 m at max vel (+ 5 m dacc) + 3 x 20 m at 9 km/h + 2 x 20 m at 14 km/h] + 3´ rec – LIST [118]	--			Pre > post SMD = -0.88– -1.42 MD = -25.36– -36.11%	
Simulated soccer demands (including ball skills)							
Ferraz et al. [15]	Pre-mid-post	5 x 90´´ exercises (~168 m including jumping, skipping, multiple COD, dribble, passing, jog and 90´´ resting)	--		Pre = post SMD = -0.19– -0.44 MD = -4.58– -10.23%		

Ferraz et al. [94]	Post-only Randomized RM	EX: Exercise circuit (~177 m) including jumping, skipping, multiple fast COD, ball conduction, passing, explosive sprints and low-speed running EX_1: 15´ warm-up (jog + kick exercises) EX_2: EX performed slowly and comfortably EX_3: EX performed a bit slower than EX_4 EX_4: EX performed at preferred tempo EX_5: EX performed a bit faster than EX_4 EX_6: EX performed as fast as possible	--		Post- EX_1 = $EX_{2–6}$ SMD = -0.01 – -0.69 MD = -0.04 – -4.55%	Post- EX_1 = $EX_{2–6}$ SMD = 0.05–0.3 MD = 2.65–13.76%	
Ferraz et al. [96]	Pre-mid-post Randomized RM	5 x 90´´ exercises (~168 m including jumping, skipping, multiple COD, dribble, passing, jog and 90´´ resting)	--		Pre = post SMD = -0.37 [-0.94; 0.20] MD = 2.06%	Pre = post SMD = 0.44 [-0.13; 1.01] MD = 15.21%	
Russell et al. [39]	Pre-mid-post	2 x 45´ (7 rep x 4.5´ exercise, 3 repeated cycles: 3 x 20 m walking, 1 x side walking, 1 x 15 m sprint or 20 m dribble + 4´´ rec + 5 x 20 m jog at 40% VO_{2max} + 20 m backward jog at 40% VO_{2max} + 2 steps x 20 m at 85% VO_{2max} + 2´ passing + 1´ rec) – SMS [121]	15		Pre > post SMD = -1.50 [-2.33; -0.68] MD = 10.25%	Pre = post SMD = -0.10 [-0.81; 0.62] MD = -5.82%	
Russell et al. [16]	Pre-mid-post	2 x 45´ (7 rep x 4.5´ exercise, 3 repeated cycles: 3 x 20 m walking, 1 x side walking, 1 x 15 m sprint or 20 m dribble + 4´´ rec + 5 x 20 m jog at 40% VO_{2max} + 20 m backward jog at 40% VO_{2max} + 2 steps x 20 m at 85% VO_{2max} + 2´ passing + 1´ rec) – SMS [121]	15		Pre = post SMD = 0.45 [-0.28; 1.17] MD = 4.67%	Pre vs. post SMD = -0.53 [-1.26; 0.20] MD = -25.95%	
Stevenson et al. [14]	Pre-mid-post	2 x 45´ + 2 x 15´: adapted version of the SMS [121] including extra-time	15		Pre = post SMD = -0.45 [-1.05; 0.15] MD = 5.88%	Pre = post SMD = 0.07 [-0.52; 0.66] MD = 3.23%	
Laboratory-based protocols							
Abt et al. [86]	Pre-post	60´ treadmill running (reps 5´ at 12 km/h and 2.5º + 30´´ at 12 km/h and 7º + 75´´ at 4km/h and 0º inclination)	--			Pre = post SMD = -0.38 [-1.53; 0.77] MD = 3.44%	
Greig [97]	Pre-mid-post	6 x 15´ intermittent treadmill running simulating match-play bouts (stationary, walking, jogging, cruising and sprinting) [122]	15	Pre = post SMD = -0.20 [-1.08; 0.68] MD = -1.07%			Pre = mid = post Thigh and shank ang disp SMD = -0.16 – 1.56 MD = -22.82 – 21.75%
11 vs. 11 soccer match-play demands							
Gaspar et al. [114]	Pre-post	35´ simulated soccer match	--		Pre vs. post SMD = -0.12 [-0.74; 0.50] MD = 1.78%	Pre vs. post SMD = -0.04 [-0.66; 0.58] MD = 2.18%	
Izquierdo et al. [116]	Pre-mid-post RM	2 x 45´ soccer competition match-play	15		Pre > post SMD = -0.57– -1.04 MD = -2.91– -6.51%		

Zemková and Hamar [113]	Pre-mid-post	2 x 45´ soccer match-play	15–20		Pre = post SMD = -0.39– -0.55 MD = -2.55– -3.69%		
General intermittent high-intensity EX							
Gharbi et al. [20]	Pre-post Randomized RM	EX_1: 10 x 20 m max running with 20´´ passive recovery EX_2: 10 x 20 m max running with 20´´ active recovery (juggling exercises without using upper limbs)				Pre = post SMD = 0.09–0.13 MD = 1.91–2.65%	
Masmoudi et al. [103]	Pre-post	10 x 20 m max slalom running with the ball, with 90´´ rec between efforts	--			Pre = post SMD = -0.92–0.35 MD = -14.46–7.29%	
Sánchez-Sánchez et al. [21]	Pre-post	6 x 40 m (20 + 20 m) sprints with 20´´ active recovery	--		Pre > post SMD = -1.06 [-1.77; -0.36] MD = 9.45%		
General graded until exhaustion endurance EX							
Katis et al. [64]	Pre-post	Treadmill running until exhaustion (2´ at 10 km/h + 2´ at 12 km/h + increments of 2º inclination per 1´ until 12%)	--		Pre > post SMD = -0.85 [-1.77; 0.08] MD = 8.15%		
Katis et al. [101]	Pre-post	Treadmill running until exhaustion (2´ at 10 km/h + 2´ at 12 km/h + increments of 2º inclination per 1´ until 12%)	--		Pre > post (DL and NDL) SMD = -1.19– -1.14 MD = -10.45– -14.86%		Pre > post (DL and NDL) Hip, knee and ankle max linear and ang vel SMD = 0.45 – 1.51 MD = -6.42 – 13.77%
Radman et al. [110]	Pre-mid-post Randomized Cross-over RM	EX_1: shuttle run max (3´ 20 m at 8 km/h with 180º COD + 3´ rec) with 1 km/h increments until exhaustion EX_2: 7 x 3´ self-selected low-speed running + 3´ rec INT_1: baseline-pre INT_2: blood lactate < 1.5 mmol/L INT_3: blood lactate between 1.5 mmol/L – LT1 INT_4: blood lactate between LT1 – LT2 INT_5: blood lactate > LT2 INT_6: max intensity where running cessation	--		INT_1 > post-INT_6 (EX_1) SMD = -0.58 MD = -4.25%	INT_1 > post-INT_6 (EX_1) SMD = -0.63 MD = -12.72%	
Local all-out high-intensity EX							
Amiri-Khorasani et al. [89]	Pre-mid-post	10 max consecutive kicks without recovery	--		Pre > post SMD = -4.18 [-6.84; -1.52] MD = 5.41%		Pre > post Leg and thigh ang vel SMD = 6.16–6.43 MD = 4.81–6.16%
Amiri-Khorasani et al. [87]	Pre-mid-post	10 max consecutive kicks without recovery	--				Pre > post Concentric max ang vel $P \leq 0.01$

Torreblanca-Martinez et al. [13]	Pre-post	15´´ max continuous CMJs without recovery	--	Pre = post SMD = -0.10 [-0.81; 0.62] MD = 1.94%			
Local submaximal fixed-intensity endurance EX							
Apriantono et al. [23]	Pre-post	3 x max knee flexion (40% BW–35, 25 and 20 rep) and extension (50% BW–41, 30 and 23 rep), without interval between sets	--	Pre > post SMD = -0.82 [-1.93; 0.28] MD = 4.06%	Pre > post SMD = -1.09 [-2.24; 0.06] MD = 5.63%		Pre > post Shank max ang vel SMD = -0.45 [-1.51; 0.62] MD = -3.77%
Draganidis et al. [93]	Pre-post Randomized Counterbalanced RM	EX_1: control EX_2: 40 – 45´ strength training [4 x 4 LL exercises x 8–10 rep (65 – 70% 1RM) with 1´ rec between series] EX_3: 40 – 45´ strength training [4 x 4 LL exercises x 4–6 rep (85 – 90% 1RM) with 5´ rec between series]	--			Pre- > post-$EX_{2,3}$ SMD = 1.02 MD = -15.88–48.82%	
General all-out endurance EX							
Ferraz et al. [95]	Pre-post	2´ circuit with multiple, short and intense actions (e.g. sprint, skipping, jumping, COD with ball) at 85–95% HR_{max}	--		Pre > post $P < 0.05$ MD = 8.54%		
General submaximal fixed-intensity endurance EX							
Juarez et al. [100]	Pre-post	20´ treadmill running at 80% HR_{max}	--	Pre = post SMD = -0.11 [-0.71; 0.50] MD = 0.54%	Pre = post SMD = -0.18 [-0.43; 0.78] MD = -0.90%		Pre = post Hip, knee and ankle max linear vel SMD = -0.14 – 0.11 MD = -0.72 – 0.91%
Local graded until exhaustion endurance EX							
McMorris et al. [104]	Pre-post Randomized Counterbalanced RM	EX: Cycle ergometer at 70 rpm: 5´ resting + 2´ at 35 W + 28 W increments per 2 minutes EX_1: Resting–pre EX_2: EX performed at epinephrine threshold EX_3: EX performed until max power	--			EX_1 = post- $EX_{2,3}$ SMD = -0.88– -0.14 MD = -95.31–29.17%	
Soccer practice EX							
Cariolo et al. [91]	Pre-post	124–134´ soccer practice session	--			Pre = post SMD = -0.17–0.49 MD = -16.80–31.23%	

SMD = standardised mean difference [upper; lower confidence limits or range], *MD* = mean percentage difference, *HT* half-time, *RM* repeated measures, *rep* repetitions, *jog* jogging, *max* maximal, *rec* recovery, VO_{2max} maximal oxygen uptake, *INT* intensity, *BW* body weight, *vel* velocity, *COD* change-of-direction, FC_{max} maximal heart rate, *dacc* deceleration, *LIST* Loughborough Intermittent Shuttle Test, *Yo-Yo IRT1* Yo-Yo Intermittent Recovery Test Level 1, *SMS* soccer match simulation, *LT1* first lactate threshold, *LT2* second lactate threshold, *CMJ* countermovement jump, *LL* lower limbs, *DL* dominant limb, *NDL* non-dominant limb, *ang* angular, *disp* displacement. -- = information not reported or unclear.

2.4.5. Influence of recovery-related strategies on soccer kicking

2.4.5.1. Overview

Five studies reported data collected immediately after the end of the first-half and prior to the beginning of the second-half during match activity simulations (i.e. general intermittent endurance physical effort). Results revealed that following the 15-minute interval (half-time) foot velocity [97], ball velocity [14, 16, 38, 39] and accuracy [14, 16, 39] were not significantly modified. Two studies analyzed the time-course for recovery following cessation of physical exercise [64, 93] while one addressed the effects of a habitual night of sleep versus total sleep deprivation on subsequent kick performance (limited evidence) [109]. Eight studies determined the effects of ergogenic aids on recovery in kicking performance following general intermittent endurance physical efforts (Table 2.6). These frequently involved pre- [86] or pre/mid-exercise carbohydrate supplementation [14, 17, 18, 39, 85, 117]. The effects of water intake were secondarily addressed (limited evidence) [91, 107]. Finally, six additional studies analyzed the effects of ergogenic aids applied to players in a resting state. Strategies included kinesiotape [106], elastic taping [111], lumbar spine manipulation [92], and compression garments (socks [98, 99] or shorts [115]). Except for the latter, all these strategies demonstrated limited evidence of their impact on soccer kicking performance. A more detailed classification of evidence level is provided below for distinct recovery-related strategies, variables of kicking and subgroups.

2.4.5.2. Passive resting

Half-time. There was strong evidence indicating that passive resting during the 15-minute half-time pause did not significantly modify ball velocity in senior players (irrespective of standard) (SMD = 0.16–0.36) [14, 16, 39]. When participants were split according to playing standard, the evidence for no changes in ball velocity following half-time was moderate in elite (SMD = 0.17–0.36) [16, 39] and sub-elite senior (SMD = 0.16) [14] and limited in sub-elite youth players (SMD = 0.58) [38].

Time-course of changes. Limited evidence was observed for the effects of additional passive resting conditions on kicking performance, such as in time-course studies. The acute decrease in accuracy as a result of a strength training session applied to lower limbs was reestablished within 24 h (MD = -16.12–15.19%), in a study using sampling windows of 1 day (until 3 days after exercise being completed) [93]. When 30 s intervals were used between repeated measures of kicking performance, approximately one minute was sufficient to recover declines in ball velocity induced by an incremental running protocol until exhaustion (SMD = 0.43–0.45) [64].

2.4.5.3. Ergogenic aids

Carbohydrate provision. In sub-elite senior players, evidence on the effects of pre/mid-exercise carbohydrate supplementation on kicking accuracy (SMD = 0.13–0.57) was conflicting [14, 17, 18, 85] while there was moderate evidence of no significant effects regarding ball velocity (SMD = 0.18–0.41) [14, 17]. Moderate evidence indicated that, in elite senior players, pre/mid-exercise carbohydrate supplementation produced significant effects on ball kicking velocity (SMD = 0.67) but not accuracy (SMD = 0.01) [39].

Electrical stimulation. A separate study provided limited evidence that low-frequency electrical stimulation, applied at half-time pause of simulated soccer match-play demands, had a significant effect on subsequent kicking ball velocity in sub-elite youth players (SMD = 0.56) [38].

Compression garments. There was moderate evidence that using either high and low compression shorts did not modify ball velocity in sub-elite senior players (SMD = 0.09–0.12) [115].

Table 2.6. Effects of recovery-related strategies on soccer kicking performance reported in studies included in the review.

Study (*N* = 21)	Design	Prior exercise (EX)	Recovery-related strategy (RES)	Main results			
				Foot velocity	Ball velocity	Accuracy	Additional kinematics
Passive resting							
Beliard et al. [38]	Pre-post	36´: 3 bouts x 12´ (standing + walking + jogging + running + sprinting) – SAFT[90] [119]	15´ resting after EX (half-time pause)		Pre vs. post SMD = -0.58 [-1.19, 0.02] MD = -5.13%		
Greig [97]	Pre-post	3 x 15´ intermittent treadmill running simulating match-play bouts (stationary, walking, jogging, cruising and sprinting) [122]	15´ resting after EX (half-time pause)	Pre = post SMD = -0.58 [-0.32; 1.48] MD = 5.47%			Pre = post Thigh and shank ang disp and pelvic orientation SMD = -0.15–0.56 MD = -4.38–18.17%
Russell et al. [39]	Pre-post	45´ (7 rep x 4.5´ exercise, 3 repeated cycles: 3 x 20 m walking, 1 x side walking, 1 x 15 m sprint or 20 m dribble + 4´´ rec + 5 x 20 m jog at 40% VO_{2max} + 20 m backward jog at 40% VO_{2max} + 2 steps x 20 m at 85% VO_{2max} + 2´ passing + 1´ rec) – SMS [121]	15´ resting after EX (half-time pause)		Pre = post SMD = 0.17 [-0.54; 0.89] MD = 1.09%	Pre = post SMD = -0.04 [-0.76; 0.67] MD = -2.06%	
Russell et al. [16]	Pre-post	45´ (7 rep x 4.5´ exercise, 3 repeated cycles: 3 x 20 m walking, 1 x side walking, 1 x 15 m sprint or 20 m dribble + 4´´ rec + 5 x 20 m jog at 40% VO_{2max} + 20 m backward jog at 40% VO_{2max} + 2 steps x 20 m at 85% VO_{2max} + 2´ passing + 1´ rec) – SMS [121]	15´ resting after EX (half-time pause)		Pre = post SMD = -0.36 [-1.09; 0.36] MD = -3.16%	Pre = post SMD = 0.95 [0.19; 1.71] MD = 32.42%	
Stevenson et al. [14]	Pre-post	45´ adapted version of the SMS [121]	15´ resting after EX (half-time pause)		Pre = post SMD = -0.16 [-0.75; 0.43] MD = -2.19%	Pre = post SMD = -0.36 [-0.95; 0.24] MD = -15.33%	
Draganidis et al. [93]	Pre-post Randomized Counterbalanced RM	EX_1: control EX_2: 40 – 45´ strength training [4 x 4 LL exercises x 8–10 rep (65 – 70% 1RM) with 1´ rec between series] EX_3: 40 – 45´ strength training [4 x 4 LL exercises x 4–6 rep (85 – 90% 1RM) with 5´ rec between series]	RES_1: 24 h after EX RES_2: 48 h after EX			Post-EX < RES_{1-2} $P < 0.05$ MD = 11.92–124.83% $RES_1 = RES_2$ $P > 0.05$ MD = -16.12–15.19%	
Katis et al. [64]	Pre-post RM	Treadmill running until exhaustion (2´ at 10 km/h + 2´ at 12 km/h + increments of 2º inclination per 1´ until 12%)	RES_1: 30´´ resting after EX RES_2: 60´´ resting after EX		Post-EX vs. $RES_{1,2}$ SMD = -0.43–0.45 MD = -4.58– -5.11% RES_1 vs. RES_2 SMD = -0.04 [-0.84; 0.92] MD = -0.50%		
Pallesen et al. [109]	Post-only	--	RES_1: habitual sleep night			$RES_1 > RES_2$	

	Randomized Counterbalanced RM		RES$_2$: 24 h of total sleep deprivation			SMD = 0.17 [-0.47; 0.80] MD = 1.71%	
Ergogenic aids (pre/mid-exercise)							
Abbey and Rankin [85]	Mid-post Randomized	5 x 3 rep 15´ (jog 55% VO$_{2max}$ + running at 120% VO$_{2max}$ + walking + jog at 55% VO$_{2max}$ + sprint max)	RES$_1$: placebo RES$_2$: 6% carbohydrate-rich drink – 1g/kg (pre/mid-EX) RES$_3$: RES$_1$ + honey sweetened (pre/mid-EX)			RES$_1$ = RES$_{2,3}$ SMD = -0.23– -0.13 MD = -5.83– -2.89%	
Abt et al. [86]	Pre-post Randomized RM	60´ treadmill running (reps 5´ at 12 km/h and 2.5º + 30´´ at 12 km/h and 7º + 75´´ at 4km/h and 0º inclination)	RES$_1$: control RES$_2$: 48 h diet (80% carbohydrate, 10% fat and 10% protein) (pre-EX)			RES$_1$ = RES$_2$ SMD = 1.01 [-0.23; 2.24] MD = 7.09%	
Ali et al. [17]	Pre-post Randomized Double-blind Cross-over RM	6 x 15´ x 10–12 rep (walking + running at 95% VO$_{2max}$ + jog at 55% VO$_{2max}$ + sprint + 3´ resting) – LIST [118]	RES$_1$: placebo RES$_2$: 6.4% carbohydrate-rich drink – 2–5 mL/kg (pre/mid-EX)		RES$_1$ = RES$_2$ SMD = 0.41 [-0.29; 1.12] MD = 2.95%	RES$_1$ < RES$_2$ SMD = 0.42 [-0.28; 1.12] MD = 16.67%	
Beliard et al. [38]	Pre-mid-post Randomized RM	2 x 36´: 3 bouts x 12´ (standing + walking + jogging + running + sprinting) – SAFT^{90} [119]	RES$_1$: placebo RES$_2$: low-frequency electrical stimulation on the medial/lateral calf at half-time pause (mid-EX)		RES$_1$ < RES$_2$ SMD = -0.56 [-0.93; -0.04] MD = -4.8%		
Currell et al. [18]	Pre-mid-post Randomized RM	10 x 6´ [4 rep 90´´: 10´´ walking + 2 x (10´´ jog at 50% max vel + 10´´ at 95% max vel) + 15´´ walking + 5´´ sprint + 15´´ jog at 50% max vel + 5´´ sprint]	RES$_1$: placebo RES$_2$: 7.5% carbohydrate-rich drink – 1 mL/kg (pre/mid-EX)			RES$_1$ < RES$_2$ *P* = 0.01 MD = 3.5%	
Kaviani et al. [117]	Pre-mid-post Randomized Counterbalanced Double-blind Cross-over RM	10 x 6´ (alternated between 60 m walking at 25% max int, 60 m jogging at 55% max int, 60 m running at 95% max int and 20 m sprinting)	RES$_1$: consumption of nutrition bar (0.38–1.5 g/kg) glycemic index 45 (pre/mid-EX) RES$_2$: consumption of nutrition bar (0.38–1.5 g/kg) glycemic index 10 (pre/mid-EX)			RES$_1$ = RES$_2$ SMD = 0.10 [-0.88; 1.09] MD = 5.07%	
Russell et al. [39]	Pre-mid-post Randomized Double-blind Cross-over RM	2 x 45´ (7 rep x 4.5´ exercise, 3 repeated cycles: 3 x 20 m walking, 1 x side walking, 1 x 15 m sprint or 20 m dribble + 4´´ rec + 5 x 20 m jog at 40% VO$_{2max}$ + 20 m backward jog at 40% VO$_{2max}$ + 2 steps x 20 m at 85% VO$_{2max}$ + 2´ passing + 1´ rec) – SMS [121]	RES$_1$: placebo RES$_2$: 6% carbohydrate-rich drink – 3.5 mL/kg (pre/mid-EX)		RES$_1$ < RES$_2$ SMD = 0.67 [-0.07; 1.41] MD = 4.55%	RES$_1$ = RES$_2$ SMD = 0.01 [-0.71; 0.72] MD = 0.36%	
Stevenson et al. [14]	Pre-mid-post Randomized Double-blind Cross-over RM	2 x 45´ + 2 x 15´: adapted version of the SMS [121] including extra-time	RES$_1$: placebo RES$_2$: maltodextrin + 8% carbohydrate-rich drink RES$_3$: isomaltulose + 8% carbohydrate-rich drink (pre/mid-EX)		RES$_1$ = RES$_{2,3}$ SMD = -0.18–0.18 MD = -2.27–4.35%	RES$_1$ = RES$_{2,3}$ SMD = -0.57–0.49 MD = -30–15.38%	
Water intake							
Cariolo et al. [91]	Pre-post RM	124–134´ soccer practice session	RES$_1$: ad libitum water consumption RES$_2$: prescribed water consumption (to cover 100% sweat loss) (mid-EX)			RES$_1$ < RES$_2$ SMD = -0.27–0.31 MD = -27.51–12.4%	
Owen et al. [107]	Pre-post Randomized RM	6 blocks x 15´ x 11 rep (20 m walking, sprint, running at 95% VO$_{2max}$ + jog at 55% VO$_{2max}$), with 3´ interval between	RES$_1$: without fluid ingestion RES$_2$: ad libitum water consumption (mid-EX) RES$_3$: prescribed water consumption (to cover		RES$_1$ = RES$_{2,3}$ SMD = -0.28– -0.06 MD = -1.73– -0.39%	RES$_1$ = RES$_{2,3}$ SMD = -0.18–0.17 MD = -9.09–7.69%	

		blocks – LIST [118]	100% sweat loss) (mid-EX)				
Ergogenic aids (rested players)							
Deutschmann et al. [92]	Pre-post Non-randomized Single-blind	--	RES$_1$: sham laser RES$_2$: lumbar spine manipulation RES$_3$: sacroiliac joint manipulation RES$_4$: RES$_1$ + RES$_2$		Pre < post (RES$_{2–4}$) $P \leq 0.009$ MD = 3.76–5.76%		
Hasan et al. [99]	Post-only Randomized RM	--	RES$_1$: smooth socks with smooth insoles–control RES$_2$: smooth socks with textured insoles RES$_3$: compression socks with smooth insoles RES$_4$: compression socks with textured insoles				RES$_1$ = RES$_{2–4}$ Hip and knee ROM SMD = -0.21– -0.13 MD = -4– -1.69%
Hasan et al. [98]	Post-only Randomized RM	--	RES$_1$: smooth socks with smooth insoles–control RES$_2$: smooth socks with textured insoles RES$_3$: compression socks with smooth insoles RES$_4$: compression socks with textured insoles	RES$_1$ = RES$_{2–4}$ SMD = -0.16–0.01 MD = -1.19–0.09%	RES$_{1,2}$ < RES$_3$ SMD = -0.43– -0.36 MD = -6.25– -5.23%		RES$_2$ < RES$_{3,4}$ Ankle flex/ext ROM SMD = -0.47– -0.39 MD = -3.05%
Muller and Brandes [106]	Post-only Randomized	--	RES$_1$: without kinesiotape RES$_2$: using kinesiotape		RES$_1$ < RES$_2$ SMD = -0.19 [-0.35; 0.73] MD = -1.79%	RES$_1$ > RES$_2$ SMD = 0.66 [0.10; 1.22] MD = 10.78%	
Otten et al. [115]	Post-only Randomized Double-blind RM	--	RES$_1$: no compression short RES$_2$: zoned high compression short RES$_3$: non zoned low compression short		RES$_1$ = RES$_{2,3}$ SMD = -0.12– -0.09 MD = -1.35– -1.01%		
Sasadai et al. [111]	Randomized RM	--	RES$_1$: without elastic taping RES$_2$: elastic taping–0º plantar flexion RES$_3$: elastic taping–15º plantar flexion RES$_4$: elastic taping–30º plantar flexion	RES$_1$ = RES$_{2–4}$ SMD = -0.08–0.15 MD = -0.67–1.33%	RES$_1$ > RES$_{2,3}$ SMD = 0.83–1.55 MD = 6.1–11.7%		RES$_1$ > RES$_{2–4}$ Max ang plantar flex SMD = 0.8–2.09 MD = 19.95–53.13%

SMD = standardised mean difference [upper; lower confidence limits or range], *MD* = mean percentage difference, *RM* repeated measures, *rep* repetitions, *jog* jogging, *max* maximal, *rec* recovery, *int* intensity, *SMS* soccer match simulation, *LIST* Loughborough Intermittent Shuttle Test, *LL* lower limbs, *ROM* range-of-motion, *ang* angle, *disp* displacement, *flex* flexion, *ext* extension. -- = information not reported or unclear.

2.5. Discussion

The purpose of the current study was to systematically review and critically appraise original research articles in the scientific literature addressing the acute effects of warm-up, exercise and/or recovery-related intervention strategies on ball kicking kinematics and performance in male soccer players. In general, task constraints used across studies to testing kick performance generally lacked real-world resemblance to the competition environment while simple notational-based outcome measures of accuracy were generally adopted. Most evidence derived from the interventions synthesized was associated with moderate level and unclear-to-high risk of bias. Nevertheless, results showed that kicking performance improved following warm-ups involving dynamic but not static stretching. Intermittent or graded until exhaustion endurance exercise without inclusion of ball skills impaired subsequent ball kicking velocity while accuracy was less frequently affected by exercise. Carbohydrate supplementation pre and mid-exercise demonstrated some benefits in counteracting the deleterious effects of endurance exercise on ball velocity in senior elite but not sub-elite players.

2.5.1. Research Paradigm

2.5.1.1. Methodological quality and samples

Overall, a moderate mean methodological rating was observed across studies with these generally providing sufficient information to characterize study samples. However, essential information relating to the data collection environment and ball standardization (e.g. dimensions/pressure) was frequently omitted. In addition, selective reporting occurred, blinding aspects were poorly accounted for, and allocation concealment was not always ensured. These sources of bias are limitations to the current evidence base, thereby implying caution when interpreting and/or applying the findings collated here. Finally, adult players were predominantly investigated (42/52 studies). Accordingly, additional research in youth players across different age categories is warranted especially as kicking kinematics and performance are strongly age-dependent [62, 63, 127].

2.5.1.2. Kicking tasks

Scientific studies investigating the biomechanics of kicking tend to demonstrate substantial citation rates [128]. Yet the practical applications of available research findings are still debatable with perhaps a need for more holistic real-world approaches to investigating kicking performance [34]. Indeed, the conditions in which the mechanics and accuracy of the kicking task were evaluated along with associated contextual constraints merit scrutiny. First, discrepancies were noted regarding instructions provided to the participants on how they should perform kicking actions. Instructions on both velocity and accuracy were only provided in approximately 27% of the selected studies [15, 19, 23, 48, 50, 64, 88, 94, 96, 101, 105, 106, 108, 110]. A single study also instructed players to hit a target with 'realistic velocity' (match specific) [110]. In contrast, in 62% of the studies, subjects were asked to kick maximally without explicit instructions relating to accuracy or were instructed to hit a target without directives on ball velocity (Table 2.2).

There is evidence supporting Fitts' law [129] which indicates a trade-off between velocity and accuracy in soccer kicking [28], and research demonstrates that the provision of instructions emphasizing both, velocity and accuracy can reduce bias in these variables [27]. The distance at which kicks were performed from the goal is an additional factor potentially influencing the balance between kick velocity and accuracy [33]. In over half of the studies (see Table 2.3), kicks were performed at a distance of 11-m from the goal (e.g. penalty kick simulations) [21, 23, 37, 48, 50, 90, 94–96, 102, 108] or from shorter distances [15, 20, 38, 47, 49, 51, 64, 87–89, 98–101, 103–106, 109, 115, 116]. This limitation reduces the extrapolation of these research findings to other frequent game actions. For example, kicks from distance (e.g. performed outside penalty area) are frequent in soccer [130, 131] but received less attention in the literature (< ¼ studies [16–18, 39, 85, 86, 93, 110, 112, 117]). Similarly, players were instructed to kick at the center of the goal more frequently than to the corner areas. Utilizing targets positioned only in the goal center suggests lower external validity as this zone is where goalkeepers generally stand prior to an opponent kicking the ball [27]. Kicks were also mostly examined in the absence of opposition except for two studies that used wooden static goalkeepers [17, 107]. The absence of opposition players such as goalkeepers (i.e. human) or defenders during a kick can bias results [29, 30]. Approach run velocity is constrained by the initial distance of the opponent as well as by its simple presence during task performance. Hence the expression of kicking behaviour is highly modulated by the context; if a defender is not present as a task constraint, some movement regulation features would likely not emerge [30]. Future work should therefore consider the inclusion of opponents contesting kicks and more match-realistic conditions in an attempt to augment the ecological validity of kicking kinematic analyses whilst also reporting between-trials consistency measures.

A further issue concerned the players' approach to the ball when performing a kicking action. Arguably, imposing constraints on the approach run can alter kicking patterns [62, 68], yet when the initial player position (e.g. distance to the ball or approach angle) was not controlled or measured in experimental designs it likely added undesirable variance across trials, particularly in movement mechanics in the later stages of the task (i.e. impact phase) [72, 132]. While players frequently vary their approach run in match-play conditions making experimental design difficult, the lack of consistency across studies (presented in section 2.4.2.2) nevertheless influences interpretations of the potential effects of any intervention used to test changes in kicking performance as well as rendering difficult comparisons of findings across the literature. Overall, it is difficult to directly apply some of the findings from the current literature to the performance environment [133] and these methodological limitations indicate a need to reconcile study designs with the real-world demands of soccer competition.

2.5.1.3. Data acquisition methods

Foot velocity is considered to be one of the main variables in lower limb movement kinematics, because it largely reflects the momentum transferred via proximal–distal interaction between body segments when kicking [134]. Ball velocity and accuracy are also recognized as key indicators of kicking performance [1, 36, 135, 136], being also strongly associated with limb movement kinematics [77, 134, 137]. Given the theoretical relationships between ball flight behavior and additional lower limb features (e.g. striking mass) [138, 139], it seems reasonable to suggest that when the inertial properties of the impact segment remain relatively invariable throughout a testing session, standardization of the ball characteristics is essential. However, standardization was systematically omitted as less than half of studies provided key information on ball dimension [14–16, 19, 89, 94–96, 98, 99, 114, 115] and only a quarter additionally reported ball pressure [23, 37, 47–49, 51, 87, 88, 90, 101, 105, 111] (Table 2.2). Ball size [140, 141] and pressure [69] influence foot–ball impact and subsequent kicking performance and this information should be reported and standardized (see review by Lees et al. [1]).

Across the literature, ball velocity was generally calculated using either radar or video kinematic systems. Preliminary data indicate a strong association ($r = 0.994$) between ball kicking velocity obtained via radar and 2-D video kinematic systems [142]. Ball angular trajectory and velocity analyses of softball batting also demonstrated agreement (to within 0.09 rad and 2 m/s, respectively) between radar and video kinematic (3D) outcomes, suggesting potential interchangeability of data [143]. Replication studies using soccer kicking are required to confirm concurrent validity of radar outcomes against gold standard measures, given the 3D nature of the task [1] which may be distorted/underestimated in 2D procedures [144]. Knowing that video kinematic systems generally require specialized staff for data processing, a laboratory setting, and high costs [145], radar is a pertinent alternative especially in practical settings. However, while information on the positioning of radars was generally provided [15, 19, 38, 50, 92, 94–96, 108, 114, 115], data on sensitivity and measurement error was less frequently provided (41% of studies [15, 19, 92, 94–96, 115]) while acquisition frequency was rarely described [19, 114] thereby rendering difficult comparisons across study findings.

It is recognized that there are discrepancies in lower limb distal extremity velocities during the impact phase of kicking, with a difference in amplitude of up to ~10 m/s depending on the region of the foot or ankle used for the calculations [146]. Consequently, a lack of conformity regarding the number of markers used and their positioning to calculate foot velocity (fully described in 3.3.3) suggests caution when attempting to directly compare results from studies using video kinematic systems. Conversely, while a standard marker set configuration for foot kinematic analysis has not yet been defined in literature [147] it may have contributed to the aforementioned issue. Similarly, critical appraisal of the sampling and filtering procedures used prior to extraction of movement kinematics revealed discrepancies. Nunome and collaborators [32] demonstrated that using an automatic time–frequency filter together with high acquisition frequency (1000 Hz) was efficient in identifying sudden changes in the lower limb kinematics during the ball impact phase. In contrast these changes were not observed at a lower sampling rate (250 Hz) and after traditional filtering (i.e. Butterworth in low and constant cut-off frequency). Investigations quantifying lower limb kinematics and foot velocity, acquisition frequencies ranged from 50–500 Hz (Table 2.2) - all below or equal to half the frequency recommended [32]. In addition, a Butterworth filter was also used in 37% of cases (cut-off frequency ranging 12–16 Hz) [37, 49, 64, 99, 101, 102, 111] otherwise the filtering procedure was not described in 47% [13, 47, 48, 87–90, 97, 105]. Alternative data treatment techniques potentially useful for time-series data are also available. These include extrapolation [148], quintic spline [66], robust non-parametric locally weighted function [68] and most recently a modified fractional Fourier filter [149]. However, only a few studies (16%) considered these techniques [23, 98, 100]. Given the absence of a clear consensus on best practice regarding minimum sampling rates in analyzing kicking parameters and how to correctly filter time-series, some research groups have also ruled out impact data as input arguments to the smoothing program [65, 66, 68] aiming to minimize systematic error.

Although the use of video kinematic systems has become more frequent compared to the beginning of the 2010's [11], kicking accuracy was still mostly determined by simple notational-based methods (Table 2.2 and Section 2.4.2.3). Outcome metrics included the total/percentage number of kicks hitting a given target or using criterion measures (e.g. punctuations) arbitrarily defined according to ball placement when it crosses the goal line. Questions have been raised concerning the reliability, objectivity, and sensitivity of such metrics [11, 63, 150, 151]. For example, studies included in the current review reported that: (1) ballistic compared to static stretching improved accuracy when computed as the deviation from the target, but this was not the case when the number of total missed kicks (ball outside the target) was computed [51]; (2) an exercise protocol of a similar duration to a match did not significantly affect the percentage of successful kicks (ball contacted the goal or target) but increased the absolute deviation of the ball from the target [16] and, (3) a large beneficial effect (SMD = 0.95; ~32%) was observed for ball deviation from a target after a 15-min half-time pause, whereas changes in success percentage (ball contacted the goal/target) were small (SMD = 0.47; ~16%) [16]. Thus, it is arguably necessary that future research moves beyond simple gross measures of accuracy and is reconciled more with real-world characteristics of play. Indeed, work has shown that scores in a commonly used field test of technical performance lacked validity in relation to actual competition demands [25].

2.5.2. Kinematics and performance of soccer kicking following interventions

2.5.2.1. Warm-up

Warm-up routines are performed prior to competitive events and training sessions to enhance readiness for subsequent performance [41]. Moderate evidence here suggests that kicking accuracy in youth sub-elite players, and ball velocity in senior sub-elite and elite players, are both improved following a warm-up consisting of dynamic stretching but not static stretches. These observations corroborate those reported in another two reviews that detected analogous results in soccer physical capacity as a consequence of applying dynamic versus static stretching exercises in the warm-up [40, 42]. Both kicking accuracy and ball velocity are governed by movement kinematics and muscle activation of the kicking limb [77, 134, 137]. Static stretching exercises are typically part of soccer warm-up routines [40]. These are often considered easier and safer to apply in comparison to other modalities [152, 153] and may not modify lower limb kinematics in vigorous lower limb muscle contractions [154]. However, static stretching acutely decreases neuromuscular activity [155–157] while footballers might also perceive greater effort when performing passive static stretching compared to ballistic stretching exercises of equalized volume [158]. Accordingly, preference should be towards inclusion of dynamic exercises in warm-ups while static stretching routines only should specifically be avoided immediately prior to testing kicking performance. In addition, while a combination of short static stretching exercises followed by dynamic movements has positive effects on physical performance measures [41, 159, 160], only limited evidence is available to date regarding their effects on kicking output [50].

A previous systematic review of the literature showed that when performing explosive athletic tasks, a specific preparation is required which is frequently not matched by the traditional warm-ups in most of the football codes [41]. Warm-up routines commonly performed in soccer include locomotor activities, resistance tasks, and specific drills [40] and not only simple running exercises followed by stretching [161]. Among strength exercises included in warm-ups prior to kicking evaluations, only unloaded squats using both lower limbs were tested [108]. However, kick and other soccer actions (e.g. sprinting, jumping and COD) are commonly performed unilaterally or with the weight transferred to one leg at a given moment [162]. Additionally, the evidence of the effects of a game-specific technical warm-up (e.g. ball juggling plus wall volley exercise) is limited [105]. In sum, a closer resemblance between the protocols used in practical contexts and those in research studies is again necessary. For example, to establish the effects of common pre-exercise practices, studies should include loaded strength stimuli, specific skill tasks as well as technical-tactical exercises (e.g. small-sided games) [40].

When prescribing and tailoring warm-up routines to ensure readiness to perform, external constraints (i.e. logistics) must typically be accounted for [163] and one example is the transition time between the end of the warm-up and the performance test. In studies verifying the beneficial effects of warm-up on kicking parameters, transition time ranged from 1 minute [51], most commonly 2 minutes [37, 47–49, 88, 90] to a maximum of 5 minutes [50]. In the sole study not detecting any difference in kicking outcomes, it is noteworthy that there was a very short interval following the warm-up (20 s) [105]. Yet analysis of warm-up strategies in professional soccer competition showed this duration can be substantially longer [52]. While the current literature generally reports beneficial effects of a warm-up on kicking performance, the transition time from warm-up to performance testing might be considered suboptimal across studies. According to a meta-analysis [164], a 7–10 minute rest period following cessation of the warm-up routine enhanced ensuing power performance; it is likely that a balance favouring increases in muscle contractile response and dissipation of transient fatigue is achieved to a greater magnitude within this time-window than using shorter periods. However, the question arises as to the duration that the benefits gained from a given warm-up persist as specifically regards kicking velocity? Also, kicking performance should be also assessed after longer rest periods, for example, between the pre-match warm-up end and subsequent evaluation, in attempt to improve ecological validity through respecting the realities of the competition setting. Indeed, work has reported a time interval lasting an average of 12.4 minute (standard deviation = 3.8) interval between the end of the warm-up and match kick-off [52].

2.5.2.2. Exercise

In general, analyses of ball kicking velocity most frequently reported a decline following exercise although the exercise-induced effects on velocity were dependent on the type of protocol utilized. Moderate evidence indicates ball velocity reductions in senior players following general intermittent endurance efforts without inclusion of any ball skills, despite mixed results observed in subgroups across different competitive standards (limited evidence of declines in elite and conflicting outcomes in sub-elite players). Most specifically in sub-elite senior players, the velocity of the ball declined following general graded until exhaustion endurance exercise while no significant changes were observed as a consequence of general intermittent endurance exercise interspersed with execution of ball skills (moderate evidence in both cases). Thus, when exercise protocols prioritized locomotor capacity without inclusion of ball skills, a greater acute negative impact on subsequent kicks tended to occur. Conversely, intermittent endurance physical activity interspersed with execution of ball skills reported lower effects on subsequent ball velocity. Indeed, the inclusion of ball-drills in exercise circuits can reduce both perceived effort [165] as well as actual exercise intensity [166] possibly aiding reduction of any transient effect of fatigue on kicking capacity and this needs to be taken into account when designing experimental protocols.

While declines in neuromuscular outputs in match-play simulations are elicited mainly due to central fatigue occurrence, these appeared to insignificantly modify kicking velocity measured at the end of the protocols [9, 167]. In a number of exercise protocols reviewed, there was a generally acceptable degree of relationship between performance outcomes (i.e. 6 x 40 m repeated sprints, Yo-Yo intermittent recovery test level 1, laboratory treadmill exhaustive effort) and running activity performed in actual match-play (i.e. construct validity supported) [168–170] while others (e.g. soccer match simulation, Loughborough Intermittent Shuttle Test and SAFT[90]) are reported to achieve similar loading to that required in a soccer match [118, 119, 121]. Yet only limited evidence was obtained from the current scientific literature on the consequences of match-play demands (11 versus 11) on components of kicking performance. Additional research is arguably necessary to improve understanding of the effects of game-related fatigue on kick kinematics and performance. Assessments of potential impairments in kicking ability following occurrence of intense periods of locomotor activity (e.g., peak periods of high-intensity running commonly observed in match-play) are merited. Exercise protocols also need to combine physical, technical and tactical elements and better respect the stochastic nature of match running activity [171]. Match physical demands have also substantially evolved over recent years [172] and future exercise testing protocols should account for this change.

In contrast to ball velocity, kicking accuracy was less frequently affected by exercise. There are three possible explanations for this discrepancy. First, where decreased velocities were generally observed due to exercise, kicking accuracy might have been favored; in other words existence of the velocity–accuracy trade-off [28, 74, 173]. Second, the inability to shoot within the prescribed time requirements of tests can result in poorer shooting scores, rather than assessing the ability to shoot on target [112]. Third, fatigue seems to affect to a greater extent the muscle properties in charge of generating force compared to movement coordination in explosive tasks using the lower limbs [174, 175]. The first two premises might be more plausible since it is still unclear whether there is a dominance of coordination over force on the control of kicking accuracy [176]. Work is required to explore whether kicks dependent on high ball velocity (e.g. performed from longer distances to the goal) demonstrate greater impairments as a consequence of exercise-induced fatigue compared to those placing greater demands on controlling ball placement rather than velocity. Integrating analyses of cognitive skills such as decision-making demands and visual searching would also be pertinent.

2.5.2.3. Recovery-related strategies

Studies using game-play running activity simulations [14, 16, 38, 39, 97] identified that a 15-minute half-time pause spent in passive recovery did not modify kicking performance (notably velocity outputs). The level of evidence for ball velocity outcomes was moderate in elite and sub-elite senior players while strong evidence was obtained when pooling all senior players. Indeed, a passive rest during the pause generally led to decrements in muscle temperature which can subsequently inhibit lower limb power performance [177, 178]. Thus, reducing the time spent resting passively could be beneficial in tempering possible previous declines of kicking velocity. While work has shown positive results of such practice on running outputs in simulated or friendly matches [178, 179] no evidence exists for kicking performance [180].

Inadequate recovery during and following competition can impair subsequent athletic performance and potentially predispose players to injuries [181]. Intervention strategies to accelerate recovery are thereby warranted. Investigations on the effects of a carbohydrate replacement on kicking accuracy and velocity showed contrasting results. Conflicting evidence was observed for kicking accuracy in sub-elite senior players while moderate evidence for no significant effects was observed in elite senior peers, which is unsurprising since kicking accuracy is seemingly less affected by exercise. In contrast, moderate evidence pointed to a significant effect following consumption of a carbohydrate-rich drink in counteracting the potential impact of fatigue on ball velocity in elite senior players following extended physical efforts, which is in agreement with previous reviews [46, 182]. Knowing that decreased muscle glycogen stores occurring at the end of senior soccer matches can affect knee extension force generated [183], a carbohydrate supplementation over prolonged exercise might prevent muscle force decrements and also help preserve functioning of the CNS [184] as well as general running activity [185]. Associations between strength measurements and kicking velocity are sometimes unclear [36, 167] but central inputs play an important role in modulating performance of goal-directed sport skills [186, 187]. However, the question arises as to what is the real-world impact of the reduction observed here in ball velocity due to exercising (e.g. overall percentage and raw changes respectively equals to approximately 6% and -1.41 m/s in senior players across studies) on match technical performance outputs. An inverse relationship ($R^2 = 0.82$) between ball velocity and the likelihood a shot is saved by a goalkeeper was shown in a controlled setting [135].

Other recovery methods are also used ubiquitously in soccer [43] yet their effects on kicking performance remain unknown (e.g. cooling techniques in extreme temperature) [188]. Furthermore, single studies [38, 92, 106] or those conducted by the same research group [98, 99] provided only limited evidence on the effects of using of some therapeutic methods for recovery (e.g. electrical stimulation, kinesiotape and massage). Further replication studies particularly considering inclusion of demands during extended physical effort in addition to these interventions are necessary to confirm whether these common strategies [43] aid recovery of kicking performance during and following exercise. Finally, sleep is recognized as an important recovery process [43, 80, 189, 190]. However kicking performance following habitual sleep nights was compared only to that after total sleep deprivation [109] which is not the most common sleep-related issue in athletic populations (compared to disrupted or partial sleep deprivation) [191, 192].

2.5.3. Limitations of included studies

Over the course of this review, five main limitations of studies were identified. Firstly, critical risk of bias related to blinding of participants, outcome assessor and selective reporting of results, indicates that these aspects should be more carefully treated in future research. However, some procedures are not always feasible in applied research in team sports [193]. Second, methods notably varied across studies and in addition to the mentioned potential risk of bias, pooling the data of interventions in a meta-analysis was deemed inappropriate. Third, intervention protocols were not completely reported in methods of eight studies (15%) [37, 47–49, 88, 90, 91, 113]–for example, details of the duration, type of exercise, number of exercises and series performed. Fourth, while 33% of all studies clearly reported that kicks were performed using dominant limb, 56% omitted this information while other 15% allowed players to use both limbs or self-select the lower limb, which may have influenced response to the interventions. Finally, kicking velocity [194] and match physical loads [195] in soccer vary substantially according to positional role yet only two studies [86, 116] accounted for this parameter.

2.5.4. Limitations of the current review

There are several limitations of the current review. A decision was made to only include studies written in English which could have resulted in the loss of research published in other languages. The checklist adopted here was adapted from a previous study [59] which has also served as basis to two recent reviews [168, 196]. However, as outlined in recent critiques [197], our choice for a non-validated tool in appraising methodological quality of comparator trials can be considered another limitation. The qualitative synthesis produced has been based on and is likely influenced by the risk of sources of bias identified. In addition, only half of studies considered for review employed randomized designs including a control condition. Six studies investigated the effects on kicking performance of ergogenic aids applied to players only in a resting state, and therefore these results may not be feasibly extrapolated to a mid/post-exercise recovery-focused purpose. Finally, we noted during the literature search and this was also highlighted in a recent publication [198], that studies in women's soccer are insufficient in number and therefore the synthesis presented here comprised only male players.

2.6. Conclusions

To conclude, moderate evidence indicates that a warm-up composed of dynamic stretching is shown to be beneficial for ensuing kicking accuracy (in youth sub-elite players) or ball velocity in senior players (sub-elite and elite) while static stretching only can impair velocity outputs. Research conducted in sub-elite senior soccer (moderate evidence) demonstrates that the velocity of the ball was notably reduced following general graded until exhaustion endurance exercise while no changes occur after general intermittent endurance efforts interspersed with execution of ball skills. Accuracy is less frequently hampered by prior physical exercises demands. Moderate evidence indicates that a passive recovery during the half-time pause did not modify ball kicking velocity (in elite and sub-elite senior players) while benefits of consuming carbohydrate-rich drinks before and during extended exercise were observed in senior elite but not in sub-elite players. Higher quality studies with low risk of bias are necessary to investigate the benefits of habitual soccer warm-up modalities, recovery-related interventions as well as the effects of official match-play (11 vs 11) demands on kicking kinematics. There is a general need to re-examine methodological protocols to improve ecological validity in testing soccer kicking performance.

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Electronic Supplementary Material Table S1. Full search strategy for each database with arguments presented as they were used.

	PubMed
#1	((((kick*[tw]) OR shoot*[tw]) OR skill[tw]) OR technical[tw]) AND ((((soccer[tw]) OR football*[tw]) OR association football[tw]) OR 11-a-side[tw]) AND ((((((warm-up*[tw]) OR heat*[tw]) OR stretch*[tw]) OR strength[tw]) OR postactivation potentiation[tw]) OR pre-match[tw])
#2	((((kick*[tw]) OR shoot*[tw]) OR skill[tw]) OR technical[tw]) AND ((((soccer[tw]) OR football*[tw]) OR association football[tw]) OR 11-a-side[tw]) AND ((((((exercise*[tw]) OR fatigue*[tw]) OR match demands*[tw]) OR match-related fatigue[tw]) OR effort[tw]) OR running[tw])
#3	((((kick*[tw]) OR shoot*[tw]) OR skill[tw]) OR technical[tw]) AND ((((soccer[tw]) OR football*[tw]) OR association football[tw]) OR 11-a-side[tw]) AND (((((((((((recover*[tw]) OR rest*[tw]) OR nutrition[tw]) OR supplementation[tw]) OR ingestion[tw]) OR cold water immersion[tw]) OR compression garments[tw]) OR massage[tw]) OR electrical stimulation[tw]) OR sleep[tw]) OR post-match[tw])
	Web of Science
#1	((((kick*) OR shoot*) OR skill) OR technical) AND ((((soccer) OR football*) OR association football) OR 11-a-side) AND ((((((warm-up*) OR heat*) OR stretch*) OR strength) OR postactivation potentiation) OR pre-match)
#2	((((kick*) OR shoot*) OR skill) OR technical) AND ((((soccer) OR football*) OR association football) OR 11-a-side) AND ((((((exercise*) OR fatigue*) OR match demands*) OR match-related fatigue) OR effort) OR running)
#3	((((kick*) OR shoot*) OR skill) OR technical) AND ((((soccer) OR football*) OR association football) OR 11-a-side) AND (((((((((((recover*) OR rest*) OR nutrition) OR supplementation) OR ingestion) OR cold water immersion) OR compression garments) OR massage) OR electrical stimulation) OR sleep) OR post-match)
	SPORTDiscus
#1	(kick* OR shoot* OR skill OR technical) AND (soccer OR football* OR association football OR 11-a-side) AND (warm-up* OR heat* OR stretch* OR strength OR postactivation potentiation OR pre-match)
#2	(kick* OR shoot* OR skill OR technical) AND (soccer OR football* OR association football OR 11-a-side) AND (exercise* OR fatigue* OR match demands* OR match-related fatigue OR effort OR running)
#3	(kick* OR shoot* OR skill OR technical) AND (soccer OR football* OR association football OR 11-a-side) AND (recover* OR rest* OR nutrition OR supplementation OR ingestion OR cold water immersion OR compression garments OR massage OR electrical stimulation OR sleep OR post-match)
	SCOPUS
#1	(TITLE-ABS-KEY (kick* OR shoot* OR skill OR technical) AND TITLE-ABS-KEY (soccer OR football* OR "association football" OR 11-a-side) AND TITLE-ABS-KEY (warm-up* OR heat* OR stretch* OR strength OR "postactivation potentiation" OR pre-match))

#2	(TITLE-ABS-KEY (kick* OR shoot* OR skill OR technical) AND TITLE-ABS-KEY (soccer OR football* OR "association football" OR 11-a-side) AND TITLE-ABS-KEY (exercise* OR fatigue* OR "match demands*" OR "match-related fatigue" OR effort OR running))
#3	(TITLE-ABS-KEY (kick* OR shoot* OR skill OR technical) AND TITLE-ABS-KEY (soccer OR football* OR "association football" OR 11-a-side) AND TITLE-ABS-KEY (recover* OR rest* OR nutrition OR supplementation OR ingestion OR "cold water immersion" OR "compression garments" OR massage OR "electrical stimulation" OR sleep OR post-match))
	ProQuest
#1	noft(((((kick*) OR shoot*) OR skill) OR technical)) AND noft(((((soccer) OR football*) OR association football) OR 11-a-side)) AND noft((((((warm-up*) OR heat*) OR stretch*) OR strength) OR postactivation potentiation) OR pre-match))
#2	noft(((((kick*) OR shoot*) OR skill) OR technical)) AND noft(((((soccer) OR football*) OR association football) OR 11-a-side)) AND noft((((((exercise*) OR fatigue*) OR match demands*) OR match-related fatigue) OR effort) OR running))
#3	noft(((((kick*) OR shoot*) OR skill) OR technical)) AND noft(((((soccer) OR football*) OR association football) OR 11-a-side)) AND noft(((((((((((recover*) OR rest*) OR nutrition) OR supplementation) OR ingestion) OR cold water immersion) OR compression garments) OR massage) OR electrical stimulation) OR sleep) OR post-match))

Where: input terms used in literature search of 'warm-up' (**#1**); exercise (**#2**) and 'recovery-related' (**#3**) effects on soccer kicking for all databases. *tw* text words, *noft* anywhere except full text. Searches on Web of Science database were using 'Title/Keywords/Abstract' fields.

Electronic Supplementary Material Table S2. Criteria used in methodological quality assessments (adapted from Palucci Vieira et al. [59], with permission).

	Question	Options	Score
Q1	Study objective(s)/purpose(s)/hypothesis(es) is/are clearly set out	Yes = 2; Partially = 1; No = 0	0 – 2
Q2	Included players were characterized (sample size, age, competitive level)	Yes = 2; Partially = 1; No = 0	0 – 2
Q3	Detailed design regarding kicking task (objective instruction, lower limb used, approach run, target specification, trials and whether defenders participated).	Yes = 2; Partially = 1; No = 0	0 – 2
Q4	Ball standardization [sizes, inflation pressure, condition (e.g. rolling/stationary)] and location where data collection took place	Yes = 2; Partially = 1; No = 0	0 – 2
Q5	Validity/reliability or error of measurement system/equipment is not stated, mentioned as a citation of previous study(s) or measured under local conditions	Measured = 2; Mentioned = 1; Not stated = 0	0 – 2
Q6	Random sequence generated (assessed according to RoB analysis)	Low risk = 2; Unclear risk = null; High risk = 0	0 – 2
Q7	Allocation concealed (assessed according to RoB analysis)	Low risk = 2; Unclear risk = null; High risk = 0	0 – 2
Q8	Outcome assessor blinded (assessed according to RoB analysis)	Low risk = 2; Unclear risk = null; High risk = 0	0 – 2
Q9	Dependent variables defined	Yes = 2; Partially = 1; No = 0	0 – 2
Q10	Statistical treatment to analyze main outcomes were deemed appropriate	Yes = 2; Partially = 1; No = 0	0 – 2
Q11	Data are detailed (mean and standard deviation, percent change/difference, effect size/mechanistic magnitude-based inference)	Yes = 2; Partially = 1; No = 0	0 – 2
Q12	Conclusions are insightful (clear, practical applications, and future directions)	Yes = 2; Partially = 1; No = 0	0 – 2
Total			0 – 24

RoB risk of bias, *null* unable to determine. Strict rules applied to Q2 (No information = 0 point; 1 – 2 items described = 1 point; all items described = 2 points); Q3 (0 – 2 items described = 0 point; 3 – 4 items described = 1 point; 5 – 6 items described = 2 points); Q4 (No information = 0 point; 1 – 2 items described = 1 point; 3 – 4 items described = 2 points); and Q11 [description of mean, standard deviation and null hypothesis significance test (p-value) = 1 point; also included effect size/magnitude-based inferences = 2 points].

Electronic Supplementary Material Table S3. Scores attributed to each study according to twelve criteria used in evaluating methodological quality.

Study	Year	Q1	Q2	Q3	Q4	Q5	Q6	Q7	Q8	Q9	Q10	Q11	Q12	Total (∑)	Quality Score [rating]
Abbey and Rankin [85]	2009	1	2	1	1	0	2	--	--	2	2	1	1	13	54% [moderate]
Abt et al. [86]	1998	1	2	1	1	0	2	--	--	2	1	1	1	12	50% [moderate]
Ali et al. [17]	2008	1	2	1	1	1	2	--	--	1	2	2	2	15	63% [moderate]
Amiri-Khorasani et al. [87]	2010	2	2	2	2	2	--	--	--	2	2	1	2	17	71% [moderate]
Amiri-Khorasani and Kellis [47]	2013	2	2	1	1	2	2	--	--	2	1	2	2	17	71% [moderate]
Amiri-Khorasani et al. [88]	2010	2	1	2	2	2	2	--	--	1	1	1	2	16	67% [moderate]
Amiri-Khorasani et al. [89]	2011	2	2	2	1	2	2	--	--	2	2	1	2	18	75% [high]
Amiri-Khorasani et al. [48]	2012	2	2	2	2	2	2	--	--	2	2	1	2	19	79% [high]
Amiri-Khorasani [49]	2013	2	2	2	2	2	--	--	--	2	2	1	2	17	71% [moderate]
Amiri-Khorasani and Ferdinands [37]	2014	2	2	2	2	2	2	0	--	2	2	1	2	19	79% [high]
Amiri-Khorasani et al. [90]	2011	2	2	2	2	2	--	0	--	2	2	1	2	17	71% [moderate]
Apriantono et al. [23]	2006	1	2	2	1	2	--	--	--	1	1	2	1	13	54% [moderate]
Beliard et al. [38]	2019	1	2	1	1	0	2	--	--	2	2	1	2	14	58% [moderate]
Cariolo et al. [91]	2018	1	2	1	0	1	--	--	--	0	2	1	2	10	42% [low]
Currell et al. [18]	2009	1	2	1	1	0	2	--	--	1	2	1	1	12	50% [moderate]
Deutschmann et al. [92]	2015	1	2	1	1	2	0	--	--	1	2	2	2	14	58% [moderate]
Draganidis et al. [93]	2013	2	2	0	1	1	2	--	--	1	2	2	1	14	58% [moderate]
Ferraz et al. [94]	2016	2	2	1	1	2	2	--	--	2	2	2	2	18	75% [high]

Ferraz et al. [15]	2017	2	2	1	1	2	--	--	--	2	2	2	2	16	67% [moderate]
Ferraz et al. [95]	2012	2	2	1	1	2	--	--	--	2	2	2	2	16	67% [moderate]
Ferraz et al. [96]	2019	1	1	1	1	2	2	--	--	1	1	1	1	12	50% [moderate]
Frikha et al. [51]	2017	1	2	2	2	2	2	2	--	1	2	2	2	20	83% [high]
Gaspar et al. [114]	2019	1	2	2	1	1	--	--	--	2	2	1	2	14	58% [moderate]
Gelen [50]	2010	2	2	1	0	2	2	2	--	1	1	2	2	17	71% [moderate]
Gharbi et al. [20]	2017	1	2	1	0	1	2	--	--	2	2	1	1	13	54% [moderate]
Greig [97]	2018	2	2	1	1	2	--	--	--	1	2	2	2	15	63% [moderate]
Hasan et al. [98]	2016	1	2	1	1	2	2	--	--	2	2	2	2	17	71% [moderate]
Hasan et al. [99]	2016	1	2	1	1	2	2	--	--	2	2	2	2	17	71% [moderate]
Izquierdo et al. [116]	2020	2	2	1	1	1	0	--	--	2	2	2	2	15	63% [moderate]
Juarez et al. [100]	2011	1	2	1	1	2	--	--	--	1	2	1	2	13	54% [moderate]
Katis et al. [64]	2014	2	2	1	1	2	--	--	--	2	2	1	2	15	63% [moderate]
Katis et al. [101]	2017	2	2	1	2	2	--	--	--	2	2	1	2	16	67% [moderate]
Kaviani et al. [117]	2020	2	2	0	1	1	2	2	--	1	2	1	1	15	63% [moderate]
Kellis et al. [102]	2006	2	2	1	0	2	--	--	--	2	2	1	2	14	58% [moderate]
Maly et al. [19]	2018	1	2	1	1	2	--	--	--	2	2	2	2	15	63% [moderate]
Masmoudi et al. [103]	2016	2	2	0	1	1	--	--	--	2	1	1	1	11	46% [low]
McMorris et al. [104]	2000	1	2	1	0	1	2	--	--	2	2	1	2	14	58% [moderate]
McMorris et al. [105]	2006	2	2	1	1	1	2	--	--	2	2	2	1	16	67% [moderate]
Muller and Brandes [106]	2015	1	2	1	1	1	2	2	--	2	2	2	1	17	71% [moderate]

Otten et al. [115]	2019	1	2	1	2	1	2	2	2	2	2	2	1	20	83% [high]
Owen et al. [107]	2013	2	2	2	0	1	2	--	--	2	2	2	2	17	71% [moderate]
Ozturk and Gelen [108]	2015	2	2	1	1	1	2	--	--	2	1	1	2	15	63% [moderate]
Pallesen et al. [109]	2017	2	2	0	0	0	2	0	--	1	1	1	1	10	42% [low]
Radman et al. [110]	2016	1	2	2	1	2	2	--	--	1	2	1	1	15	63% [moderate]
Russell et al. [39]	2012	1	2	1	1	2	2	2	--	2	2	1	2	18	75% [high]
Russell et al. [16]	2012	2	2	1	0	2	2	--	--	2	2	1	2	16	67% [moderate]
Sánchez-Sánchez et al. [21]	2014	1	2	1	2	1	--	--	--	2	2	1	2	14	58% [moderate]
Sasadai et al. [111]	2015	2	2	0	1	2	2	--	--	1	2	1	1	14	58% [moderate]
Stevenson et al. [14]	2017	2	2	1	1	1	2	2	--	2	2	2	2	19	79% [high]
Stone and Oliver [112]	2009	1	2	2	2	1	--	--	--	1	2	2	2	15	63% [moderate]
Torreblanca-Martinez et al. [13]	2016	2	2	0	0	2	--	--	--	2	2	2	1	13	54% [moderate]
Zemková and Hamar [113]	2009	1	2	0	0	1	--	--	--	1	1	1	1	8	33% [low]

-- Unable to determine (0).

CHAPTER 3

BRAIN DYNAMICS, KICKING KINEMATICS AND PERFORMANCE

3. PAPER 2 – Modelling the relationships between EEG signals, movement kinematics and outcome in soccer kicking [(3)]

Palucci Vieira, L.H., Carling, C., Silva, J.P., Santinelli, F.B., Polastri, P.F., Santiago, P.R.P., & Barbieri, F.A. (2023). Modelling the relationships between EEG signals, movement kinematics and outcome in soccer kicking. *Cognitive Neurodynamics* [Online ahead of print]. **https://doi.org/10.1007/s11571-022-09786-2**

(3) APPENDIX 3 - document obtained allowing reuse of this previously published study in the current thesis

3.1. Abstract

The contribution of cortical activity (e.g. EEG recordings) in various brain regions to motor control during goal-directed manipulative tasks using lower limbs remains unexplored. Therefore, the aim of the current study was to determine the magnitude of associations between EEG-derived brain activity and soccer kicking parameters. Twenty-four under-17 players performed an instep kicking task (18 m from the goal) aiming to hit 1x1 m targets allocated in the goalpost upper corners in the presence of a goalkeeper. Using a portable 64-channel EEG system, brain oscillations in delta, theta, alpha, beta and gamma frequency bands were determined at the frontal, motor, parietal and occipital regions separately for three phases of the kicks: preparatory, approach and immediately prior to ball contact. Movement kinematic measures included segmental linear and relative velocities, angular joint displacement and velocities. Mean radial error and ball velocity were assumed as outcome indicators. A significant influence of frontal theta power immediately prior to ball contact was observed in the variance of ball velocity (R^2 = 35%, $p = 0.01$) while the expression of occipital alpha component recorded during the preparatory phase contributed to the mean radial error (R^2 = 20%, $p = 0.049$). Ankle eversion angle at impact moment likely mediated the association between frontal theta power and subsequent ball velocity ($\beta = 0.151$, $p = 0.06$). The present analysis showed that the brain signalling at cortical level may be determinant in movement control, ball velocity and accuracy when performing kick attempts from the edge of penalty area.

Keywords: neuropsychophysiology, accuracy, prediction, 3-dimensional analysis, team sports, motor control.

Trial registration number: #RBR-8prx2m - Brazilian Registry of Clinical Trials ReBec

3.2. Introduction

Skilled kicking performance in soccer is evidently associated with an increased likelihood of winning in competition, implying a need to identify the determinant factors for this skill (Hunter et al. 2018; Palucci Vieira et al. 2021b). Fast ball velocity and accurate ball placement are key characteristics of kicking performance (Hunter et al. 2018). Achieving high standards in kicking requires a skilled strategy that is dependent first upon processing and cognitive planning (Collins et al. 1991; Noël and Kamp 2012) as well as optimal movement coordination between lower limb segments (Putnam 1991; De Witt and Hinrichs 2012). While the underpinning role of kinematic components of movement [e.g., hip range-of-motion (ROM), knee flexion/extension angle and foot velocity] directly involved in the development of kicking outcomes is well established (Levanon and Dapena 1998; Nunome et al. 2002; Lees et al. 2010), evidence of the central functioning during the task is lacking (Collins et al. 1991; Palucci Vieira et al. 2021a; Slutter et al. 2021). A holistic approach beyond typical kicking measures that integrates neuropsychophysiological aspects commonly related to sports outcomes, such as signalling from the cerebral cortex (Babiloni et al. 2008; Ermutlu et al. 2015; Tharawadeepimuk and Wongsawat 2017; Pluta et al. 2018) is useful in understanding neural activity patterns which may favor performance. It can also potentially assist in obtaining insights into specific mental states associated with successful behavior (Pluta et al. 2018).

In previous studies, cortical activity, in particular the alpha spectral power in various brain regions (frontal, motor and occipital), enabled prediction of outcomes related to accuracy in a range of goal-directed sport skills (e.g. shooting, archery and golf putting) (Salazar et al. 1990; Crews and Landers 1993; Landers et al. 1994; Loze et al. 2001; Babiloni et al. 2008; Baumeister et al. 2008). Recent research has reported contrasting results compared to those previously observed in investigations of movements pertaining to team sports such as ice hockey shooting (Christie et al. 2017), baseball batting (Pluta et al. 2018) and basketball throwing (Chuang et al. 2013). Higher frontal-midline theta power [6–8 Hz; (Chuang et al. 2013)] and reduced frontal-posterior beta [13–30 Hz; (Pluta et al. 2018)] in the preparatory phase were identified as cortical rhythms that were moderate-to-strongly related respectively to throwing accuracy and batting power. Of note was a lack of association between either the task (shooting, batting or throwing) accuracy and athletes' alpha power in the considered fronto-parieto-occipital sites [7–14 Hz; (Christie et al. 2017)]. Taken collectively, this indicates a need not to restrict analysis to short (e.g. single) waveband range and particularly when little information exists on associations between brain signalling and a given task performance (e.g. Ermutlu et al. 2015). Following on from their literature review, Cheron et al. (2016) proposed a theoretical model where all EEG frequency bands are hierarchically organised and have specific functions in motor control of sports performance. As for example, in addition to the previous cited rhythms (theta-to-beta range), the capacity to extract advanced sensory information present in open sport scenarios/decision-making (Ermutlu et al. 2015) and distal muscle activation (i.e. tibialis anterior; Petersen et al. 2012) is seemingly linked to scalp delta and gamma activities, respectively. Importantly, caution is necessary when attempting to extrapolate consistently reported correlations between sport performance and cortical activity to sports that require tasks with more complex parameters to be controlled. In contrast to sports requiring relatively simple voluntary movements performed in a (semi) static upright position (Hatfield et al. 2004; Cooke 2013; Nakata 2015), soccer players, when kicking the ball must acquire and process pertinent environmental information, perform approach running to the ball, and subsequently produce a coordinated multi-joint movement while also accounting for concomitant ball velocity output in order not to compromise accuracy. The latter represents an additional issue notably across adolescence, when velocity-accuracy trade-offs seemingly occur in kicking outputs which are probably a consequence related to the peak growth spurt (Vieira et al. 2018). Since biological maturity can partly explain performance discrepancies among age-matched players, inclusion of this factor is required in modelling brain-body interactions during soccer kick analyses.

Evidence gathered over the last decade recognises that the motor cortex controls the lower limbs during dynamic multiarticular tasks such as walking/running (Gwin et al. 2010; Petersen et al. 2012; Presacco et al. 2012). Although these publications investigating locomotion have already demonstrated a corticomuscular coupling in the legs, similar to that occurring in other regions like upper extremities, a functional segregation of movement-related cortical activity is generally assumed (Salmelin et al. 1995). The muscular activation and kinematic features of the lower contact limb during kicking modulates ensuing ball flight such as its placement in the goal and velocity (Palucci Vieira et al. 2021b), implying the likely participation of the supra-spinal inputs to the variance in movement parameters and performance. There is also preliminary evidence in soccer pointing to a substantial contribution of the measures derived from resting state EEG to skill-related performance fluctuations as determined by subjective ratings of coaches (Tharawadeepimuk and Wongsawat 2017). To our knowledge however, only one study including EEG metrics has investigated drills such as kicking directly involving a ball. Despite reporting novel information [i.e. higher alpha power in temporal sites during successful trials (ball passing or not cones)], the study included collegiate athletes, who were asked to perform unopposed kicks aimed at small targets on the ground, at a very short distance (7 m) and with high-accuracy low-effort demand required (Collins et al. 1991). Kicking in soccer is generally ballistic in nature and involves open circuit control. As such, it is plausible to state that the existing knowledge on motor control during ball kicking has been derived only from artificial experimental situations. Recent recommendations have been formulated to better align kicking assessment constraints with real-world soccer demands. For example, analysis of motor control is necessary during kicking actions performed over longer distances and including the presence of opponents contesting kicks, such as a goalkeeper. This is important in order to avoid unreliable ball placement and velocity during shots at goal (Palucci Vieira et al. 2021b). In addition, most evidence relating brain activity and technical performance in soccer is derived from studies in senior athletes (Collins et al. 1991; Tharawadeepimuk and Wongsawat 2017; Slutter et al. 2021). Owing to the fact that various kicking outputs (e.g. movement mechanics, ball placement and velocity) are highly age-dependent (Vieira et al. 2018; Palucci Vieira et al. 2021a), results from adult categories cannot be simply extrapolated to developing players. Furthermore, future studies need to make use of recent advances in contemporary imaging technologies enabling collection of EEG data during movement and outside a laboratory context (Park et al. 2015; Cheron et al. 2016; Perrey and Besson 2018). Consequently, opportunities to gather empirical data in field conditions will further knowledge of the behavior of underlying mechanisms that potentially play a role in the planning phase, motor adjustments and effectiveness during soccer kicking.

Therefore, the main purpose of the current study was to analyse, in youth soccer players, the possible associations between brain activity and concomitant lower limb kinematic and performance measures derived from ball kicking. A secondary goal was to evaluate whether (unknown) relationships among EEG-derived brain activity and kicking outcomes are mediated by movement characteristics and inter-individual estimated maturity. Based upon previous findings, our hypotheses were that 1) motor cortex high-frequency signals will contribute to the development of kicking velocity (Pfurtscheller and Lopes da Silva 1999; Gwin et al. 2010), 2) occipital alpha oscillations will have significant power to predict the magnitude of error in placing the ball in the goal (Haufler et al. 2000; Loze et al. 2001; di Fronso et al. 2016) and 3) associations between EEG and kicking outcomes will be mediated by movement features (e.g. ankle kinematics) (Katis and Kellis 2010; Ishii et al. 2012; Palucci Vieira et al. 2021a).

3.3. Materials and methods

3.3.1. Sample

Altogether, twenty-four youth U17 soccer players (15.9 ± 0.8 years-old; 60 ± 8.3 kg; 172 ± 9 cm and 1.92 ± 0.74 years from the estimated age of peak height velocity [APHV] (Moore et al. 2015)) competing in state-level (1st place in São Paulo Interior League 2020, Brazil) representing all outfield playing positions, completed the current study from a total of 28 initially recruited. According to an *a priori* calculation (G*Power v.3.1.9.4; Franz Faul, Universität Kiel, Germany), the final sample is justified based on the assumption of possible strong EEG influence on kicking performance variance ($R^2 > 0.26$; effect size $f^2 = 0.37$; power = 80%; alpha = 0.05). The study protocol was pre-registered, as a part of an umbrella research project, in the Brazilian Registry of Clinical Trials (register number RBR-8prx2m) and approved by the Local University Human Research Ethics Committee (protocol CAAE85994318.3.0000.5398), in accordance with 466/2012 resolution of the National Health Council. Players' guardians provided previous verbal and written permissions, while the players signed an assent form to agree to take part in the study as a volunteer.

3.3.2. Kicking task

The participants wore the same shoes and clothes they habitually used in training and competition in an attempt to minimise any potential effects of the experimental testing conditions on the players' natural kicking patterns. Each participant wore eight spherical markers (25 mm Ø) which were fixed with the aid of small kinesiotaping strips (Tmax Medical Co., Ltd, South Korea) in the bone protuberances of anterior superior iliac spine, greater femoral trochanter (also in the non-dominant limb), lateral femoral epicondyle, lateral malleolus, calcaneus and distal phalanx of fifth metatarsal head (only in dominant limb).

A standard warm-up routine composed of 4 min of moderate-intensity running (3/4 rating of perceived exertion–Borg CR-10 scale) followed by dynamic stretching was performed prior to kick testing. The kicking protocol was conducted during the habitual training schedule for the age group assessed (between 15:00–17:00 h) on a natural grass pitch with and in the presence of sunlight. Two 1 m^2 square targets were fixed in the upper extremities of the goalpost (7.32 x 2.44 m). The participants completed 20 trials in total (three conditions: seven kicks directed to each side and six for the goal centre; randomized using the https://www.random.org interface) distributed into four blocks of five kicks each. An interval of 3 min and 40 s for passive recovery (van den Tillaar and Fuglstad 2017) was implemented between blocks and trials, respectively. Prior to each attempt, the ball (PENALTY® FIFA-approved; 5 sized, 70 cm of diameter and 430 g weight) was positioned at a distance of 18 m from the midpoint goal line. Ball pressure was controlled across the experiment (Poker digital calibrator 09053, Cauduro Ind e Com Vest LTDA, Brazil) to be constant at 0.7 atm.

Players kicked the stationary ball using the instep foot region, after a beep (electronic whistle FOX 40®, Fox 40 International Inc., Canada) and with an approach run of 3.5 m and 45 degrees in relation to the kick mark (Kellis et al. 2004). The aim of the task was explained to participants: ‘kick the ball to hit the target centre so that the goalkeeper cannot intercept the ball’. Two youth goalkeepers of similar age, height and skill level (determined according to coaching staff) were asked to try to defend the kicks, remaining 1.2 m in front of the midpoint goal line, keeping their hands on the knee until the instant the ball was kicked and without prior knowledge of where the players would aim their kick (i.e. centre, ipsilateral or contralateral side conditions). Reliability of this kick testing protocol has recently been confirmed (Palucci Vieira et al. 2022).

3.3.3. EEG measures

To record signals from the cerebral cortex (Figure 3.1), a portable system was used (1024 Hz; eegoTM sports EEG system LE-200, ANT Neuro b.v., Enschede, Netherlands) (Christie et al. 2017). This includes a cap with 64-channel (WaveGuardTM original cap; 10/10 international electrode positioning system), connected to an amplifier (2 kHz; eego amplifier CE Class IIa medical device) and a tablet (TRAVELline T10-B5 Pro Tablet, Atom(TM) x5-Z8350 1.44 GHz, Bluechip Computer AG, Germany), inserted into a small backpack, which recorded and displayed the signal online via a Wi-Fi connection with an off-field computer (Dell Inc., Intel(R) Core™ i7-10510U). The reliability of this system is reported elsewhere (Fiedler et al. 2015; di Fronso et al. 2019). Using conductive gel (neurgel; Spes medica Srl – Italy), the impedance of electrodes was maintained below 30 kΩ during the experiment (ground < 10 kΩ).

The collected data were subsequently exported to the MATLAB® (R2019a; MathWorks Natick, MA, EUA) and processing conducted using the open-source toolbox EEGLAB v2020.0 (Delorme and Makeig 2004). Raw data were treated with a Butterworth band-pass 0.3–50 Hz, in addition to a 60 Hz notch filter, and then were re-sampled to 512 Hz. The artifacts were initially rejected by visual inspection considering excessively noise periods (Petersen et al. 2012) and automatically, eliminating those channels with kurtosis > 3 standard deviations from the mean value and epochs with absolute difference > 150 mV (Pluta et al. 2018; Duru and Assem 2018). All remaining channels (57 ± 3 per participant) were then re-referenced to the common average and some typical artifacts such as coming from linear trend, eye blink/movement, muscle or cardiac activity were identified and removed with assist of data decomposition by independent component analysis [ICA; see Delorme et al. (2007) for more information].

Trials were divided into three periods, lasting -6 to -3 s before kicking (preparatory phase), -3 to -1 s (approach phase) and -1 s until approximately the foot-ball contact moment (impact phase). Ball impact was marked by the examiner using a proprietary program feature (eegoTM software, ANT Neuro b.v., Enschede, Netherlands) and confirmed by the EEG burst at such time. For each, the average power spectral density of the frontal (F3, Fz, F4), motor (C3, Cz, C4), parietal (P3, Pz, P4) and occipital (O1, Oz e O2) (Presacco et al. 2012) regions of interest (ROIs) considering delta (δ; 0.5–3 Hz), theta (θ; 4–7 Hz), alpha (α; 8–12 Hz), beta (β; 13–30 Hz) and gamma (γ; 31–50 Hz) frequency bands were extracted. Event-related synchronisation/desynchronisation (ERS/ERD) was calculated using input parameters (spectral power during time-windows of -5 to -4 s as the baseline period and -1 s to impact as the event period) and equation (ERS/ERD = [(event period – baseline period) / baseline period] × 100) following literature-based recommendations (Babiloni et al. 2008; Pfurtscheller and Lopes da Silva 1999). Inter-trials reliability of discrete EEG spectral power and ERS/ERD outcomes were determined, separately for all kick phases (exclusively concerning power measures in this case), as well as considering whole trials (see below). Furthermore, for each ROI event-related spectral perturbation (ERSP) images (Makeig, 1993) and inter-trial coherence (ITC) images (Makeig et al. 2004) were computed through their respective "STUDY" functions available in the EEGLAB environment (Delorme and Makeig 2004). For this analysis, zero indicates the beginning of impact phase. Four players among those initially recruited were excluded from the additional analysis owing to identification of an unacceptable percentage of artifacts (>30%) contaminating their EEG data (valid trials per participant included = 94 ± 6%).

3.3.4. Kinematic procedures

Four digital video cameras were used (GoPro® Hero 7 Black Edition, GoPro GmbH, München, Germany), adjusted at a sampling frequency of 240 frames/s (Wide field-of-view 1280 x 960 pixel of resolution; 1/480 s shutter speed and NTSC standard). These were synchronized using

Wi-Fi (GoPro smart remote control) and coupled with fixed tripods and positioned laterally (~2.5 m) to where the kicks took place, allowing capture of the kicker's movement and ball trajectory immediately after contact.

In the DVIDEOW interface (version 4.0; Laboratory of Instrumentation for Biomechanics & Institute of Computing UNICAMP, Brazil) (Figueroa et al. 2003), the following sequence of steps was completed: (i) calibration (4.4 x 3.5 x 1.3 m respectively in anterior-posterior, medio-lateral and vertical directions), (ii) semiautomatic tracking of markers and the ball and (iii) three-dimensional (3-D) reconstruction using the direct linear transformation method (DLT), embedded into the software. Thereafter, data matrices containing the spatial information as a function of time were exported into MATLAB R2019a environment (MathWorks Natick, MA, USA). Using the same procedures employed in a previous study (Vieira et al. 2018) radial distortion of image sequences was corrected before 3-D DLT reconstruction (uncertainties = 0.9 cm [precision], 2.1 cm [bias] and 2.3 cm [overall accuracy] in the present study). With the intention of minimizing systematic errors generally arising from the foot-ball impact, the movement data were linearly extrapolated (20%, at the beginning and end of time-series) and filtered using Butterworth (cut-off frequency = 25 Hz) followed by non-parametric locally weighted function rloess (span = 0.1) (Barbieri et al. 2015; Palucci Vieira et al. 2021a); in both cases, the smoothing parameters were selected after residual analysis.

In accordance with definitions available in the scientific literature regarding the reference frame of the joint and segment centers, it was possible to compute the angular joint displacement of the hip (internal/external rotation, abduction/adduction and flexion/extension), knee (flexion/extension) and ankle (plantarflexion/dorsiflexion, abduction/adduction and eversion/inversion), as well as the associated angular joint velocity in each case (Palucci Vieira et al. 2021a). Relative linear velocities between joints were also obtained (De Witt and Hinrichs 2012). Range-of-motion (ROM) was defined as the difference between minimal and maximal values for each movement component observed during the duration of the trial. To measure foot velocity, the barycentre of the ankle, calcaneus and toe coordinates was used (Palucci Vieira et al.

2021a). Ball velocity was determined using its centroid trajectory and calculated as an average of 10 frames following ball contact [for more details of calculation see (Levanon and Dapena 1998)].

To capture ball placement after kicking, one camera operating at 60 frames/s (Linear field-of-view 1920 x 1080 pixel of resolution), of the same model and brand of the previous, was fixed frontally 23 m away from the midpoint between goalposts. An auxiliary camera (configured at the same parameters of frontal one) was positioned in the intersection between the penalty area and goal lines, with its focus parallel to the ball trajectory. For each trial, using the same software and kinematic procedures described above, 2-D ball position was digitized in the instant it crossed the goal line. The Euclidean distance between the ball centroid and the target centre was then measured and the mean radial error calculated, separately for each of the experimental conditions (Vieira et al. 2018). Kick attempts were classified as successful (i.e. kicks on-target/goal) or unsuccessful (i.e. missed kicks).

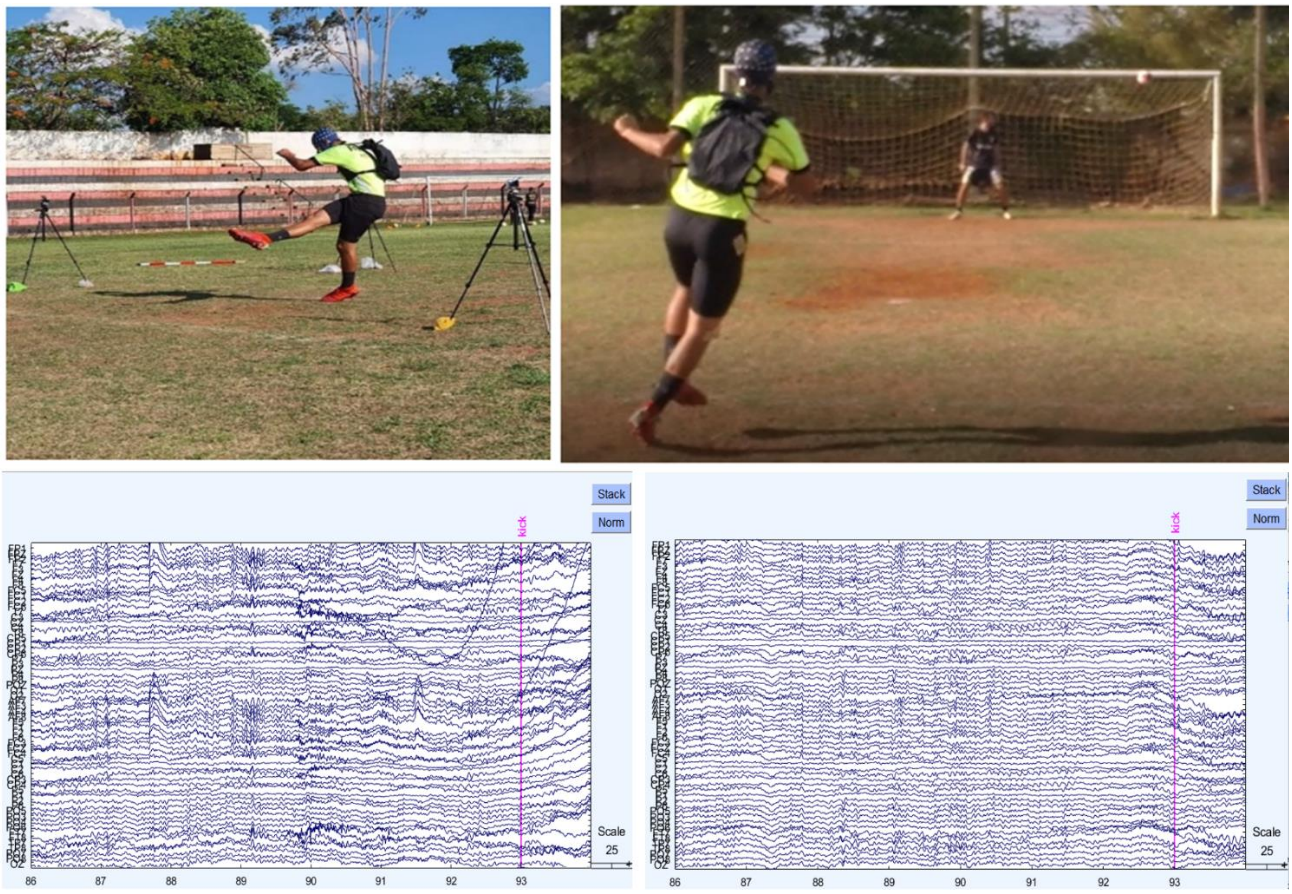


Figure 3.1. Experimental setup adopted for data collection/player montage (upper panel) and example of EEG raw (bottom left) and cleaned data (bottom right).

3.3.5. Statistical Analysis

Initially, outliers were automatically identified and removed (1.47% of all eligible data cells) using the z-score principle (i.e. -3.29 > *z* > +3.29; (Tabachnick and Fidell 2019)). As many variables did not fulfil the normality assumption evaluated by the Shapiro-Wilk test, kurtosis and visual inspection, we applied a Box-Cox transformation to the dataset, aiming to reduce problems arising from non-additivity, non-normality and heteroscedasticity. Intraclass correlation coefficient (ICC) were taken as reliability estimates of EEG spectral power and ERS/ERD measurements across trials (using an Excel® spreadsheet freely available in sportsci.org/2015/ValidRely.htm domain), and were interpreted as being poor (< 0.50), moderate (0.50–0.75), good (0.75–0.90) or excellent (> 0.90). One-way analysis of variance tests (ANOVAs) were used to compare lower limb kinematics, ball velocity and EEG between experimental conditions while Student t test for paired samples was used in mean radial error comparisons. Repeated measures ANOVAs (RM-ANOVAs) designed in 2 (performance [kicks on-target, kicks off-target]) × 3 (phase [preparatory, approach, impact]) × 4 (ROI [frontal, motor, parietal, occipital]) were performed, separately for each EEG power frequency band. Additional RM-ANOVAS of 2 (performance) × 4 (ROI) were performed, separately for each EEG ERS/ERD frequency band. Resulting grand average ERSP and ITC images were obtained across all subjects considering kicks on-target/goal and missed kicks and then compared using paired t-test; its non-significant outcomes are masked in plots. In an attempt to control for inflation in type I error rate, Pearson’s product-moment correlation coefficients were computed between mean radial error in the kicks and lower limb kinematic parameters/ball velocity with EEG spectral power measures only considering the preparatory and impact phases, respectively. In the case of ERS/ERD, such restriction was not applied. Linear regressions (stepwise method) were subsequently run to identify the relative contribution of the EEG to the variance in kicking performance indicators. Structural equation modelling (SEM) was used to analyse if lower limb movement kinematics or estimated biological maturity (APHV) were significant moderators in the significant associations between EEG and kicking performance (mean radial error and ball velocity), as well as whether there was any trade-off between the two last mentioned dependent factors. Software used included MATLAB® (outliers exclusion, ERSP and ITC comparisons; R2019a, MathWorks Natick, MA, USA), IBM SPSS Statistics (data transformation, ANOVAs, correlations and regressions; v.25, IBM Corp.©, USA) and Stata (SEM; v.13 for Windows, StataCorp LP, Texas, USA) and for all cases, a statistical significance level of $p \leq 0.05$ was assumed unless otherwise stated.

3.4. Results

3.4.1. Comparisons between kicking conditions

The ERSP and associated ITC results are shown separately for each ROI in Figures 3.2–3.5. In general, regarding ERSPs it was possible to observe that successful kick attempts, as compared to missed kicks, showed a significant higher decline in frontal theta power around -200 ms to zero and increase in alpha power starting at 200 ms until the end of the window (Figure 3.2). In the motor region, beta power raised (50 to 200 ms) in successful kicks while it decreased in the same period for missed kicks. Also, an increase in motor alpha activity (300 ms to the end) was significantly greater in successful compared to missed kicks (Figure 3.3). No change or slightly decrease were identified in parietal theta (-100 ms to zero) during successful kicks whilst missed kicks presented augmented power is this same frequency band/period. There was a decrease in occipital theta (-300 to -200 ms) and increase in alpha and beta from 300 ms to the end of successful kicks when compared to missed kick attempts (Figure 3.5). The ITCs were significantly greater in motor theta (-300 to -100 ms), frontal (-200 to ~0) and parietal (100 to 200 ms) alpha and lower in occipital theta (300 ms to end) in successful versus unsuccessful kicks.

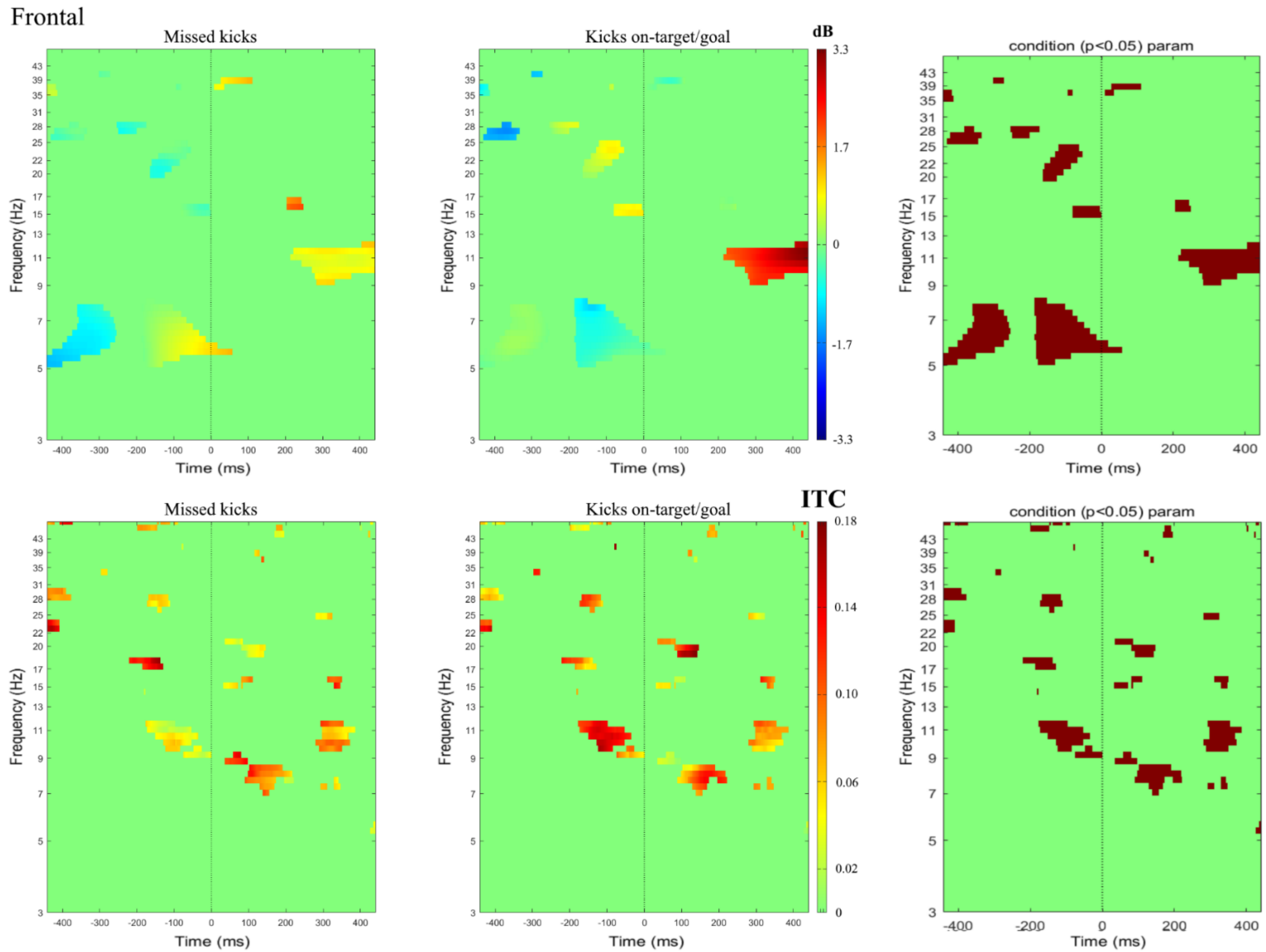


Figure 3.2. Grand average event-related spectral perturbation (ERSP) and inter-trial coherence (ITC) outcomes, respectively in the first and second lines, representative of frontal brain region according to kick conditions. The green area represents absence of statistically significant values in both group level or resulting plots for the comparison made; the same is valid for remainder similar figures.

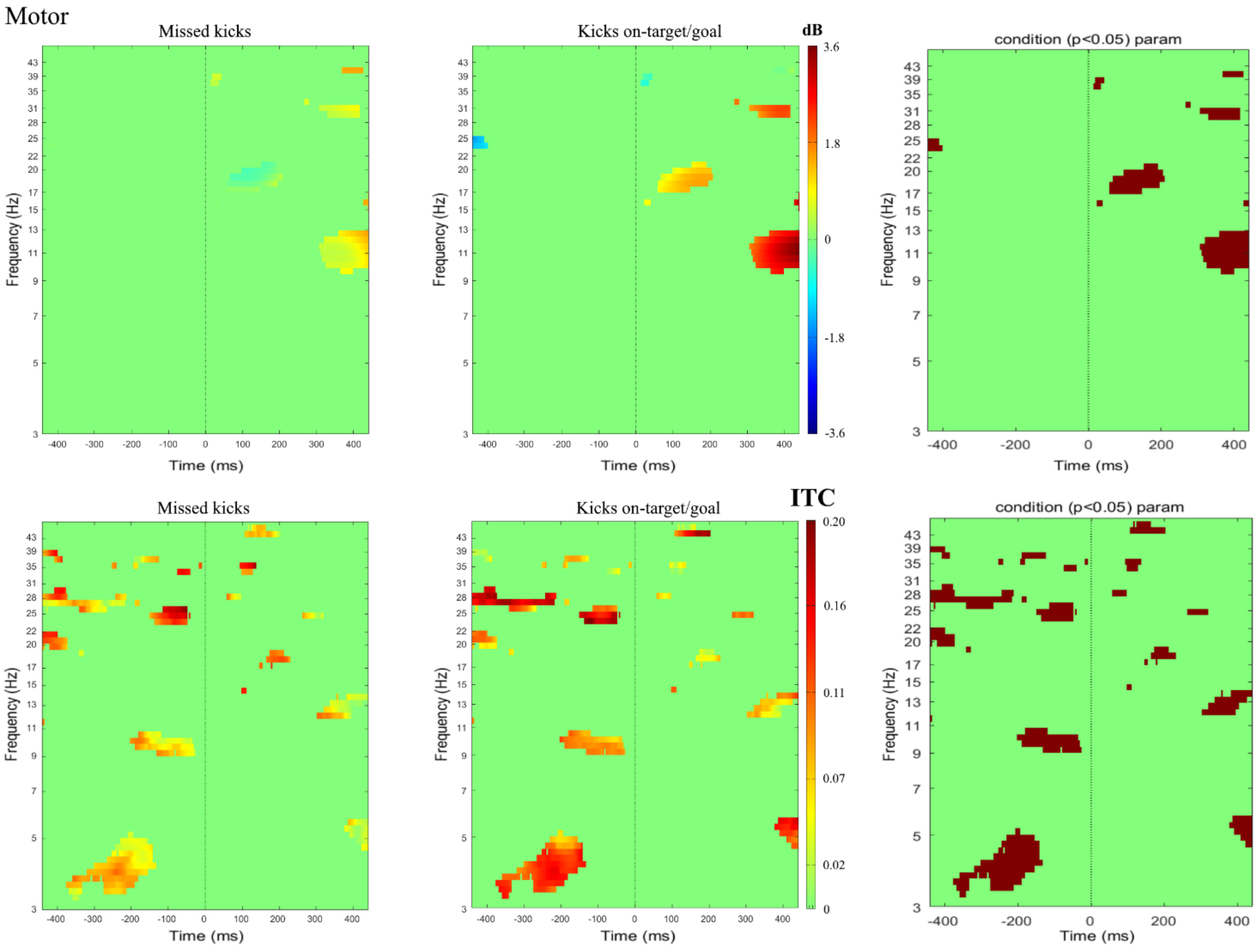


Figure 3.3. Grand average ERSP and ITC outcomes, respectively in the first and second lines, representative of motor brain region according to kick conditions.

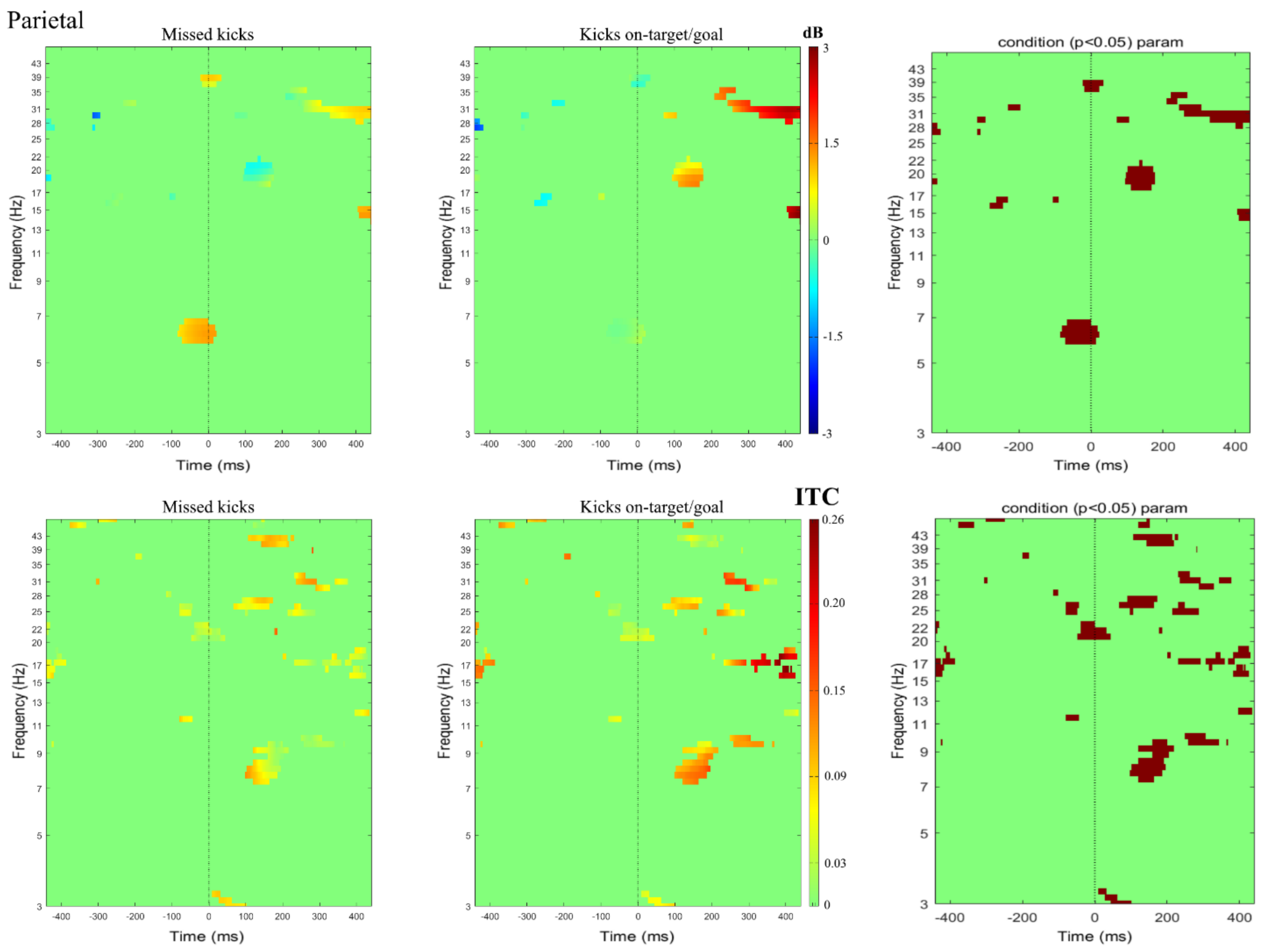


Figure 3.4. Grand average ERSP and ITC outcomes, respectively in the first and second lines, representative of parietal brain region according to kick conditions.

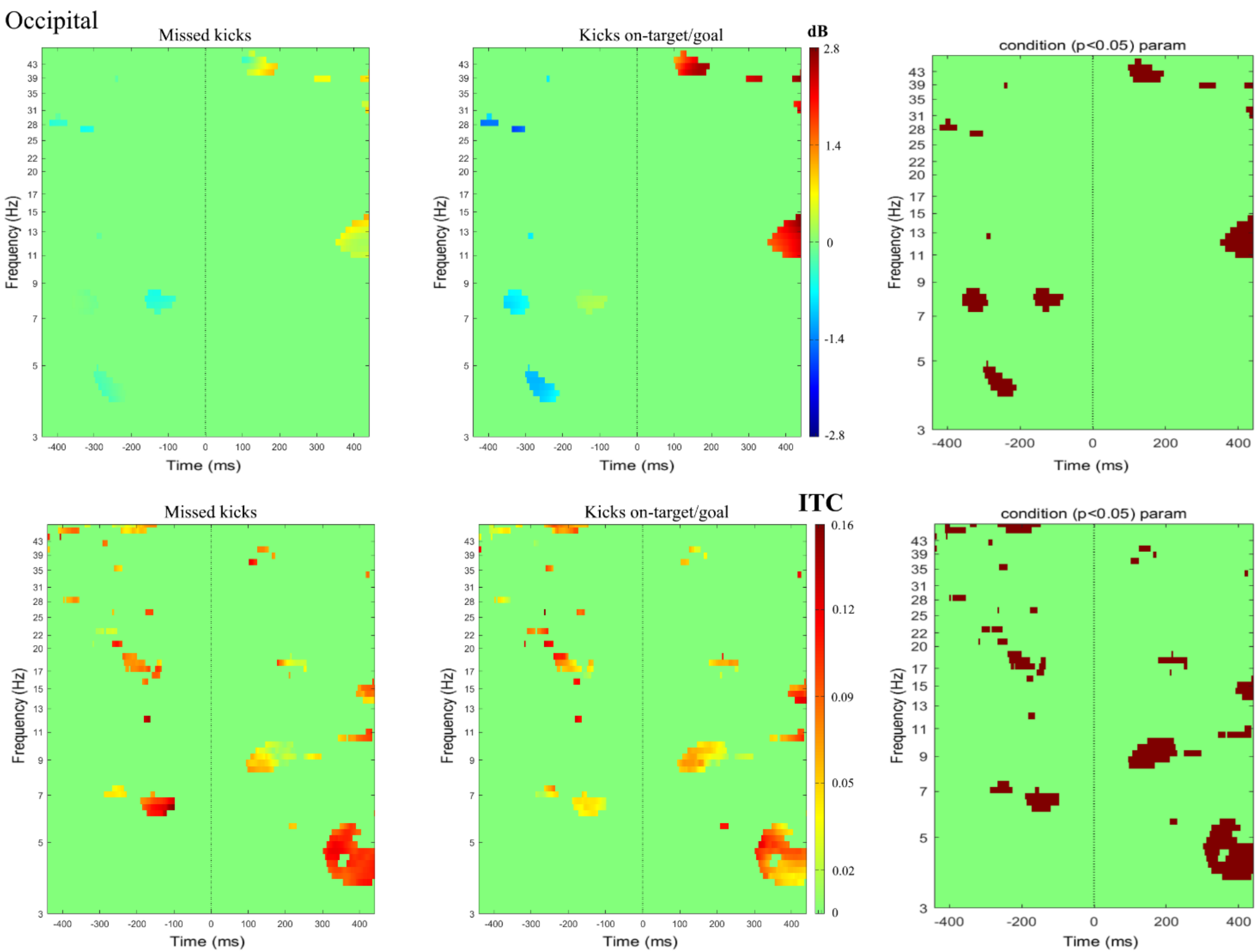


Figure 3.5. Grand average ERSP and ITC outcomes, respectively in the first and second lines, representative of occipital brain region according to kick conditions.

Non-time-series EEG extracted measures (spectral power: $F_{2,53} \leq 2.11$; $p \geq 0.13$; $\eta^2 \leq 0.07$; ERS/ERD: $F_{2,52} \leq 2.79$; $p \geq 0.07$; $\eta^2 \leq 0.07$), lower limb kinematics ($F_{2,67} \leq 1.48$; $p \geq 0.24$; $\eta^2 \leq 0.04$) and kicking performance (ball velocity: $F_{2,67} = 0.591$; $p = 0.56$; $\eta^2 = 0.02$ and mean radial error: $t_{1,23} = -1.688$; $p = 0.11$; $d = 0.49$) did not exhibit significant differences between experimental conditions, allowing us to group all trials for further statistical analysis (i.e. 20 representative trials of the ball velocity/lower limb kinematic results and 14 used to compute the variable of ball placement in the goal– this was not determined for kicks directed to the goal centre). ICC values (ranged from poor to excellent) are presented as supplementary online materials 1 and 2. The results of RM-ANOVAs also pointed to the absence of a statistically significant interactive effect between performance × period × ROI (Figure 3.6), for all EEG power frequency bands included (delta: $F_{6,54} = 0.769$; $p = 0.60$; $\eta^2 = 0.08$; theta: $F_{6,60} = 0.677$; $p = 0.67$; $\eta^2 = 0.06$; alpha: $F_{6,72} = 1.420$; $p = 0.22$; $\eta^2 = 0.11$; beta: $F_{6,72} = 1.026$; $p = 0.42$; $\eta^2 = 0.08$ and gamma: $F_{6,54} = 0.508$; $p = 0.80$; $\eta^2 = 0.05$) and no significant performance × ROI interaction (Table 3.1) concerning ERS/ERDs (delta: $F_{3,27} = 0.510$; $p = 0.68$; $\eta^2 = 0.05$; theta: $F_{3,27} = 0.778$; $p = 0.52$; $\eta^2 = 0.08$; alpha: $F_{3,27} = 0.596$; $p = 0.62$; $\eta^2 = 0.06$; beta: $F_{3,27} = 0.504$; $p = 0.68$; $\eta^2 = 0.05$ and gamma: $F_{3,27} = 0.106$; $p = 0.96$; $\eta^2 = 0.01$) as well as separate performance main effects ($p \geq 0.43$; $\eta^2 \leq 0.07$).

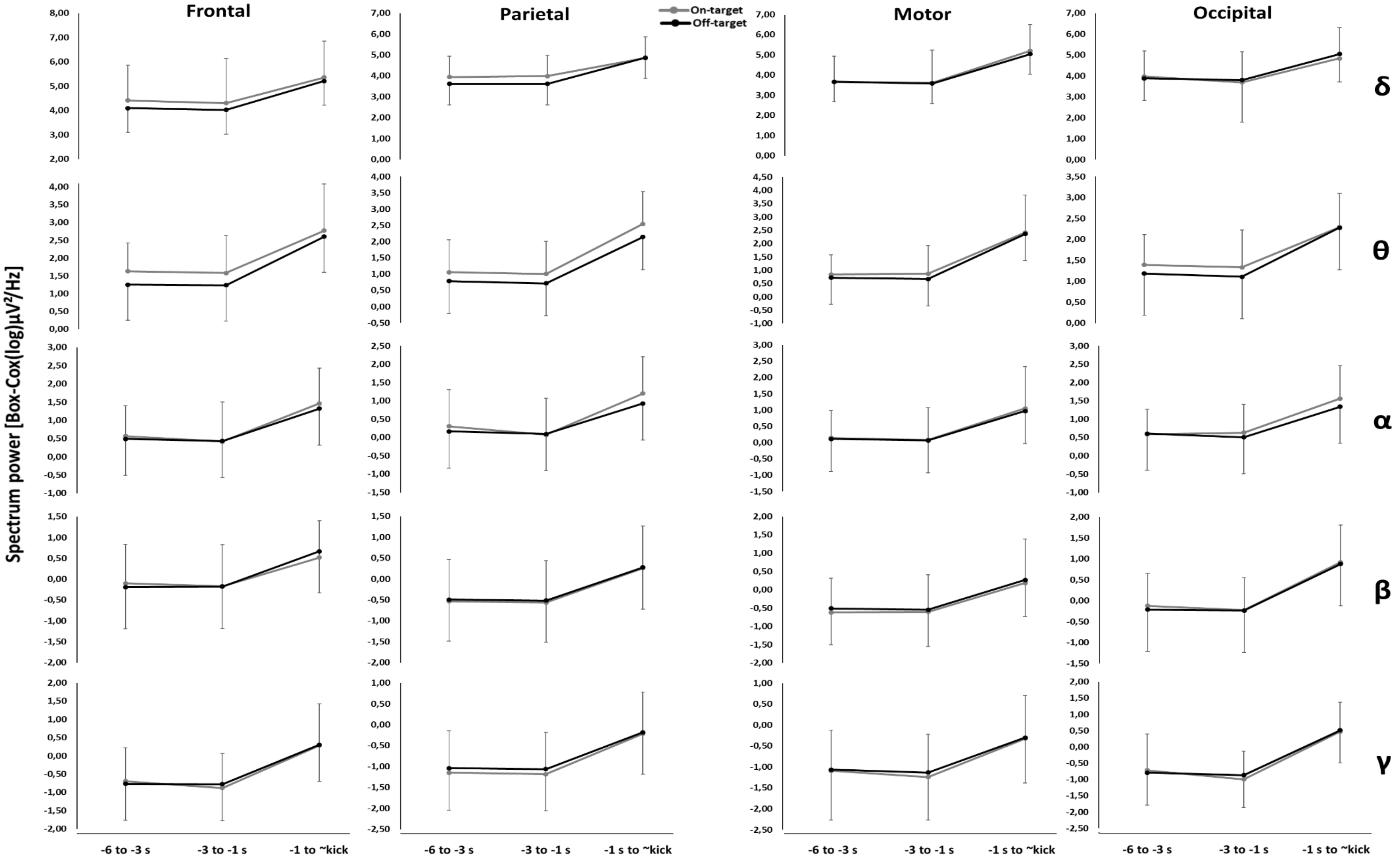


Figure 3.6. EEG spectral power verified in the kicking trials on- and off-target.

Table 3.1. EEG ERS/ERD verified in the successful and unsuccessful kicking trials.

		ERS/ERD [Box-Cox(log)µV²/Hz]			
		Kicks on-target/goal	Missed kicks	*p*-value	Effect size (*d*)
Frontal	Delta	3.52 ± 1.03	3.43 ± 1.21	0.88	0.08
	Theta	1.14 ± 0.69	1.33 ± 1.04	0.53	-0.22
	Alpha	0.06 ± 0.82	0.53 ± 1.08	0.25	-0.50
	Beta	-0.44 ± 0.70	-0.04 ± 0.75	0.29	-0.55
	Gamma	-0.90 ± 0.74	-0.61 ± 0.97	0.53	-0.34
Parietal	Delta	3.27 ± 1.23	2.84 ± 1.33	0.54	0.34
	Theta	0.74 ± 0.79	0.35 ± 1.10	0.38	0.41
	Alpha	-0.27 ± 0.78	-0.04 ± 1.19	0.52	-0.24
	Beta	-0.81 ± 0.73	-0.63 ± 1.03	0.69	-0.19
	Gamma	-1.34 ± 0.91	-1.03 ± 1.16	0.51	-0.30
Motor	Delta	3.15 ± 1.11	3.15 ± 1.85	1.00	0.00
	Theta	0.61 ± 0.71	0.55 ± 0.94	0.86	0.08
	Alpha	-0.05 ± 0.81	-0.02 ± 1.11	0.96	-0.03
	Beta	-0.83 ± 0.75	-0.37 ± 0.99	0.35	-0.53
	Gamma	-1.25 ± 0.83	-0.87 ± 1.16	0.49	-0.38
Occipital	Delta	3.20 ± 0.98	2.80 ± 1.50	0.58	0.32
	Theta	1.01 ± 0.78	0.87 ± 1.15	0.81	0.13
	Alpha	0.35 ± 1.04	0.35 ± 0.73	0.98	0.01
	Beta	-0.33 ± 0.57	-0.23 ± 0.94	0.80	-0.12
	Gamma	-0.86 ± 0.94	-0.69 ± 0.75	0.65	-0.20

3.4.2. Correlations between EEG, kinematics and outcomes

Significant correlation coefficients (with their respective confidence limits) were obtained from the associations between selected kicking components with the EEG spectral power (Table 3.2) and ERS/ERD values (Table 3.3). Specifically, the knee ROM (1.15 ± 0.16 rad) was moderately correlated with frontal, parietal gamma and frontal delta powers (2.75 ± 3.05, 1.74 ± 2.06, 518.43 ± 638.12 µV²/Hz, respectively) and largely correlated with motor, parietal and occipital gamma ERS/ERDs (-22.98 ± 166.25%, -49.77 ± 154.94%, -98.65 ± 182.31%, respectively). Frontal theta power (30.19 ± 32.37 $\mu V^2/Hz$) was moderately and largely correlated with ankle eversion (0.05 ± 0.32 rad) and hip flexion angles (0.57 ± 0.12 rad) at impact, respectively. Hip flexion angle at impact was also moderately and largely correlated with parietal and motor delta, theta and alpha powers (340.03 ± 328.66, 19.55 ± 15.29 and 4.96 ± 4.16 $\mu V^2/Hz$, respectively for the latter), while the ankle eversion angle at impact showed moderate inverse relationships with frontal alpha power (7.71 ± 7.88 $\mu V^2/Hz$) and occipital theta ERS/ERD (+86.73 ± 212.53%). Significant large and moderate relationships occurred between hip flexion angle at impact and motor theta ERS/ERDs (+100.76 ± 215.35%), parietal gamma and theta (-9.70 ± 302.02%) ERS/ERDs, respectively. Furthermore, the relative velocity between foot centre of mass and knee linear velocities at impact instant (50.15 ± 5.35 km/h) exhibited moderate correlations with occipital beta (3.59 ± 2.39 $\mu V^2/Hz$) and gamma (2.61 ± 1.93 $\mu V^2/Hz$) powers.

Table 3.2. Correlations (± 90% confidence limits) between selected kicking performance parameters and lower limb kinematics with EEG spectral power in each frequency band/brain region.

		EEG spectral power				
		Delta	Theta	Alpha	Beta	Gamma
Frontal	Mean radial error	-0.31 (± 0.23)	-0.09 (± 0.23)	-0.06 (± 0.23)	0.02 (± 0.21)	-0.21 (± 0.22)
	Ball velocity	**0.45*** (± 0.27)	**0.50*** (± 0.34)	0.36 (± 0.29)	0.23 (± 0.23)	0.21 (± 0.23)
	Hip flexion	0.19 (± 0.35)	**0.53**** (± 0.28)	0.36 (± 0.28)	0.13 (± 0.23)	-0.01 (± 0.25)
	Knee range of motion	**0.42*** (± 0.29)	0.01 (± 0.19)	0.11 (± 0.21)	0.27 (± 0.25)	**0.43*** (± 0.32)
	Ankle eversion	-0.37 (± 0.29)	**-0.46*** (± 0.31)	**-0.43*** (± 0.25)	-0.30 (± 0.26)	-0.21 (± 0.26)
Parietal	Mean radial error	-0.01 (± 0.16)	0.05 (± 0.19)	-0.03 (± 0.15)	-0.04 (± 0.16)	-0.05 (± 0.15)
	Ball velocity	**0.46*** (± 0.34)	0.17 (± 0.25)	0.26 (± 0.29)	0.15 (± 0.22)	0.09 (± 0.16)
	Hip flexion	**0.53**** (± 0.35)	**0.41*** (± 0.33)	0.36 (± 0.36)	0.04 (± 0.38)	-0.10 (± 0.32)
	Knee range of motion	0.01 (± 0.22)	-0.10 (± 0.22)	0.03 (± 0.24)	0.36 (± 0.32)	**0.41*** (± 0.32)
	Ankle eversion	-0.23 (± 0.25)	-0.11 (± 0.26)	-0.13 (± 0.24)	0.07 (± 0.20)	0.12 (± 0.20)
Motor	Mean radial error	0.02 (± 0.18)	0.07 (± 0.16)	-0.01 (± 0.20)	0.12 (± 0.19)	-0.01 (± 0.17)
	Ball velocity	0.33 (± 0.30)	0.17 (± 0.26)	0.20 (± 0.30)	0.06 (± 0.16)	0.05 (± 0.13)
	Hip flexion	**0.46*** (± 0.39)	**0.47*** (± 0.37)	**0.54**** (± 0.36)	0.15 (± 0.38)	0.01 (± 0.35)
	Knee range of motion	0.01 (± 0.24)	-0.02 (± 0.22)	-0.14 (± 0.23)	0.19 (± 0.30)	0.25 (± 0.28)
	Ankle eversion	-0.20 (± 0.26)	-0.02 (± 0.25)	-0.01 (± 0.26)	0.03 (± 0.21)	-0.23 (± 0.19)
Occipital	Mean radial error	-0.28 (± 0.28)	-0.27 (± 0.24)	**-0.45*** (± 0.27)	-0.21 (± 0.23)	-0.20 (± 0.22)
	Ball velocity	**0.58**** (± 0.36)	0.24 (± 0.31)	0.18 (± 0.27)	0.18 (± 0.25)	0.20 (± 0.22)
	Hip flexion	0.33 (± 0.31)	0.23 (± 0.32)	-0.01 (± 0.36)	-0.04 (± 0.33)	-0.12 (± 0.29)
	Knee range of motion	0.19 (± 0.36)	0.12 (± 0.24)	0.32 (± 0.31)	0.34 (± 0.33)	0.42 (± 0.34)
	Ankle eversion	-0.34 (± 0.31)	-0.12 (± 0.25)	-0.07 (± 0.27)	0.01 (± 0.22)	0.01 (± 0.20)

* $p < 0.05$; ** $p < 0.01$.

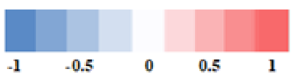
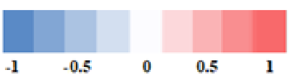


Table 3.3. Correlations (± 90% confidence limits) between selected kicking performance parameters and lower limb kinematics with EEG ERS/ERD in each frequency band/brain region.

		EEG ERS/ERD				
		Delta	Theta	Alpha	Beta	Gamma
Frontal	Mean radial error	0.16 (± 0.22)	0.29 (± 0.24)	0.10 (± 0.21)	0.01 (± 0.15)	-0.12 (± 0.24)
	Ball velocity	-0.30 (± 0.26)	-0.13 (± 0.22)	-0.02 (± 0.22)	-0.09 (± 0.22)	0.11 (± 0.19)
	Hip flexion	-0.15 (± 0.20)	0.13 (± 0.16)	0.23 (± 0.25)	-0.28 (± 0.28)	-0.01 (± 0.25)
	Knee range of motion	-0.11 (± 0.24)	0.06 (± 0.20)	-0.02 (± 0.20)	0.31 (± 0.25)	0.33 (± 0.33)
	Ankle eversion	0.02 (± 0.20)	0.16 (± 0.22)	0.07 (± 0.19)	-0.20 (± 0.27)	-0.07 (± 0.21)
Parietal	Mean radial error	0.23 (± 0.26)	-0.04 (± 0.18)	0.11 (± 0.23)	-0.28 (± 0.30)	-0.36 (± 0.21)
	Ball velocity	-0.38 (± 0.25)	-0.01 (± 0.21)	0.05 (± 0.15)	0.28 (± 0.18)	0.01 (± 0.18)
	Hip flexion	-0.29 (± 0.25)	**0.42*** (± 0.22)	0.20 (± 0.19)	0.03 (± 0.17)	**-0.46*** (± 0.33)
	Knee range of motion	-0.23 (± 0.23)	-0.16 (± 0.25)	0.32 (± 0.14)	**0.47*** (± 0.16)	**0.55**** (± 0.27)
	Ankle eversion	0.04 (± 0.22)	0.10 (± 0.22)	-0.08 (± 0.19)	-0.02 (± 0.19)	0.15 (± 0.21)
Motor	Mean radial error	0.19 (± 0.21)	0.17 (± 0.24)	0.34 (± 0.28)	-0.06 (± 0.27)	-0.02 (± 0.14)
	Ball velocity	-0.22 (± 0.22)	-0.02 (± 0.23)	-0.14 (± 0.18)	-0.13 (± 0.28)	0.02 (± 0.12)
	Hip flexion	-0.38 (± 0.27)	**0.50*** (± 0.27)	0.21 (± 0.14)	-0.08 (± 0.22)	-0.38 (± 0.31)
	Knee range of motion	0.03 (± 0.21)	-0.19 (± 0.21)	-0.08 (± 0.16)	0.21 (± 0.25)	**0.61**** (± 0.29)
	Ankle eversion	-0.04 (± 0.22)	-0.05 (± 0.24)	0.06 (± 0.25)	-0.13 (± 0.23)	0.10 (± 0.20)
Occipital	Mean radial error	-0.04 (± 0.24)	-0.16 (± 0.22)	-0.09 (± 0.24)	**-0.42*** (± 0.29)	0.01 (± 0.13)
	Ball velocity	-0.24 (± 0.25)	0.24 (± 0.28)	0.08 (± 0.18)	0.21 (± 0.24)	0.07 (± 0.13)
	Hip flexion	-0.35 (± 0.30)	0.10 (± 0.21)	0.21 (± 0.24)	-0.19 (± 0.19)	-0.33 (± 0.30)
	Knee range of motion	-0.17 (± 0.24)	0.01 (± 0.15)	0.23 (± 0.25)	**0.53**** (± 0.19)	**0.57**** (± 0.32)
	Ankle eversion	-0.18 (± 0.25)	**-0.53**** (± 0.30)	-0.04 (± 0.20)	0.07 (± 0.20)	0.04 (± 0.20)

ERS/ERD, event-related synchronisation/event-related desynchronization. * $p < 0.05$; ** $p < 0.01$.



Moderate to large significant correlations were observed between ball velocity (95.13 ± 7.45 km/h) and EEG spectral power during the impact phase (-1 s to ~kick), in reference to the frontal theta (30.19 ± 32.37 $\mu V^2/Hz$) and fronto-parieto-occipital delta levels (Table 3.2). ERS/ERD indices were non-significantly related to ball velocity (Table 3.3). Finally, the occipital alpha (2.40 ± 1.17 $\mu V^2/Hz$) during the preparatory phase (-6 to -3 s) was the sole EEG spectral power measure (Table 3.2) moderately correlated with the mean radial error (2.08 ± 0.35 m). Occipital beta ERS/ERD (-87.59 ± 276.24%) also showed a moderate inverse relationship with mean radial error (Table 3.3).

3.4.3. Linear regressions and mediational models

The linear regression models (Figure 3.7 and Supplementary online material 3) revealed a 35% contribution of the frontal theta EEG spectral power (-1 s to ~kick) to the variance in ball velocity ($Z_{(1,19)} = 9.641$; standardised β coefficient = 0.591; $p = 0.01$) while 18 to 20% of the variance in mean radial error was explained respectively by the occipital beta ERS/ERD ($Z_{(1,19)} = 4.911$; standardised β coefficient = -0.463; $p = 0.04$) and EEG power expression in alpha band during the preparatory phase (-6 to -3 s) obtained in the occipital region ($Z_{(1,19)} = 4.453$; standardised β coefficient = -0.445; $p = 0.049$). Other EEG parameters did not demonstrate significant power to predict the kick outcome measures (i.e. ball velocity or mean radial error). The SEM models pointed to a mediation with borderline significance (Table 3.4) of the ankle eversion angle in the association between frontal theta power (1 s to ~kick) and subsequent ball velocity [relative χ^2 (χ^2/gl) = 4.208 (satisfactory value < 5.00); $p = 0.06$; Figure 3.8(A)]. No significant mediators (i.e. indirect effects) were detected for the association between EEG and mean radial error (e.g. Figure 3.8(B)).

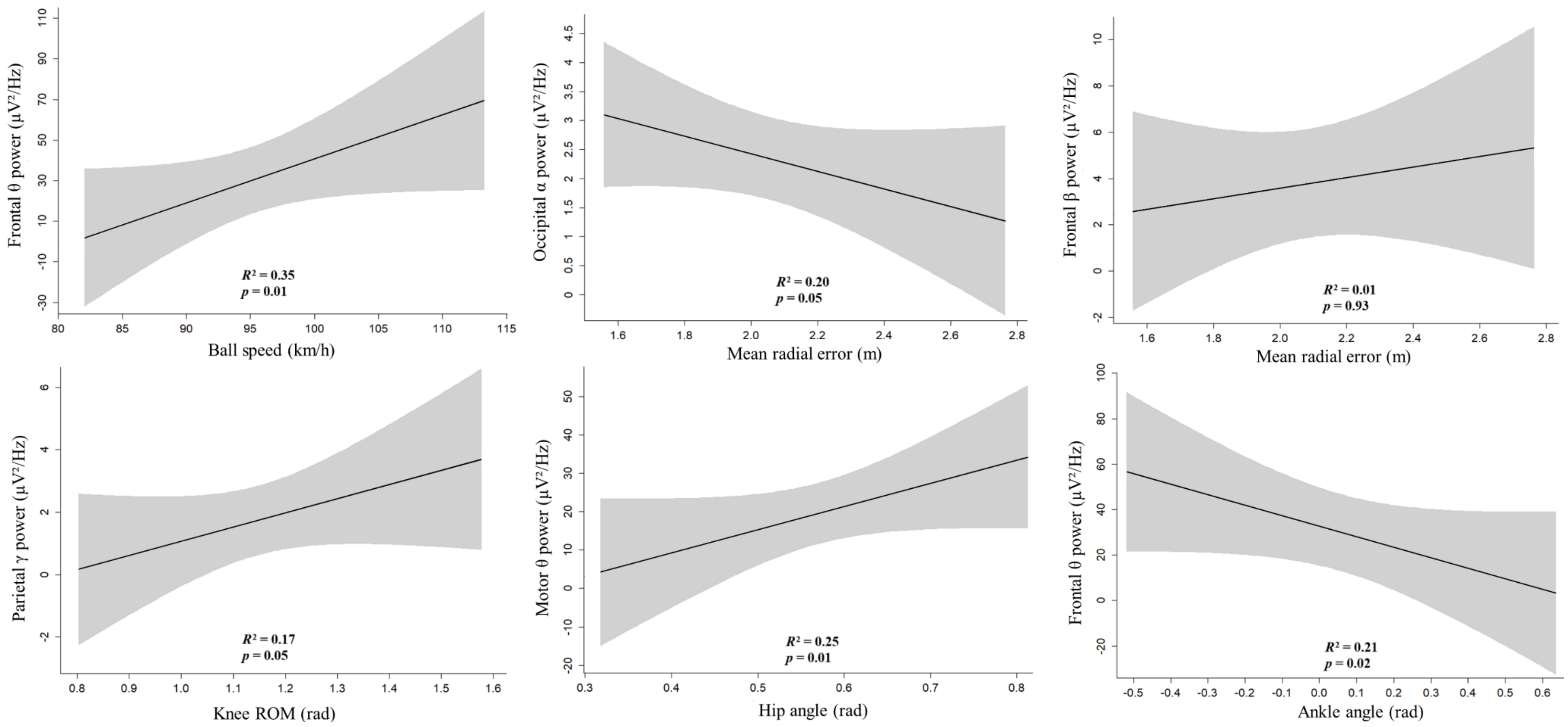


Figure 3.7. General overview of the plots resulting from the associations between EEG spectral power and soccer kicking performance. Note: The shaded area represents the confidence interval of regression line. Hip angle is in reference of extension (-) and flexion (+) and ankle angle is in reference of inversion (+) and eversion (-) movements at impact instant. ROM = range of motion.

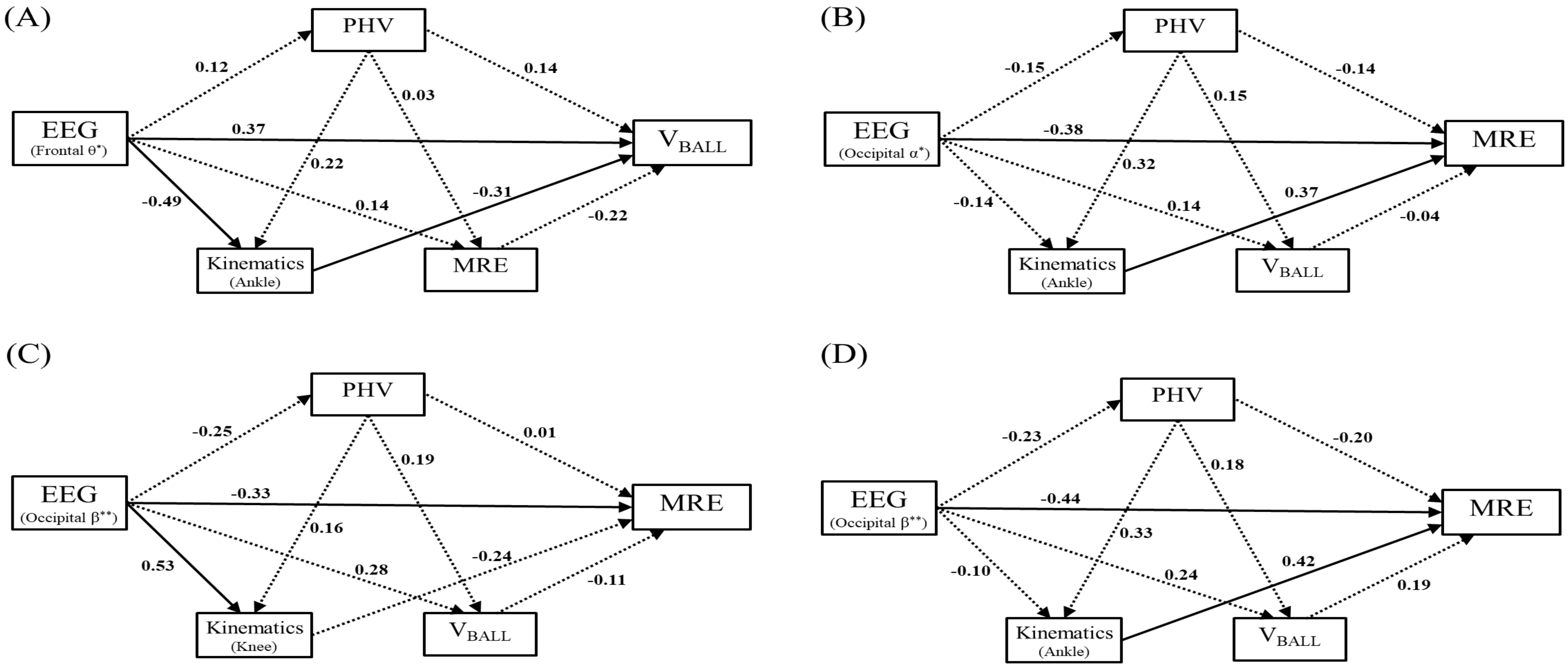


Figure 3.8. Mediational models of the associations between EEG and soccer kicking performance. MRE = mean radial error; PHV = estimated biological maturity (age of peak height velocity); V_{BALL} = ball velocity; ROM = range of motion. (A) model with final outcome being the velocity, where ankle kinematics are in reference of eversion movement; (B) to (D) models with final outcome being the ball placement in the goal, where knee kinematics are in reference of range-of-motion and ankle kinematics are in reference to the plantarflexion movement; *EEG spectral power; **ERS/ERD. The solid continuous lines represent significant associations between two given factors while the dashed lines indicate the absence of statistical significant at the level of $p \leq 0.05$.

Table 3.4. Direct, indirect and total effects obtained from the mediational models including EEG, lower limb kinematics and soccer kicking performance parameters.

	β coefficient	Standard error	Z	*p*-value	Confidence interval (90%)
Model A					
Direct	0.3726	0.16	2.29	0.02	0.11 – 0.64
Indirect	0.1513	0.08	1.87	0.06	0.18 – 0.28
Total	0.1605	0.09	1.70	0.09	-0.01 – 0.32
Model B					
Direct	-0.3857	0.19	-2.01	0.04	-0.76 – -0.01
Indirect	-0.0537	0.10	-0.55	0.58	-0.24 – 0.14
Total	-0.4395	0.22	-2.02	0.04	-0.87 – -0.01
Model C					
Direct	-0.1801	0.30	-0.59	0.55	-0.78 – 0.41
Indirect	-0.1512	0.22	-0.70	0.48	-0.57 – 0.27
Total	-0.3313	0.17	-1.89	0.06	-0.67 – 0.01
Model D					
Direct	-0.4056	0.13	-3.08	0.01	-0.66 – -0.15
Indirect	-0.0065	0.11	-0.06	0.95	-0.22 – 0.20
Total	-0.4121	0.13	-3.18	0.01	-0.67 – -0.16

Note: Each model corresponds to those graphically illustrated in Figure 3.8.

3.5. Discussion

The goal of the current study was to determine whether an association exists between brain activity measured via mobile EEG and concomitant movement kinematics and instep kicking performance in youth soccer players. Most of our initial hypotheses have been confirmed. In sum, both the ball velocity and its placement on the goal target were correlated, generally at a moderate magnitude, with the inter-individual EEG oscillations. In contrast, no differences were observed, for any spectral power measurements, following a simple classification of kicking attempts that successfully attained or not the target. When considering successful (pooled kicks on-target and goals) versus unsuccessful attempts (missed kicks) as well as time-series (ERSP images) rather than only extracted single power values representative of a given epoch, some differences were evidenced. These included: (i) frequent (frontal, motor, parietal and occipital) increased alpha activity (~200 ms to the cycle end); (ii) declines in theta power (frontal, parietal and occipital) mainly around zero time-moment and (iii) augmented beta (motor and occipital) roughly from 50 ms to the end, that collectively were greater during successful compared to missed kicks. High-frequency signals were not always determinant parameters in kicking velocity. Nonetheless, different cortex regions and frequency bands of the EEG signal seemed to play a role in controlling distinct aspects required in the kicking skill (i.e. velocity and accuracy). The occipital alpha power during the preparatory phase prior to the approach run and occipital beta ERS/ERD notably influenced the mean radial error of kicks while ball velocity was more dependent upon the frontal theta power component immediately before foot-ball impact. In addition, these EEG factors generally showed moderate reliability. The results also revealed likely mediation of the ankle kinematics in the association between EEG (frontal theta power) and ball velocity. Among the mediation factors computed here, these only had non-significant influences on the associations between EEG and mean radial error. When significant, ITCs were generally greater in kicks on-target/goal compared to missed kicks over various brain regions only with the exception of in the occipital lobe. In the following paragraphs, interpretations of the observed correlations regarding EEG and performance measures are proposed focusing on the possible role of cerebral inputs to planning and motor responses when kicking.

In the present young soccer players, faster ball velocity during instep kicking was shown to be related to greater cortical activity in the theta band, recorded at the frontal cortex region. This main finding reinforced evidence collated in a review of EEG markers as potential indicators of sports performance. In the review (Cheron et al. 2016), the emerging role of theta oscillations to motor control of sport skills was highlighted and preliminary data presented by the authors in a pilot study (partly reported in that same text–Introduction, pp. 2) also pointed to an occurrence of this specific rhythm, in a frontal channel. Indeed, increased frontal-midline theta spectral power is sensitive in discriminating distinct levels of performance in a variety of goal-directed sports tasks, although the current literature supports this behavior only for upper limb tasks (Baumeister et al. 2008; Doppelmayr et al. 2008; Chuang et al. 2013; di Fronso et al. 2016). Additionally, the quickness of movement in ballistic tasks was previously correlated with the magnitude of brain oscillations in theta domain (Ofori et al. 2015). There is evidence of a substantial participation of frontal cortical activity in movement control during running (Suzuki et al. 2004). Traditionally, central executive processes, which integrate long-term and working memory, are recognised to rely on frontal functioning (Collette and Van der Linden 2002). In our experiment, the cognitive demand can be exemplified by the necessity to direct the ball to a far target while producing adequate velocity levels to avoid placing it outside the goal or a goalkeeper block. The frontal region may also be acting in coupling such complex task parameters. Conversely, excessive frontal theta spectral power may be indicative of high attentional control during a given movement (Haufler et al. 2000; Baumeister et al. 2008; Baumeister et al. 2010; Chuang et al. 2013). This is occasionally deemed as a possible risky strategy since errors can be generated in the task in relation to accuracy demands (Kao et al. 2013). However, in our study, there was no statistical confirmation of a velocity-accuracy trade-off in the experiment carried out (e.g. non-significant correlations between these components – see Figure 3.8). Hence, some sustained concentration in the final phase of soccer kicking may help produce faster ball velocity.

To the extent of our knowledge, most studies relevant to current work have attempted to model the relationships between EEG and the outcomes of sports skills, using either indirect (Tharawadeepimuk and Wongsawat 2017; Pluta et al. 2018) or direct performance measures (Collins et al. 1991; Chuang et al. 2013; Christie et al. 2017). However, these have not considered the characteristics of the movement technique that can mediate this process, as done in the current study. Here, it is noteworthy that the frontal theta power, in addition to its influence on the development of high ball velocity, also showed important correlations with the hip flexion and ankle eversion angular joint displacements at the foot-ball impact instant. Previous studies generally confirm the benefits of movement patterns characterized as high hip flexion and ankle eversion in reaching maximal ball velocity when performing instep kicks (Katis and Kellis 2010; Ishii et al. 2012; Palucci Vieira et al. 2021a). In particular, greater ankle eversion can permit an increase in the foot-ball contact area during instep kicking. Consequently, the programming of motor action to position the foot properly and produce high ball velocity is supported by mutual relationships between frontal theta power, ankle movement and ball velocity. Differently and contrary to our hypotheses, gamma power was associated only with the knee ROM and the motor region of the cortex showed influence more frequently in hip movements as compared to knee (single significant correlation) and ankle/foot movements (no associations). These results suggest that there is likely a greater role of the motor cortex in the proximal joint involved in kicking than in the distal endpoint; and high-frequency brain signals may not be necessarily responsible for the movement velocity in this skill. On the other hand, motor cortex-hip relationships may signify that foundation signals to control kicking movement are sent to this specific joint. In fact, considering the traditional somatotopic organisation of the sensorimotor cortex, despite lower limb segments appears to recruit almost the same region, hip is located closer to the scalp as compared to ankle and foot specially in output region (motor cortex) (de Klerk et al. 2015) and this could help explain the above-mentioned result. The correlations reported between delta power in various ROIs and kick outcomes (i.e. ball velocity) require careful interpretation due to the fact that oscillations in this band have been removed from the regression models because they do not meet the established assumptions; their real contribution to lower limb kinematics is also uncertain (Castermans et al. 2014), can be highly coupled with high-frequency cortical activity (Händel and Haarmeier 2009) and disappear when considering ERS/ERD values.

Here, a single EEG spectral power measure directly associated with the ball placement error in the designed target on the goal was identified. The greater the occipital alpha power in the preparatory phase of kick immediately before the approach run to the ball, the lower the observed mean radial error. Conversely, occipital beta ERS/ERD was negatively related to the ball placement error; the higher the occipital beta ERD expression, the farther from target the kicks occurred. Augmented expression of occipital alpha EEG prior to execution of goal-directed skills also induced enhancements in subsequent accuracy in completing other sport tasks that are visuomotor in nature (Haufler et al. 2000; Loze et al. 2001; di Fronso et al. 2016). There are some possible putative mechanisms by which increased alpha power levels generally benefit athletic performance. As for example, alpha oscillations may reflect a more relaxed behavioral state where unnecessary/conflicting processes are inhibited to a greater degree (Klimesch et al. 2000; Goldman et al. 2002; Budnik-Przybylska et al. 2021) thus inducing a greater focus on a given desired task (Cheron et al. 2016). The visual behavior associated with higher observed levels of this specific EEG marker also deserves scrutiny. During the aiming phase of kick, players are collecting information about the environment (e.g. goalkeeper, ball and target positions). At this stage the system begins to make the calculations aiming to perform the most precise movements as possible. In this sense, it is recognized that a longer time fixing the gaze on the target during the immediately pre-kick phase (e.g. quiet eye; see Nagano et al. (2006)) and, inversely, reduced time looking at environmental distractors such as the goalkeeper (Noël and Kamp 2012), both assist in obtaining good kicking accuracy. This is further confirmed in a previous experiment which tested among ‘target-focused’ or ‘keeper-focused’ strategies in soccer kicking, where the former resulted in better shot performance (Wood and Wilson 2010). Despite information on eye movements not being captured in the present study, eye quietness has been positively correlated with concomitant determination of occipital alpha EEG (Janelle et al. 2000; Gallicchio and Ring 2020). Notwithstanding, occipital beta ERD linked with poor ball placement may be indicative of a potentially excessive attempt to capture visual information later in the kick cycle (Cordones et al. 2013) that was not beneficial to targeting the goal. Therefore, the effectiveness of placing the ball in the goal–upper corners–during soccer kick attempts at goal from the edge of the penalty area, apparently requires a mental state of focus and restricted selection of environmental information presented during the task while simultaneous control over the player’s state of excitability also seems essential while kicking. However, unlike ball velocity, it was not possible to completely clarify the possible path through which cortical activity may influence the kinematics of movement and subsequent ability to place the ball based only on the measurements considered in our work. Future studies using advanced EEG calculations (connectivity, chaotic and source estimation metrics) and statistics (e.g. multilayer neural network) may provide additional pertinent data.

The analysis of missed kicks showed these were generally linked to less consistent neural responses. This is illustrated by lower ITC values observed over various regions (frontal, motor and parietal) during missed kicks as compared to kick attempts correctly delivered to the goal or target in its upper corners. The only exception was the occipital theta manifestation later in the analysed window that was more repeatable in kicks outside the goal. Of note, suppression but not augmentation of occipital theta band activity was demonstrated previously to benefit visuomotor performance (Beatty et al. 1974) and this was the case here earlier in the kick cycle. Additionally, from the ERSP analysis it was possible to observe again that alpha activity was raised to a greater extent in successful as compared to missed kicks, over all brain regions considered. Since alpha oscillations is often related to a decrease in cortical activation (Hatfield et al. 2004), this can provide further evidence favouring the "neural efficiency hypothesis" that associates proficient sports performance to low demands placed upon cortical resources at some point; indeed this theory postulates that successful behaviour in athletes occurs as a function of experiencing a default mode or "automatic" network functioning, in which less energy is spent in producing the more skilled actions (Haufler et al. 2000; Hatfield et al. 2004; Del Percio et al. 2009; Cheron et al. 2016; di Fronso et al. 2016; Duru and Assem 2018; Budnik-Przybylska et al. 2021). Owing to the fact that a rapid deceleration of the body centre-of-mass during the last stride is related to subsequent performance in kicking (Augustus et al. 2021) and a direct association exists between theta waves with voluntary movement velocity (Cheron et al. 2016; Ofori et al. 2015), occurrences of more pronounced reductions in theta power in successful kicks–observed near the transition between approach run to the ball and kick movement itself–suggest that such EEG pattern can be important to players regulate their velocity in last step before ball contact in order to obtain effective intersegmental control and/or allow adjustments during the impact phase. Finally, concerning the increase identified in beta (e.g. motor) power expression at ~50 ms, this could characterise successful kicks as having greater levels of the so called beta rebound, a mechanism that aids re-calibration of the motor system after a forcibly interrupted movement (i.e. approach run cessation and commencement of impact phase of kicking) (Mustile et al. 2021).

The present study adds to the current knowledge about the motor control of kicking ability in soccer although several limitations must be acknowledged, implying caution in the interpretations and extrapolations made. Firstly, we chose to group electrodes of both hemispheres together with midline sites to obtain representative EEG measures for each region. Despite a previous study showing that EEG responses during low effort-high accuracy demands may be similar (Collins et al. 1991), future investigations should determine separately the contribution of each cerebral hemisphere to the soccer kicking performance in relation to players' lateral preference. A lack of concomitant collection/analysis of eye electrooculographic (EOG) and muscle electromyographic (EMG) activities related to kicking action prevents direct identifying EOG-EMG contamination of EEG signals [e.g. respectively in theta (Gasser et al. 1985) and gamma (Goncharova et al. 2003) waves] limiting consequent application of advanced data filtering procedures (Jiang et al. 2019; Mucarquer et al. 2020). Also, given our resources, the kinematics of the kick cycle were not electrically synchronized with the EEG equipment. Even reporting inter-trial reliability, it may have added some undesirable variance to the dataset. Bearing in mind that the experiment was conducted on-field, factors difficult to control across testing days (e.g., lighting) could have led to natural variations in EEG spectral power, specially the parieto-occipital alpha band (Baumeister et al. 2010). While only two of the subjects declared that the EEG apparatus used might have negatively interfered with their usual movement pattern, continual developments in technology will help improve future study designs. Regarding potential applied directions for youth athletes, obtaining accurate ball placement requires players entering into a relatively relaxed mental state which may result from: (i) anticipated programming (e.g. desired ball location defined in advance) coupled to target-focused eye behavior; (ii) avoidance of giving much weight to possible environmental distractors during preparatory phase and (iii) caution when collecting or attempts to gather visual information (feedback) available later in the kick cycle. Finally, when looking to attain fast ball velocity in kick attempts made from the edge of penalty area, (iv) volitional attentional control of the lower limb movement (i.e. ability to engage in a sustained concentration process) seems necessary during the impact phase of soccer kicking action.

3.6. Conclusion

The current study expands the notion that EEG has potential for use in forecasting sports performance, specifically in a complex manipulative task using the lower limbs in soccer. Here, we demonstrated that increased frontal theta power in the impact phase and occipital alpha in the preparatory period predict better instep kicking performance in youth players, inducing respectively faster ball velocity and lower radial error. Thus, the signalling at cortical level that may be determinant for the velocity and accuracy components of kicking varies notably in relation to the brain region and frequency band. These kicking components demands prominent and paradoxical central control mechanisms during the movement planning and execution (i.e. respectively more automaticity and sustained top-down attention), highlighting the complex nature of ball kicking aiming at a far target. While insights on central inputs that are likely acting in controlling kick velocity, can be derived from the mutual relationships observed between EEG, ankle kinematics and subsequent ball velocity, the central mechanisms responsible for motor responses determining the effective ball placement of the ball in the goal when kicking remain unclear.

3.7. References

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Supplementary online material 1. Intraclass correlation coefficients (ICC) indicating reliability of EEG spectral power measures taken between repeated kicking trials.

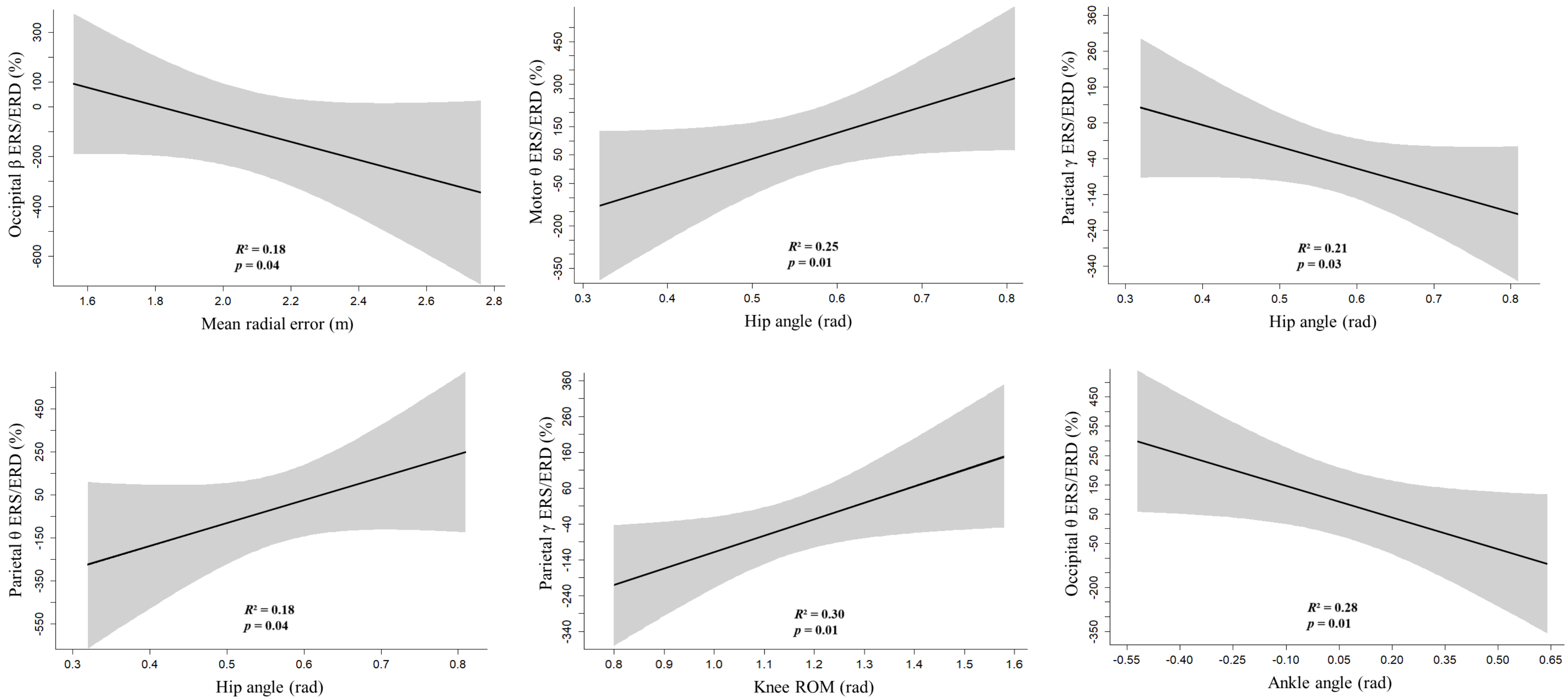
		ICC per phase of kick cycle			
Region	**band**	-6 to -3 s	-3 to -1 s	-1 s to ~kick	Whole trial
Frontal	δ	0.47 (0.35; 0.62) *poor*	0.27 (0.18; 0.42) *poor*	0.72 (0.62; 0.82) *moderate*	0.94 (0.91; 0.97) *excellent*
	θ	0.72 (0.62; 0.82) *moderate*	0.54 (0.42; 0.68) *moderate*	0.66 (0.55; 0.78) *moderate*	0.57 (0.45; 0.71) *moderate*
	α	0.90 (0.86; 0.94) *good*	0.73 (0.63; 0.83) *moderate*	0.69 (0.58; 0.80) *moderate*	0.85 (0.78; 0.91) *good*
	β	0.94 (0.91; 0.97) *excellent*	0.96 (0.94; 0.98) *excellent*	0.80 (0.72; 0.88) *good*	0.94 (0.91; 0.97) *excellent*
	γ	0.77 (0.68; 0.86) *good*	0.84 (0.76; 0.90) *good*	0.72 (0.62; 0.82) *moderate*	0.90 (0.85; 0.94) *good*
Motor	δ	0.21 (0.12; 0.34) *poor*	0.11 (0.05; 0.21) *poor*	0.53 (0.41; 0.67) *moderate*	0.70 (0.60; 0.81) *moderate*
	θ	0.72 (0.62; 0.82) *moderate*	0.10 (0.05; 0.21) *poor*	0.56 (0.45; 0.70) *moderate*	0.59 (0.47; 0.72) *moderate*
	α	0.83 (0.76; 0.90) *good*	0.43 (0.31; 0.58) *poor*	0.50 (0.38; 0.65) *moderate*	0.75 (0.66; 0.85) *moderate*
	β	0.88 (0.83; 0.93) *good*	0.75 (0.65; 0.84) *moderate*	0.70 (0.60; 0.81) *moderate*	0.86 (0.79; 0.92) *good*
	γ	0.64 (0.53; 0.77) *moderate*	0.78 (0.70; 0.87) *good*	0.62 (0.51; 0.75) *moderate*	0.76 (0.66; 0.85) *good*
Parietal	δ	0.40 (0.29; 0.56) *poor*	0.31 (0.21; 0.47) *poor*	0.46 (0.34; 0.61) *poor*	0.54 (0.42; 0.68) *moderate*
	θ	0.74 (0.64; 0.84) *moderate*	0.49 (0.37; 0.64) *poor*	0.54 (0.42; 0.68) *moderate*	0.73 (0.63; 0.83) *moderate*
	α	0.79 (0.70; 0.87) *good*	0.54 (0.42; 0.68) *moderate*	0.62 (0.51; 0.75) *moderate*	0.85 (0.78; 0.91) *good*
	β	0.92 (0.88; 0.95) *excellent*	0.83 (0.75; 0.89) *good*	0.75 (0.65; 0.84) *moderate*	0.89 (0.83; 0.93) *good*
	γ	0.45 (0.33; 0.60) *poor*	0.82 (0.75; 0.89) *good*	0.62 (0.50; 0.75) *moderate*	0.91 (0.86; 0.95) *excellent*
Occipital	δ	0.41 (0.28; 0.58) *poor*	0.14 (0.07; 0.27) *poor*	0.54 (0.41; 0.70) *moderate*	0.65 (0.53; 0.78) *moderate*
	θ	0.60 (0.47; 0.75) *moderate*	0.48 (0.35; 0.64) *poor*	0.47 (0.34; 0.63) *poor*	0.61 (0.48; 0.75) *moderate*
	α	0.59 (0.46; 0.73) *moderate*	0.41 (0.28; 0.58) *poor*	0.40 (0.28; 0.57) *poor*	0.70 (0.59; 0.82) *moderate*
	β	0.79 (0.70; 0.88) *good*	0.71 (0.60; 0.83) *moderate*	0.59 (0.46; 0.74) *moderate*	0.85 (0.77; 0.91) *good*
	γ	0.73 (0.62; 0.84) *moderate*	0.71 (0.59; 0.82) *moderate*	0.66 (0.54; 0.79) *moderate*	0.81 (0.72; 0.89) *good*

ICC values (upper; lower limits) and judgment.

0 **0.5** **1**

Supplementary online material 2. Intraclass correlation coefficients (ICC) indicating reliability of EEG ERS/ERD measures taken between repeated kicking trials.

Region	**band**	ICC	Confidence limits	Judgement
Frontal	δ	0.48	0.36 to 0.64	*Poor*
	θ	0.36	0.24 to 0.52	*Poor*
	α	0.24	0.05 to 0.83	*Poor*
	β	0.35	0.24 to 0.52	*Poor*
	γ	0.82	0.74 to 0.89	*Good*
Motor	δ	0.03	-0.01 to 0.12	*Poor*
	θ	0.09	0.02 to 0.20	*Poor*
	α	0.52	0.39 to 0.67	*Moderate*
	β	0.01	-0.03 to 0.30	*Poor*
	γ	0.25	0.15 to 0.41	*Poor*
Parietal	δ	0.29	0.18 to 0.44	*Poor*
	θ	0.38	0.26 to 0.54	*Poor*
	α	0.77	0.67 to 0.86	*Good*
	β	0.65	0.53 to 0.77	*Moderate*
	γ	0.81	0.73 to 0.88	*Good*
Occipital	δ	0.51	0.37 to 0.68	*Moderate*
	θ	0.32	0.20 to 0.49	*Poor*
	α	0.53	0.39 to 0.69	*Moderate*
	β	0.75	0.63 to 0.85	*Moderate*
	γ	0.23	0.03 to 0.93	*Poor*



Supplementary online material 3. General overview of the plots resulting from the associations between EEG ERS/ERD and soccer kicking performance. *Note*: The shaded area represents the confidence interval of regression line. Hip angle is in reference of extension (-) and flexion (+) and ankle angle is in reference of inversion (+) and eversion (-) movements at impact instant. ROM = range of motion.

CHAPTER 4

SLEEP-DERIVED PARAMETERS AND THEIR EFFECTS ON SOCCER KICKING

4. PAPER 3 – Low sleep quality and morningness-eveningness scale score may impair ball placement but not kicking velocity in youth academy soccer players [(4)]

Palucci Vieira, L.H., Lastella, M., da Silva, J.P., Cesário, T.A.I., Santinelli, F.B., Moretto, G.F., Santiago, P.R.P., & Barbieri, F.A. (2022). Low sleep quality and morningness-eveningness scale score may impair ball placement but not kicking velocity in youth academy soccer players. *Science and Medicine in Football* [Epub ahead of print]. **https://doi.org/10.1080/24733938.2021.2014550**

[(4)] APPENDIX 4 - document obtained allowing reuse of this previously published study in the current thesis

4.1. Abstract

The current study examined the possible relationships between one-off single night sleep metrics and subsequent kicking performance in a youth soccer context. Twenty-eight under-17 academy players (15.9±0.8 years-old) completed a kick testing protocol consisting in 20 attempts, 18 m from the goal and against a goalkeeper. Four digital video cameras (240 Hz) allowed to determine 3-D approach run, lower limb and ball velocities. Two additional cameras (60 Hz) were used to calculate 2-D mean radial error, bivariate variable error and accuracy. Over 24 h prior to testing, players were monitored by wrist actigraphy to determine their sleep indices. Self-reported sleep quality, sleepiness and chronotype scale scores (Horne and Östberg morningness-eveningness questionnaire) were also collected immediately before kicking experiment. Multiple linear regressions indicated that wake up time and chronotype contributed to 40% of mean radial error. Self-reported sleep quality influenced respectively on 19% and 24% of accuracy and bivariate variable error variances. Taken together self-reported sleep quality and wake up time explained 33% of accuracy (all $p<0.05$). Indicators of kicking velocity were non-significantly correlated with sleep (r = -0.30–0.29; $p>0.05$). One-off sleep measures showed some sensitivity to acutely detect inter-individual oscillations in kicking performance. Low perceived sleep quality, later wake up time and a chronotype toward evening preference seems either related to immediately subsequent worst ability of ball placement when kicking. Monitoring sleep-wake transition and perceived sleep quality may be important to help prevent acute performance declines in targeting the goal during kick attempts from the edge of penalty area.

Keywords: recovery, chronotype, skill-related performance, human movement, kinematics, team sports.

4.2. Introduction

Sleep is fundamental in day-to-day recovery of physical capacity and motor skills (Fox, Scanlan, Stanton, & Sargent, 2020b; Nédélec, Halson, Abaidia, Ahmaidi, & Dupont, 2015; Walsh et al., 2021). A night with reduced sleep may disrupt central nervous system (CNS) functioning such that it would compromise visuospatial perception, decision-making and movements' execution (Fullagar et al., 2015). At present, there are contradictory findings related to sleep duration and quality and its potential impact on sport performance aspects (Walsh et al., 2021). While some evidence confirms that poor sleep (either perceived/actigraphy-derived quality or duration) has been associated with detrimental effects [e.g. youth rifle, netball or handball; (Brandt, Bevilacqua, & Andrade, 2017; Juliff, Halson, Hebert, Forsyth, & Peiffer, 2018; Suppiah, Low, Choong, & Chia, 2016)], other data indicate that it had no impact on subsequent performance [young adults long-distance runners or swimmers; (Chennaoui et al., 2016; Lastella, Lovell, & Sargent, 2014)]. These observations may suggest that the influence of sleep is dependent on various demands of each sport and the age, in which developing players engaged in practices requiring goal-directed skills seems more negatively affected by a poor sleep pattern. Yet sleep-performance relationships are currently little explored in young football codes (Fox et al., 2020b).

While the general sleep recommendation for teenagers is longer than those for adults [14–17 years: 8–10h and 18–25 years: 7–9h; Hirshkowitz et al. (2015)], several studies have demonstrated that young soccer players obtain less sleep than their age-specific lower limits (Fowler et al., 2017; Robey et al., 2014; Whitworth-Turner, Di Michele, Muir, Gregson, & Drust, 2019) as well as sleep duration and quality (e.g. efficiency) shown a high inter- [4.9–10.3h and 51–95% in Fowler et al. (2017)] and intra-individual variability [1.03±0.5 h and 5±3% in Whitworth-Turner, Di Michele, Muir, Gregson, & Drust (2018)]. To date, it is unclear the acute impact of individual's sleep durations experienced by young soccer players or whether sleeping for less than the general benchmark may harm subsequent skill-related performance. The same does not hold true for physical performance, training and well-being components to which associations with sleep indices have been reported (Figueiredo et al., 2021; Merayo et al., 2021; Robey et al., 2014). Kicking accuracy in soccer is highly variable between repeated attempts (Berjan Bacvarevic et al., 2012) and across testing sessions (Russell, Benton, & Kingsley, 2010). In senior standards, variations in sleep duration, latency and efficiency produced no effects on match kicking accuracy (Abegg, 2015; Fowler, Duffield, & Vaile, 2014). High standards of kicking performance are associated with greater chances of winning in the sport of soccer but match-related statistics are arguably influenced by non-controllable contextual factors, barriers still exist in computing advanced kick technique features during actual game-play and results from senior players cannot be readily extrapolated to youth (Palucci Vieira et al., 2021a). Kirschen, Jones, and Hale (2020) collated specifically the independent effects of individual's sleep or its manipulations upon sports technical/tactical tasks and verified that restricted or extended sleep were associated respectively with next day impaired and improved performance (e.g. accuracy) in a range of modalities. Again, no studies addressing ball kicking drills or youth were systematically identified (Kirschen et al., 2020).

Irregularities in sleep are shown to occur among adolescents exhibiting preference towards nocturnal activities [i.e. evening chronotype; Koscec, Radosevic-Vidacek, & Bakotic (2014)]. Both suboptimal sleep and chronotype seems linked with more pronounced negative consequences on prolonged submaximal activities as compared to short-term maximal performance outputs (Nédélec et al., 2015; Vitale & Weydahl, 2017). Meanwhile, morning-type youth soccer players (14.9±1.79 years-old) exhibited peak performance on selected motor skills comprising agility, aerobic endurance and explosive leg power early in the day compared to evening peers (Roveda et al., 2020) whereas a total sleep deprivation condition in a cohort aged 14–19 worsened kicking accuracy computed as the number of successful hits in an empty wall 5 m apart from kick mark (Pallesen et al., 2017). Some methodological issues notably requires modification in kick testing according to a recent critique. Examples include a lack of opponents, very short-distance kicks and selective reports generally provided in research (non-concomitant measures of accuracy and velocity; Palucci Vieira et al., 2021a). Furthermore, sleep deprivation is rare in athletic populations thereby compromising external validity when adopting solely this condition (Lastella et al., 2014;

Walsh et al., 2021). Therefore, the present study aimed to investigate the possible relationships between one-off sleep metrics and subsequent kicking performance in a youth soccer context.

4.3. Materials and Methods

4.3.1. Participants

Thirty under-17 soccer players from a regional academy in Brazil (first place in São Paulo Interior League 2020) were initially recruited. The sample size calculation was done (G*Power© v.3.1.9.2, Universität Kiel–Germany) considering the assumption of possible strong correlations ($r > 0.50$) (Fox et al., 2020b) between sleep indices and performance in youth athletes and indicated a minimum required sample of 27 subjects (power=80%, α=0.05). To be included, players have reported the absence of musculoskeletal injuries that might have compromised in completing field test; no history of severe sleep disorders and if were not taking CNS medication. As exclusion criteria, players who napped during the monitoring period and/or failed in completing both phases (sleep monitoring and kick assessment) were not considered for further analyses. All procedures were approved by the local University Human Research Ethics Committee (protocol CAAE85994318.3.0000.5398). Players and their legal guardians signed respectively assent and consent forms confirming participation of the athlete as a volunteer. Age from peak height velocity (PHV) was estimated (Mirwald, Baxter-Jones, Bailey, & Beunen, 2002). As part of a regular schedule, players attended to training 3–4 days/week (1 conditioning session without ball drills, 1 session of isolated technical skills (e.g. crossing, heading and shooting) and 1–2 specific sessions including simulated game-play, sub-phases (e.g. GK+1 vs. 1) and/or small-sided/conditioned games) plus one official match on weekends.

4.3.2. Testing procedures

The players were firstly monitored using wrist actigraphy which allowed to record sleep quality and duration metrics in the night immediately before kick testing, completed in mid-week days (15:00–17:00h) during the off-season period. Prior to the field experiment, performed on natural grass official pitch, a standard warm-up was carried out [4 minutes of running (3/4 Borg–CR10 scale) plus dynamic stretching exercises]. Thereafter, participants undertook a testing protocol in which they kicked stationary balls (FIFA-approved, PENALTY® size 5–70cm Ø, weight=430g, air pressure=0.7 atm) positioned 18 m away from the midpoint goal line, using the instep region of the dominant foot and aiming at the centre of 1 x 1 m targets allocated in the goalpost (upper corners). The kick location (i.e. distance to the goal) was match-derived and age-specific considering the average distance where shots occurred in relation to the nearest goal point during official tournament of the category investigated [dataset (re)analysed from Palucci Vieira et al., (2019)]. Two youth goalkeepers with similar anthropometrics/skill level (according to information provided by the coaching staff; 68–71 kg; 180–181 cm) were recruited and asked to try block the shots, maintaining a standardised static posture, 1.2 m in front of the midpoint goal line (ink demarked). They were also told to avoid moving previously to contact of kickers with the ball (Navarro et al., 2013) and received no prior knowledge of the location where the kicks were directed (Makaruk, Porter, Bodasińska, & Palmer, 2020). To the outfield players, the following instruction was provided: "kick to strike the target's centre while avoid goalkeeper from intercepting the ball". The approach run was constrained to begin at 3.5 m (45°) from the initial ball position. In total, 20 kicking attempts were offered, distributed into blocks of five (Amiri-Khorasani, Osman, & Yusof, 2011) interspersed with a 3-minute recovery interval between them and 40 s separating repeated kicks (van den Tillaar & Fuglstad, 2017). Seven attempts were directed to each goal side and six requested to aim its centre, in order to prevent goalkeepers from identifying any predictable sequence. The order of kicks was randomized (https://www.random.org/) in relation to the goal location they aimed for.

4.3.3. Sleep quality and duration measures

Actigraphy-based devices [1 Hz–ActTrust®–Condor Instruments, São Paulo–Brazil; Albu, Umemura & Forner-Cordero (2019)] were used in participants' non-dominant wrist (recording mode: PIM/TAT/ZCM). These were delivered to players 24 h before field assessment (TAT threshold [default] = 1024). Through offline treatment of exported data and using Sadeh's algorithm to identify sleep-wake phases (Sadeh, Sharkey, & Carskadon, 1994), it was possible to record the bedtime, wake up time, time of lights out, time in bed, total sleep duration (automatic algorithm: probability of sleep output according to Sadeh threshold ≥ 0 (sleep epoch) and < 0 (wake epoch), based on ZCM [activity counts] input), wake after sleep onset, latency (amount of time separating the time of lights out and sleep starts), efficiency (total sleep duration as a percentage of time in bed) and number of awakenings (Fowler et al., 2017; Lastella, Roach, Halson, & Sargent, 2015; Roach et al., 2013; Whitworth-Turner et al., 2018). Immediately prior to commencing kick protocol, self-reported measures were collected including (a) sleep quality based on a Likert scale ranging from 1 to 5 (1-very poor, 2-poor, 3-average, 4-good, 5-very good) (Juliff et al., 2018); (b) perceived sleepiness (Karolinska Sleepiness Scale; Kaida et al. (2006) and (c) chronotype scale score, computed as a sum of all items contained in the Horne and Östberg morningness-eveningness questionnaire, translated into Portuguese (Benedito-Silva, Menna-Barreto, Marques, & Tenreiro, 1990).

4.3.4. Kicking velocity parameters

Spherical markers (25mm Ø) were attached externally on the participant's lower dominant limb in the following bone protuberances: anterior superior and greater femoral trochanter (also on the non-dominant side), lateral malleolus, calcaneus and distal phalanx of the fifth metatarsal head. For three-dimensional (3-D) kinematic analysis, four digital video cameras (GoPro® Hero 7 Black Edition, GoPro GmbH, München–Germany) tripod-mounted and operating at 240 Hz (1280x960 pixel; 1/480s shutter speed; Wide field-of-view mode; NTSC standard) and synchronized via Wi-Fi (GoPro smart remote control) were distributed around the region where kicks occurred in order to cover overall events of interest (passive markers and ball take-off). After semi-automatic digitisation of marker's trajectories, calibration (~3.6 x 3.2 x 1.3m) and 3-D reconstructions in DVIDEOW environment (Figueroa, Leite, & Barros, 2003), data matrices were exported to MATLAB (MathWorks Natick, MA–USA). Using a specific algorithm (Rossi, Silvatti, Dias, &

Barros, 2015) the radial distortion caused by the camera lenses was appropriately corrected, ensuring acceptable accuracy levels to the reconstructed data (random error=1.5 cm; systematic error=2.3 cm). The time-series were extrapolated in 20% and then treated by a dual filter (Butterworth+robust non-parametric locally weighted function rloess) aiming at minimize issues derived from impact (Palucci Vieira et al., 2021b). Smoothing parameters (cut-off frequency=25 Hz and span=0.1, respectively) were selected after residual analysis. The following dependent variables were determined from the centroid of coordinates: approach run velocity (using hip markers during the duration of the attempt), foot velocity (considering the markers on malleolus, calcaneus and metatarsal head three frames before impact), ball velocity (from its trajectory in ten available airborne frames following impact) and the ratio between two last factors [for more information: Palucci Vieira et al. (2021b)].

4.3.5. Ball placement

Two additional video cameras (same models as above) adjusted in 60 Hz (1920x1080 pixel; Linear field-of-view mode) were positioned one in front of the goal plane and another one above the goal line to determine measures derived from ball placement after kicking. One operator digitised the 2-D ball position (using images from the frontal camera) in the moment it crosses the goal line, which in turn was determined by the synchronization with the camera allocated over the line. These analyses were conducted in the same software used in obtaining velocity parameters and followed similar procedures. For each attempt excepting centralized kicks, it was computed the Euclidean distance between the ball and target centre, and subsequently calculated the mean radial error, bivariate variable error, accuracy as a compound of the two first measures (Vieira et al., 2018) and percentage of kicks on-target.

4.3.6. Statistical analysis

Firstly, the data distribution was checked using the Shapiro–Wilk’s test, kurtosis, skewness and visual inspection. Given the rejection of the normality assumption, the dataset was log-transformed. Test-retest reliability was computed for key kicking measures through intraclass correlation coefficient (ICC), Pearson's product–moment correlation coefficient (r), coefficient of variation (CV), ratio limits of agreement (RLOA) and minimum difference (MD). Between-attempts comparisons were performed using a repeated measures ANOVA to evaluate consistency in kicking measures across the experiment. Data sphericity was analysed by the Mauchly test and, when necessary, a Greenhouse-Geisser correction was applied. Paired Student's *t* test compared the performance between kicks directed to the two distinct goal sides and test–re-test. Separate unpaired Student's *t* test were used to compare kicking performance and sleep measures among two subgroups of players formed considering total sleep duration cut-points equals to amounts of (a) 8 hours (generic threshold; (Hirshkowitz et al., 2015); (b) 8.4 hours (soccer-specific perceived sleep need) and (c) 7 hours sleeping (soccer-specific traditional sleep duration; (Sargent et al., 2021)). Effect size measures were calculated as the Cohen's *d* (0.20, *small*; 0.50, *moderate*; and 0.80, *large*) and partial eta squared η^2 (0.01, *small*; 0.06, *moderate*; and 0.14, *large*). In addition, the median-split technique was used to dichotomize players presenting "best" and "worst" performance considering all kicking outcome measures. Subsequently, to test the diagnosis properties of sleep-derived indices on capturing differences among these created group of players, the receiver operating characteristics (ROC) analysis was used. Area under the curve (AUC) was deemed as having no accuracy (0.50), good accuracy (0.70) to perfect accuracy (1.0) (Menaspà, Sassi, & Impellizzeri, 2010; Dardouri et al., 2014). Partial correlations controlling for chronological age and body sizes (weight, height) (Hunter et al., 2021) were computed between sleep parameters and kicking performance indicators. Magnitude of correlations (r, 90% confidence interval) were assessed qualitatively as: ≤0.1 (*trivial*); >0.1–0.3 (*small*); >0.3–0.5 (*moderate*); >0.5–0.7 (*large*); >0.7–0.9 (*very large*) and >0.9–1 (*almost perfect*). Confidence intervals (CI) were estimated using bootstrapping re-sampling to 1000 (sportsci.org/2012/wghboot.htm). Stepwise multiple linear regressions were used to determine the relative contribution of sleep variables to the variance in kicking performance metrics. Models constructed respected the homoscedasticity, independence, normal distribution and no multicollinearity assumptions (Hair, Black, Babin, Anderson, & Tatham, 1998). For those parameters showing significant shared variance, structural equation modelling (SEM) were ran to test for the possible mediational effects of individual's level of estimated maturity (PHV), actigraphy-derived and self-reported selected sleep indices. All statistical analyses were performed with a significance level of $p \leq 0.05$ in IBM SPSS Statistics (v.25, IBM Corp. ©, USA) while plots of correlations and regressions were drawn respectively in Origin (v.8, OriginLab Corp., USA) and R environment (R Studio v.1.2.5042; The R Foundation for Statistical Computing, Austria).

4.4. Results

4.4.1. Overview

Table 4.1 shows a general overview of the outcomes (means, standard deviations, confidence intervals, minimal and maximal values) and according to subgroups. Two participants initially recruited were excluded since they experienced diurnal naps in the monitoring period (self-reported and confirmed by actigraphy outputs), resulting in a final sample of 28 players (mean ± standard deviation [range]: 15.9±0.8 [14.1–16.9] years-old; 62±9.7 [40–89] kg, 173±9 [149–185] cm; PHV = 1.95±0.70 [0–3.4] years from peak height velocity). The subgroups of participants who showed a total sleep duration respecting the 7, 8 and 8.4 h cut-points were composed respectively by 17, 12 and 10 players while 11, 16 and 18 individuals slept for less than the mentioned thresholds on the night prior to the kick testing, respectively.

Test-retest reliability analysis of the kicking protocol was conducted in 11 players (16.5±0.8 years-old; 63.8±12.3 kg, 171±9 cm; PHV = 2.14±0.78 years from peak height velocity) who completed two testing sessions on separate days. No significant differences accompanied by *small* effect sizes were observed across testing sessions regarding ball velocity (test: 26.03±2.55; re-test: 27.36±2.84 m/s, $t_{(10)}$= -1.542; p = 0.15, d = -0.49; ICC = 0.48, p = 0.056; r = 0.49, p = 0.13; CV = 9.3%; RLOA = 1.015 × / ÷ 0.067; MD = 1.27 m/s) and mean radial error (test: 1.94±0.45; re-test:

1.80±0.58 m, $t_{(10)}$= 0.406; *p* = 0.41, *d* = 0.27; ICC = 0.32, *p* = 0.16; r = 0.33, *p* = 0.32; CV = 29.8%; RLOA = 1.040 × / ÷ 4.343; MD = 0.25 m).

Between-attempt comparisons revealed that kicking performance measures generally kept similar throughout field experiment (e.g. ball velocity: $F_{(6.128,\ 153.211)}$=0.841, *p*=0.54, η^2=0.033; and distance between the ball and the target: $F_{(7.095,\ 156.090)}$=0.604; *p*=0.75; η^2=0.027). Likewise, there were no significant differences in kick performance when directed to the contralateral or ipsilateral side of the goal ($t_{(27)}$=-1.473 to -1.232; *p*=0.15–0.23; *d*=0.14–0.46). Therefore, the further analyses described below are representative of the computed variables considering all pooled kicking attempts independent of the side of the goal they were directed.

4.4.2. Comparisons from fixed sleep duration thresholds

Anthropometric measurements, chronological age and PHV showed no significant differences between subgroups ($t_{(26)}$=-1.242 to -0.035, *p*=0.23–0.97; *d*=0.11–0.56). The groups reaching the cut-points of total sleep duration presented greater total sleep duration and time in bed, as well as a later wake up time as compared respectively to the groups whose fell below each recommendation ($t_{(26)}$=2.175 to 8.878, *p*=0.001–0.049; *d*=0.92–3.46). However, kicking performance indicators were not significantly different between subgroups (Table 4.1 and Supplementary online Table 1), regardless of sleep duration cut-points tested ($t_{(26)}$=-2.026 to 1.190, *p*=0.06–0.92; *d*=0.03–0.79).

Table 4.1. Mean ± standard deviation [95% CI upper; lower limits] (min – max) values for the comparisons of the sleep-wake cycle and kicking performance variables between youth soccer players who reached or not the total sleep time recommended by the National Sleep Foundation (Hirshkowitz et al., 2015).

	Pooled *N* = 28	TST > 8 h *N* = 12	TST < 8 h *N* = 16	Between-group comparisons
Sleep measures				
Sleep quality (a.u.)	3.50 ± 0.96 [3.06; 3.89] (1–5)	3.50 ± 1.00 [2.86; 4.14] (1–5)	3.50 ± 0.97 [2.99; 4.01] (2–5)	t = 0.000; p = 1.00; ES = 0.00
Sleepiness (a.u.)	3.64 ± 1.45 [3.02; 4.26] (1–7)	3.67 ± 1.56 [2.68; 4.66] (1–7)	3.63 ± 1.41 [2.87; 4.38] (1–7)	t = 0.073; p = 0.94; ES = 0.03
Chronotype score (a.u.)	52.38 ± 6.96 [49.17; 54.99] (35–62)	54.42 ± 6.18 [50.75; 58.59] (42–61)	50.84 ± 7.30 [47.24; 54.88] (35–62)	t = 1.426; p = 0.17; ES = 0.53
Bedtime (hr:min)	23:12 ± 1:20 [22:44; 23:50] (19:22–1:44)	22:57 ± 1:50 [21:47; 01:07] (19:22–1:44)	23:22 ± 0:47 [22:57; 23:48] (21:58–0:26)	t = -0.733; p = 0.48; ES = 0.10
Wake up time (hr:min)	6:58 ± 1:36 [6:17; 7:38] (5:18–12:03)	7:57 ± 1:58 [6:42; 9:12] (5:41–12:03)	6:15 ± 0:41 [5:53; 6:37] (5:18–7:57)	t = 2.872; p = 0.02; ES = 1.31
Time in bed (hr:min)	7:56 ± 1:32 [7:13; 8:24] (5:15–11:00)	9:20 ± 0:58 [8:43; 9:56] (8:14–11:00)	6:53 ± 0:53 [6:24; 7:21] (5:15–8:11)	t = 6.885; p < 0.001; ES = 2.60
Total sleep duration (hr:min)	7:33 ± 1:28 [6:52; 8:06] (5:02–10:47)	8:55 ± 0:48 [8:25; 9:25] (8:06–10:47)	6:31 ± 0:54 [6:02; 6:59] (5:02–7:48)	t = 7.483; p < 0.001; ES = 2.70
Latency (min)	20 ± 16 [14; 27] (5–72)	15 ± 14 [6; 24] (5–54)	22 ± 16 [13; 30] (6–72)	t = -1.184; p = 0.25; ES = -0.47
Wake after sleep onset (min)	5 ± 22 [-5; 14] (0–118)	10 ± 34 [-12; 31] (0–118)	0 ± 0 [0; 0] (0–0)	t = 1.000; p = 0.34; ES = 0.42
Efficiency (%)	95.21 ± 4.65 [93.98; 97.10] (81.20–99.23)	95.87 ± 5.40 [92.44; 99.28] (80.45–99.23)	94.72 ± 4.12 [92.52; 96.91] (81.20–98.51)	t = 0.615; p = 0.55; ES = 0.24
Number of awakenings (a.u.)	0.04 ± 0.19 [0; 0] (0–1)	0.08 ± 0.29 [-0.10; 0.27] (0–1)	0 ± 0 [0; 0] (0–0)	t = 1.000; p = 0.34; ES = 0.39
Kicking performance				
Ball velocity (m/s)	26.54 ± 1.99 [25.77; 27.31] (22.79–31.47)	25.85 ± 1.17 [25.11; 26.59] (22.79–27.57)	27.06 ± 2.34 [25.81; 28.30] (22.91–31.47)	t = -1.789; p = 0.09; ES = 0.56
Foot velocity (m/s)	19.05 ± 1.04 [18.65; 19.46] (16.48–20.61)	19.08 ± 1.17 [18.34; 19.82] (16.66–20.45)	19.03 ± 0.97 [18.52; 19.55] (16.48–20.61)	t = 0.108; p = 0.92; ES = 0.03

Foot/ball velocity ratio (a.u.)	1.42 ± 0.16 [1.35; 1.48] (1.21–1.81)	1.38 ± 0.14 [1.29; 1.47] (1.26–1.81)	1.45 ± 0.18 [1.35; 1.54] (1.21–1.79)	*t* = -1.173; *p* = 0.25; ES = 0.30
Approach run velocity (m/s)	2.76 ± 0.78 [2.46; 3.07] (1.70–4.55)	2.75 ± 0.78 [2.25; 3.24] (2.07–4.54)	2.77 ± 0.81 [2.34; 3.21] (1.70–4.55)	*t* = -0.552; *p* = 0.59; ES = 0.25
Mean radial error (m)	2.15 ± 0.43 [1.97; 2.34] (1.56–3.55)	2.17 ± 0.54 [1.83; 2.52] (1.56–3.55)	2.13 ± 0.34 [1.95; 2.31] (1.59–2.76)	*t* = 0.249; *p* = 0.81; ES = 0.07
Bivariate variable error (m)	3.36 ± 0.43 [3.17; 3.55] (2.69–4.34)	3.41 ± 0.50 [3.10; 3.73] (2.69–4.34)	3.35 ± 0.39 [3.14; 3.56] (2.84–4.20)	*t* = 0.372; *p* = 0.71; ES = 0.20
Accuracy (m)	4.00 ± 0.49 [3.79; 4.22] (3.27–5.61)	4.06 ± 0.65 [3.65; 4.47] (3.27–5.61)	3.98 ± 0.36 [3.79; 4.18] (3.37–4.69)	*t* = 0.367; *p* = 0.72; ES = 0.18
Kicks on-target (%)	5.94 ± 4.38 [4.09; 7.78] (0–20.00)	5.13 ± 5.82 [1.43; 8.82] (0–20.00)	6.35 ± 2.99 [4.76; 7.95] (0–13.33)	*t* = -0.669 *p* = 0.51; ES = 0.49

TST = total sleep duration; ES = Cohen’s *d* effect size; CI = confidence interval.

4.4.3. Relationships between sleep measures and kicking performance

Correlation magnitudes between sleep and kicking performance variables are shown in Figure 4.1. Ball, foot, ball/foot ratio and approach run velocities demonstrated no significant correlations with the self-reported or actigraphy-derived sleep parameters (r = -0.30–0.29; all p>0.05; Figure 4.1). Sleep efficiency reached significance in ROC analysis concerning "best" versus "worst" kicking foot/ball velocity ratio groups, but with no accuracy (Supplementary online Table 2; p = 0.04; AUC = 0.26 [0.01; 0.44]; sensitivity = 0.30; specificity = 0.72). On the other hand, mean radial error and accuracy were significantly moderately correlated with wake up time (r = 0.49[±0.35]; p=0.01 and r = 0.38[±0.35]; p=0.05, respectively). The mean radial error was also largely related to the chronotype scale score (r = -0.52[±0.25]; p=0.01). Moderate inverse correlations were observed between self-reported sleep quality and bivariate variable error (r = -0.44[±0.17]; p=0.03) and accuracy (r = -0.38[±0.21]; p=0.05). ROC analysis also indicated that self-reported sleep quality had a significant discriminant ability (Figure 4.2(F)) in distinguishing "best" and "worst" kicking bivariate variable error groups, with good accuracy (Supplementary online Table 3; p = 0.002; AUC = 0.84 [0.69; 0.99]; sensitivity = 0.71; specificity = 0.14). The bivariate variable error was also moderately associated with the wake after sleep onset (r = 0.41[±0.37]; p=0.04). Finally, the percentage of kicks on-target showed moderate inverse correlations with bedtime and wake up time (r = -0.39[±0.31]; p=0.05 and r = -0.49[±0.24]; p=0.01, respectively; Figure 4.1).

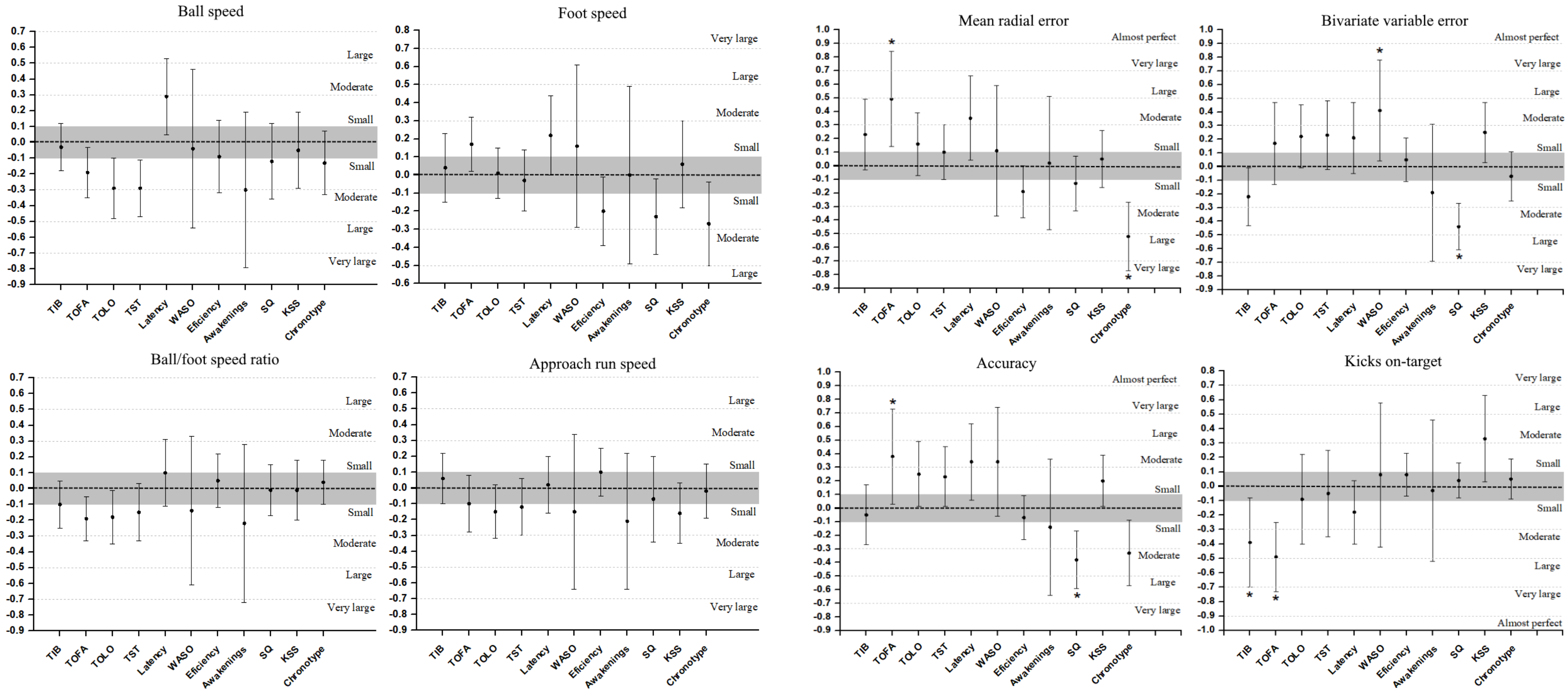


Figure 4.1. Partial correlation coefficients (together with respective confidence interval) between measures derived from sleep and soccer kicking performance components. The shaded area represents the trivial zone. * $p \leq 0.05$. *Note*: TIB, bedtime; TOFA, wake up time; TOLO, time of lights out; TST, total sleep duration; WASO, wake after sleep onset; SQ, sleep quality; KSS, Karolinska Sleepiness Scale.

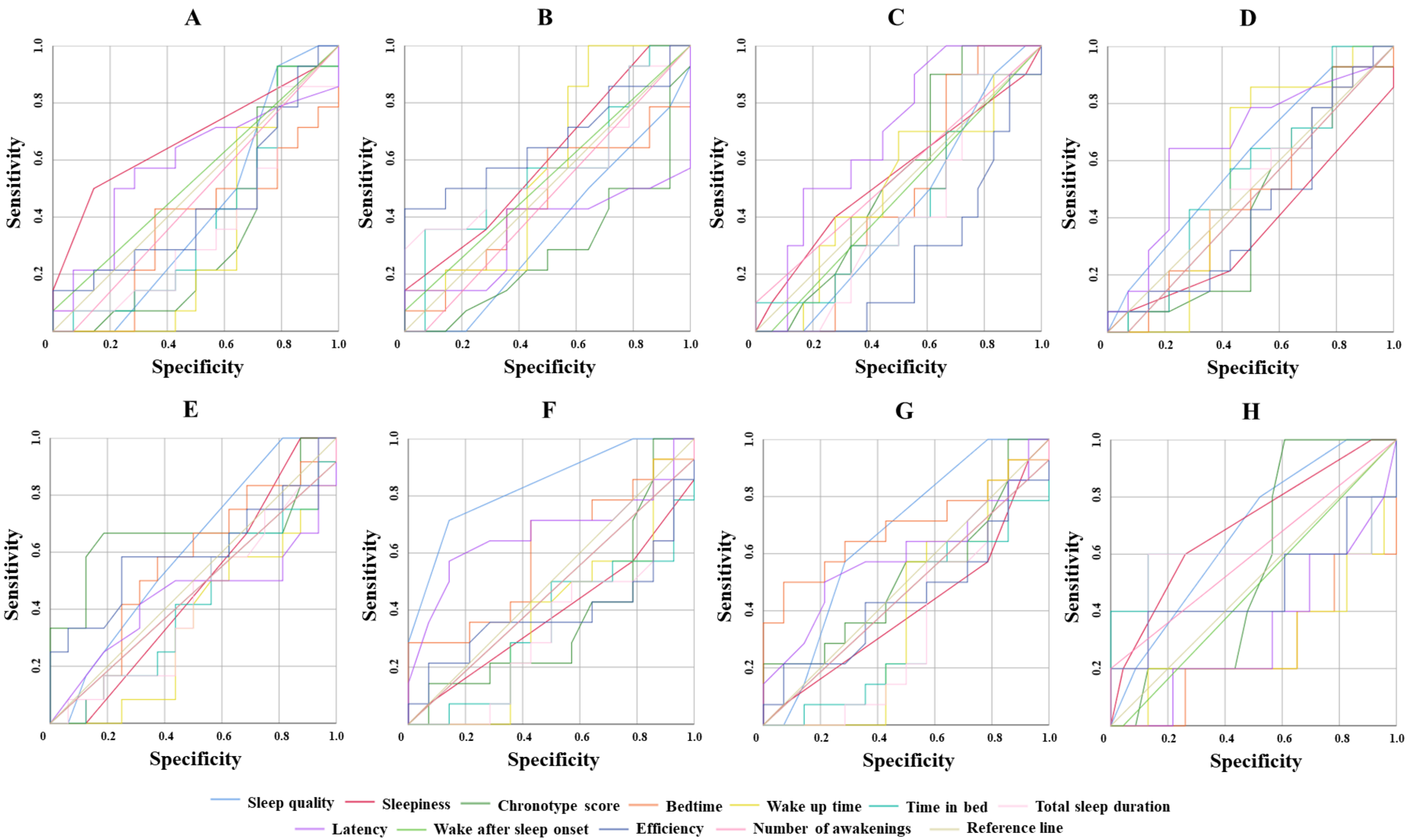


Figure 4.2. ROC curves for the sleep-derived indices between "best" and "worst" kicking performance groups. *Note:* (A) approach run velocity; (B) foot velocity; (C) ball velocity; (D) foot/ball velocity ratio; (E) mean radial error; (F) bivariate variable error; (G) accuracy and (F) percentage of kicks on-target.

Figure 4.3 contains graphical representations resulting from the associations between sleep and subsequent kicking performance. In Table 4.2, main results from the linear regression models are summarized. It was possible to identify that wake up time and chronotype scale score influenced upon 40% of the mean radial error variance ($Z_{(2,25)}$=8.348; *p*=0.002; Figure 4.3(A) and (B)) while self-reported sleep quality contributed to 19% of the variance in accuracy ($Z_{(1,26)}$=6.072; *p*=0.02; Figure 4.3(E)) and 24% of the bivariate variable error ($Z_{(1,26)}$=8.241; *p*=0.008; Figure 4.3(C)). Wake up time also represented 15% of the variance in the percentage of kicks on-target ($Z_{(1,26)}$=4.459; *p*=0.04; Figure 4.3(F)). Finally, taken together self-reported sleep quality and wake up time explained 33% of kicking accuracy ($Z_{(2,25)}$=6.013; *p*=0.007). SEM outcomes (Figure 4.4 and Supplementary online Table 4) revealed no mediational (i.e. indirect) effects upon the mentioned associations while a further relation between sleepiness and mean radial error was found as significant (β coefficient = 0.34; *p* = 0.04; Figure 4.4(A)).

Table 4.2. Relative contribution of variables related to sleep to the variance of soccer kicking performance.

Predictors	Unstandardized β coefficient	Standardised β coefficient	Adjusted R^2	*t*	*p*-value	Tolerance	VIF
Constant – Mean radial error	1.227			3.763	0.001		
Wake up time	0.00003147	0.424	0.215	2.694	0.012	0.969	1.032
Chronotype score	–0.025	–0.402	0.352	–2.554	0.017	0.969	1.032
Constant–Bivariate variable error	4.144			14.946	< 0.001		
Sleep quality	–0.220	–0.491	0.211	–2.871	0.008	1.000	1.000
WASO*				1.540	0.136	1.010	0.990
Constant – Accuracy	3.833			7.244	< 0.001		
Sleep quality	0.00003240	0.378	0.271	2.240	0.034	0.950	1.053
Wake up time	–0.180	–0.350	0.178	–2.077	0.048	0.950	1.053
Constant – Kicks on-target	13.120			3.707	0.001		
Bedtime*				–1.198	0.242	0.845	1.184
Wake up time	-0.000290	–0.383	0.114	–2.112	0.044	1.000	1.000

*Independent variables duly removed from the models. VIF = variance inflation factor.

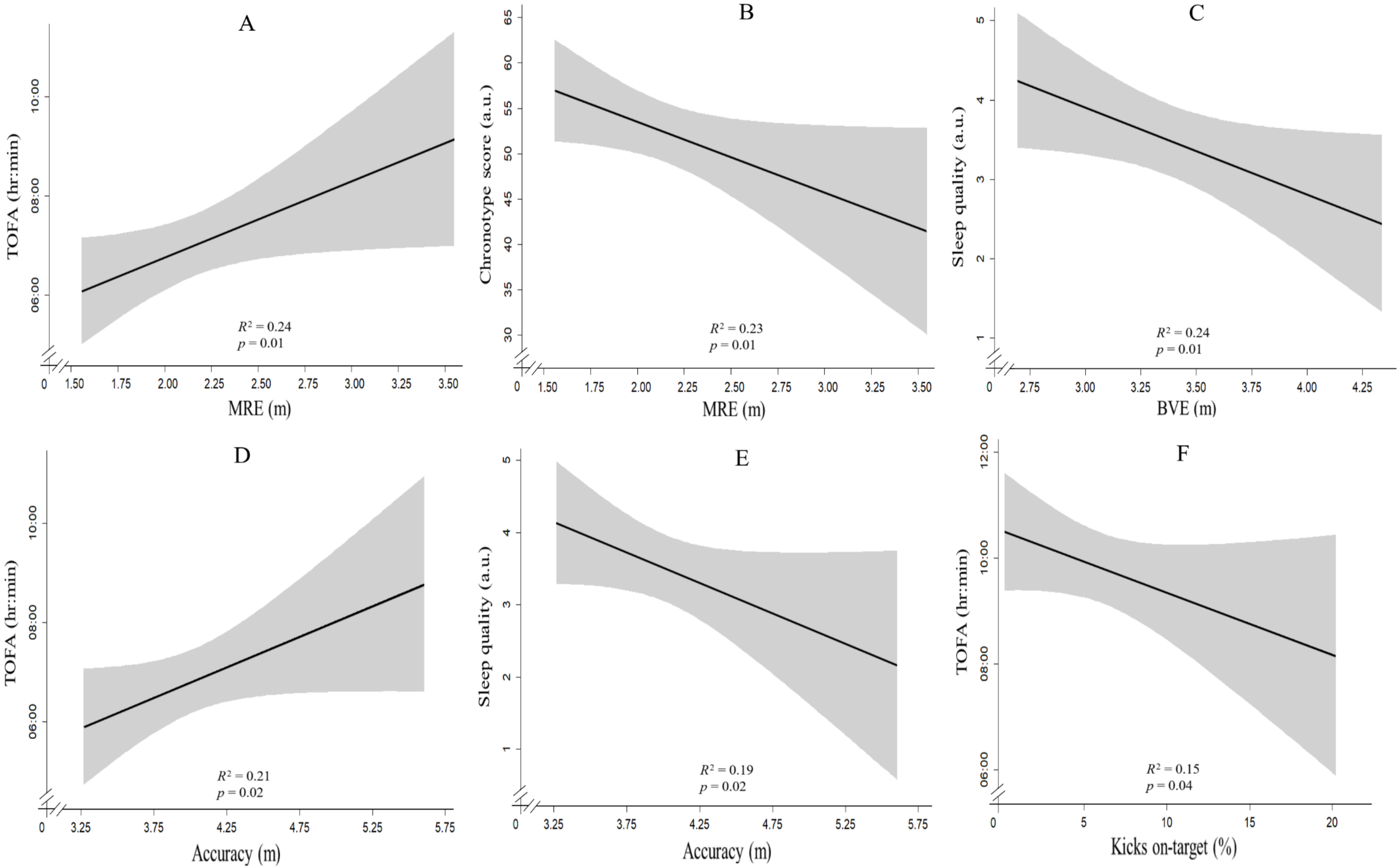


Figure 4.3. Graphical representations containing a general overview of the associations between measures of kicking ball placement with the sleep parameters. The shaded area represents the confidence interval of regression lines. *Note*: TOFA, wake up time; MRE, mean radial error; BVE, bivariate variable error.

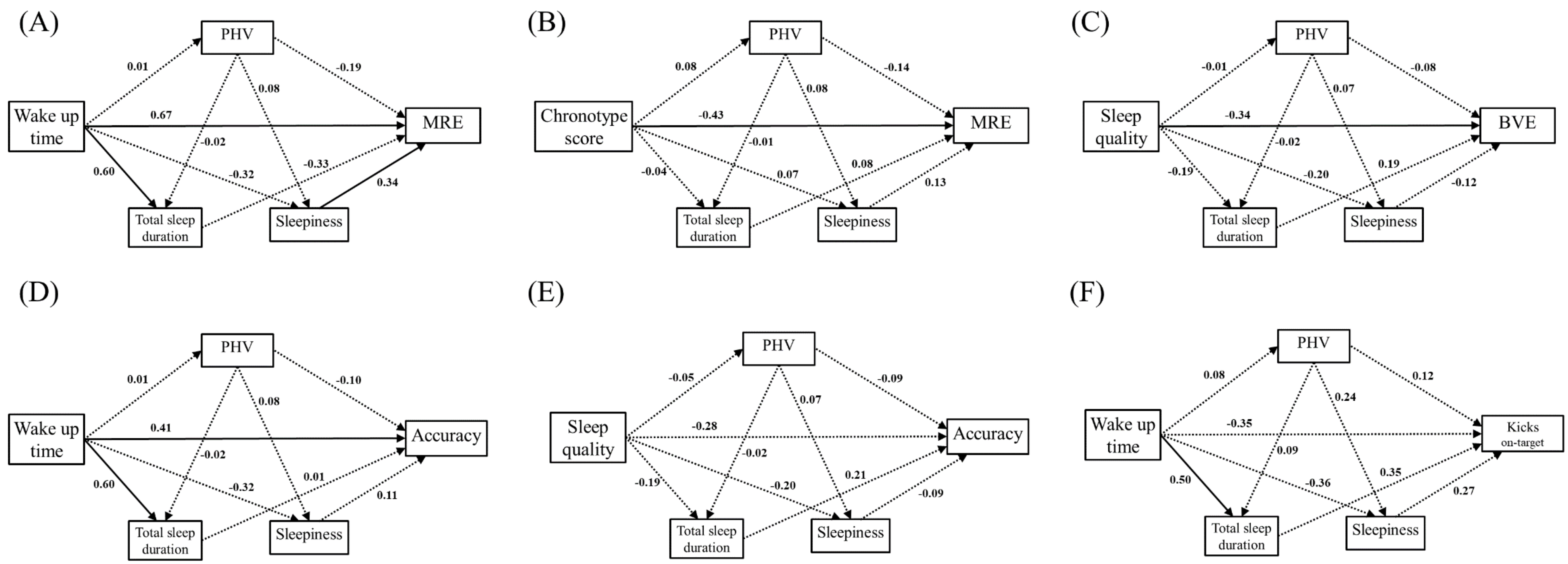


Figure 4.4. Mediational models of associations between sleep and soccer kicking performance. *Note:* MRE, mean radial error; BVE, bivariate variable error; PHV, age from peak height velocity. The solid continuous lines represent significant associations ($p \leq 0.05$) between two given factors whilst the dashed lines indicate absence of statistical significance.

4.5. Discussion

The main goal of this study was to examine the acute influence of sleep-related parameters on subsequent kicking performance components in youth soccer players. The main findings were: (1) both subjective and objective measures of sleep were associated with effectiveness in placing the ball on the goal; (2) higher perceived sleep quality was related to better kicking accuracy and lower placing variability. In contrast, athletes with later wake up time performed poorer in subsequent kicks as illustrated by fewer kicks on-target and higher mean radial error; (3) while either sleep quality and duration impacted on ball placement indices, kicking velocity properties were minimally influenced and (4) all kicking performance parameters considered were similar between youth players who slept for a total period above or below fixed cut-points of 7, 8 or 8.4 hours in an immediately previous monitoring night.

An important finding of the present study was that earlier wake up time on assessment day was related to a lower mean radial error and a higher percentage of kicks on-target. These observations were verified concomitantly with low chronotype scale scores (toward evening preference) influencing high mean radial error in kick attempts. Taken together, such results suggest that a more diurnal profile may help produce kicks with a greater likelihood of success. Firstly, it is important to highlight a possibility that part of the players was probably out of their "best performance time" at the moment of testing, thereby existing some influence of the inter-individual circadian rhythm upon kicking accuracy (Facer-Childs & Brandstaetter, 2015), despite assessments in the afternoon might have minimized such effect (Facer-Childs, Boiling, & Balanos, 2018). Likewise, an excessive accumulated time since wakening could equally impair the movement output necessary for accuracy (Edwards, Waterhouse, & Reilly, 2007) which indicates caution in interpreting a linear relationship established. Anyway, athletes showing superior competitive level tends to exhibit a preference for the morning period and/or being indifferent, but are less frequently nocturnals as it can grant additional difficulty to cope with sports demands (Lastella, Roach, Hurem, & Sargent, 2010; Silva et al., 2012) alongside reduced functional brain connectivity during resting state observed in individuals with late sleep-wake preference (Facer-Childs et al., 2019). The finding concerning kicking ball placement-chronotype relationship is in line with general conclusions of a systematic review on athletic/sport performance context (Vitale & Weydahl, 2017). Morningness–eveningness scale score was also inversely related to school achievement in youth aged 10–17 years-old (Randler & Frech, 2009). Results may be interpreted in the light of the two-process model of sleep regulation (Borbély, 1982), further suggesting that there might have an interaction of sleep-dependent (i.e. actual sleep-wake timing and quality) and sleep-independent processes (i.e. circadian component as inferred by chronotype scale score) upon resulting players' kicking ball placement ability. The relation among sleepiness and mean radial error, although significant in a SEM analysis, should be viewed with caution because it do not hold true when previously controlled by individual's age and sizes (Hunter et al. 2021). Another novel data was higher sleep quality being associated with better kicking accuracy and lower bivariate variable error. Of note, detrimental effects on performance provided by nocturnal behaviours or poor sleep seems to notably happen in the case of goal-directed motor skills (Fox, Stanton, Scalan, Teramoto, & Sargent, 2020a; Fox et al., 2020b; Jones, Kirschen, Kancharla, & Hale, 2019; Juliff et al., 2018; Suppiah et al., 2016). To be explicit, higher subjective sleep quality the night before a game demonstrated correlations with favourable shooting accuracy in basketball (Fox et al., 2020a), despite small associations with passes completed in senior soccer small-sided games (Selmi et al., 2019). To summarize, the results presented here are aligned with some literature and indicates that both the estimated chronotype profile as well as the sleep-wake cycle indicators alongside perceived sleep quality may have important consequences on critical team sports technical events, such as in kicking ability of youth footballers.

It is necessary to highlight that sleep and chronotype showed some impact on ball placement measures but not on kicking velocity parameters. Although detailed investigations are lacking on the precise mechanisms responsible for the production/adjustments of the kicking movement and outcomes (Palucci Vieira et al., 2021a, b), accuracy seems related to strict control of the angular joints involved in this motor task (Dichiera et al., 2006). Ball velocity is produced primarily by the transference of momentum between lower kicking limb segments and consequently, is largely influenced by their velocities summed (Sinclair et al., 2014). In this sense, the aspects of athletic performance dependent on higher levels of central inputs (e.g. decision-making and accuracy) have been demonstrated to be affected to a greater extent by sleep indicators than those generally demanding gross motor execution (Fox et al., 2020b; Fullagar et al., 2015) given the requirements of the former upon neuronal networks likely more complex as compared to those used in controlling the latter. The question which arises is whether kicks dependent on high accuracy would be more impaired compared to those placing greater demands on velocity rather than accuracy (e.g. kicks from longer distances to the goal).

When using fixed total sleep duration thresholds, either that generic designed for general population by the National Sleep Foundation (NSF; Hirshkowitz et al., 2015) or those obtained directly from soccer players (Sargent et al., 2021) there were no significant differences in any kicking performance metrics between originated subgroups. This is partly opposed to that found in a systematic review addressing the effects of total sleep duration in individual/team sports athletes, where greater total sleep duration was in general accompanied with enhanced technical or motor outputs (Kirschen et al., 2020). However, it is important to note that there is no mention to effects of sleep on (ball) kicking in the aforementioned review; thus its results are only valid for sport tasks demanding on the upper limbs as the major muscle guidance (e.g. rugby passing, basketball throw and tennis serving). Also, here the acute effects of sleep were determined while long-term interventions aiming at extend total sleep duration patterns presented promising results in improving not only duration but also sleepiness and goal-directed motor performance in other context (Schwartz & Simon, 2015). The lack of our consideration for additional covariates/potential confounders such as the accumulated physical exertion from prior training sessions (Whitworth-Turner et al., 2019), possible strategies to improve sleep whether used (Whitworth-Turner et al., 2017) or occurrences of sleep interruption due to external events (Fowler et al., 2017) possibly have influenced on this case. Anyway, on average (Table 4.1; 7:33 h), participants of the current study did not reach the recommended sleep duration of 8–10 h by NSF or a need of 8.4 h to feel rested (Sargent et al., 2021). Failing to attain typical sleep recommendations have been frequently reported in studies including youth soccer players from various age-groups (mean 14.2–19 years-old), pertaining to a range of other locations (Australia, Bolivia, Middle Eastern, Portugal and UK) (Figueiredo et al., 2021; Fowler et al., 2017; Roach et al., 2013; Robey et al., 2014; Whitworth-Turner, Di Michele, Muir, Gregson, & Drust, 2017; Whitworth-Turner et al., 2019). Scheduled training time, attending to school and social obligations are among frequent reasons leading into such scenario (Fox et al., 2020b). Thus, the current research failed to provide support for the acute effects of inter-individual sleep duration on performance of youth soccer. In fact, most athletes cannot reach the current recommendations and sleep duration itself probed not to be a sensitive indicator (Walsh et al. 2021) in detecting possible sleep oscillations linked with variations in kick performance. Other sleep-related indices such as sleep quality, sleep-wake transition timing and morningness-eveningness chronotype scale score may have a greater value as illustrated by the present preliminary empirical evidence.

This is the first study investigating the acute impact of inter-individual sleep parameters on subsequent performance in completing a soccer skill on a naturally occurring environment. Here, we have attempted to follow the guidelines on the use of kick test protocols highlighted in existing reviews (Russell & Kingsley, 2011; Palucci Vieira et al., 2021a). It was achieved by including, as compared to previous work (e.g. Pallesen et al., 2017), a less stationary/simple assessment context in an experiment combining kicks outside penalty area, aiming targets positioned in goalpost upper corners and against a goalkeeper (game-like; Palucci Vieira et al., 2021a). Video kinematic analysis were employed here to provide outcome measures in ecologically valid units/continuous data whilst accounting for the various components (speed, accuracy and success rate) of kick execution as recommended in (Russell & Kingsley, 2011). The absence of between-attempts differences indicates that the protocol defined was likely robust to the possible learning and/or fatigue effects resulting from an acute session of repeated kicks (Amiri-Khorasani et al., 2011), implying existence of small systematic bias. However, opposed to findings from two studies including players aged >17 (Hunter, Angilletta, Pavlic, Lichtwark, & Wilson, 2018; van den Tillaar & Fuglstad, 2017), a similarity in measures of ball placement in the goal was verified when comparing kicks directed to the ipsilateral and contralateral goal sides. A younger age, more challenging task and variations in the procedures used for calculating ball placement adopted in the present study compared to the previous ones help justify the discrepant results (Palucci Vieira et al., 2021a). Although further investigations are notably necessary to reach a consensus, our original data indicate that young soccer players can perform kicks, at the edge of the penalty area, for both goalpost sides with similar effectiveness.

A number of limitations are recognised in the present study. Firstly, despite the challenges involved in implementing repeated measurements in real-world settings, a single sleep night was collected while at least one full week has been recommended (Halson, 2019; Walsh et al., 2021). Sleep indices (Claudino et al., 2019; Fowler et al., 2017; Halson, 2019) and kicking accuracy (Russell, Benton, & Kingsley, 2010; Russell & Kingsley, 2011; Berjan Bacvarevic et al., 2012) are both highly unstable parameters. Future study designs considering a within-subject approach as in (Costa et al., 2019, 2021; Figueiredo et al., 2021) are important looking for obtaining the 'true' influence of sleep variations upon subsequent kicking performance. Self-reported sleep quality was collected just before kick assessment, implying that a systematic recall bias may have existed. Notwithstanding, results are from one kick/target type, in a relatively resting state (cf. Russell, Benton, & Kingsley, 2011) and may reflect only the behaviour of the investigated sample under specific local conditions they were living. Exclusion of players that napped can be an additional issue. Confirming the notion of Sargent et al. (2021), here only 2/30 subjects initially recruited (6.7%) showed a nap in the assessment day, i.e. there was a lack of nap consistency among participants. As a consequence, it would not be an accurate representation of the data across all sample if including these few players who napped. The benefits of napping upon players' technical outputs is yet to be explored in scientific research (Lastella et al., 2021). Finally, gold-standard sleep architecture measures (polysomnography) were not taken, and these can reveal pertinent information about the impact of recovery during sleep on motor skills performance (Fullagar et al., 2015).

4.6. Conclusion

In short, one-off self-reported or directly determined sleep measures using wrist actigraphy allowed here for detecting inter-individual variations of kicking performance in youth-soccer players. Whilst sleep quality and duration indicators seem to have limited interference on kicking velocity components, low sleep quality and chronotype scale score toward evening preference may notably produce an immediately subsequent worse ball placement in the goal when performing kicks from the edge of the penalty area. The results reinforce the need to monitor sleep-wake cycle transitions and perceived sleep quality immediately prior to testing aiming at increasing the control over individual constraints that potentially influence technical ability expression, in particular goal-directed skills. However, the present players that slept for more or less than 7, 8 or 8.4 h performed kicks at a similar proficiency level the following day. Collectively, the acute weight of sleep duration parameter to soccer kicking performance might be lower than other sleep-derived indices (perceived quality, sleep-wake transition timing and chronotype score). While the present work is limited by monitoring a one-off night, future research is required to determine the degree to which findings presented here are transferable to competition contexts as well the chronic effects of sleep on skill-related performance in soccer.

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Supplementary online Table 1. Comparisons of the sleep-wake cycle and kicking performance variables between youth soccer players who reached or not the soccer-specific perceived sleep time need (8.4 h) or traditional duration (7 h) according to Sargent et al. (2021).

	TST > 8.4h *N* = 10	TST < 8.4h *N* = 18	Between-group comparisons
Sleep measures			
Sleep quality (a.u.)	3.44 ± 1.13 [2.58; 4.31] (1–5)	3.50 ± 0.97 [2.99; 4.01] (2–5)	*t* = -0.554; *p* = 0.58; ES = -0.06
Sleepiness (a.u.)	3.67 ± 1.73 [2.34; 5.00] (1–7)	3.63 ± 1.41 [2.87; 4.38] (1–7)	*t* = 0.160; *p* = 0.87; ES = 0.03
Chronotype score (a.u.)	54.22 ± 7.05 [48.80; 59.64] (42–61)	52.44 ± 7.07 [48.67; 56.21] (35–62)	*t* = 0.939; *p* = 0.36; ES = 0.25
Bedtime (hr:min)	22:49 ± 1:58 [21:19; 01:20] (19:22–1:44)	23:20 ± 0:57 [22:49; 23:50] (21:58–1:26)	*t* = -1.029; *p* = 0.32; ES = -0.44
Wake up time (hr:min)	7:59 ± 2:10 [6:19; 9:40] (5:41–12:03)	6:25 ± 1:04 [5:51; 9:59] (5:18–9:30)	*t* = 2.175; *p* = 0.049; ES = 0.92
Time in bed (hr:min)	9:37 ± 0:57 [8:54; 10:21] (8:27– 11:00)	7:06 ± 1:00 [6:34; 7:38] (5:15–8:28)	*t* = 6.195; *p* < 0.001; ES = 2.57
Total sleep duration (hr:min)	9:09 ± 0:47 [8:33; 9:45] (8:22– 10:47)	6:44 ± 1:02 [6:11; 7:18] (5:02–8:08)	*t* = 7.081; *p* < 0.001; ES = 2.57
Latency (min)	15 ± 17 [2; 28] (5–54)	21 ± 16 [13; 30] (6–72)	*t* = -1.712; *p* = 0.10; ES = -0.36
Wake after sleep onset (min)	13 ± 39 [-17; 43] (0–118)	0 ± 0 [0; 0] (0–0)	*t* = 1.000; *p* = 0.34; ES = 0.47
Efficiency (%)	95.45 ± 6.24 [90.65; 100.25] (80.45–99.23)	94.90 ± 4.19 [92.66; 97.13] (81.20–98.51)	*t* = 0.257; *p* = 0.80; ES = 0.10
Number of awakenings (a.u.)	0.11 ± 0.33 [-0.15; 0.37] (0–1)	0 ± 0 [0; 0] (0–0)	*t* = 1.000; *p* = 0.34; ES = 0.47
Kicking performance			
Ball velocity (m/s)	25.75 ± 1.20 [24.83; 26.67] (22.79–26.67)	26.80 ± 2.35 [25.54; 28.05] (22.91–31.47)	*t* = -1.147; *p* = 0.26; ES = -0.56
Foot velocity (m/s)	19.27 ± 0.91 [18.57; 19.97] (17.19–20.04)	19.01 ± 1.02 [18.46; 19.55] (16.48–20.61)	*t* = -0.185; *p* = 0.85; ES = 0.27
Foot/ball velocity ratio (a.u.)	1.39 ± 0.15 [1.31; 1.37] (1.28–1.40)	1.43 ± 0.17 [1.34; 1.53] (1.21–1.79)	*t* = -0.678; *p* = 0.50; ES = -0.25
Approach run velocity (m/s)	2.79 ± 0.82 [2.16; 3.42] (2.07–4.54)	2.72 ± 0.68 [2.35; 3.08] (1.70–4.01)	*t* = -0.135; *p* = 0.89; ES = 0.09
Mean radial error (m)	2.25 ± 0.61 [1.79; 2.72] (1.56–3.55)	2.13 ± 0.34 [1.94; 2.31] (1.59–2.76)	*t* = 0.536; *p* = 0.60; ES = 0.24
Bivariate variable error (m)	3.53 ± 0.51 [3.14; 3.93] (2.69–4.34)	3.33 ± 0.40 [3.11; 3.54] (2.79–4.20)	*t* = 1.064; *p* = 0.30; ES = 0.44
Accuracy (m)	4.21 ± 0.68 [3.69; 4.73] (3.35–5.61)	3.96 ± 0.39 [3.76; 4.17] (3.27–4.69)	*t* = 1.083; *p* = 0.29; ES = 0.45
Kicks on-target (%)	6.09 ± 6.22 [1.31; 10.87] (0–20.00)	5.94 ± 3.39 [4.13; 7.74] (0–13.33)	*t* = 1.190; *p* = 0.25; ES = 0.03

Supplementary online Table 1 (continued)

	TST > 7h *N* = 17	TST < 7h *N* = 11	Between-group comparisons
Sleep measures			
Sleep quality (a.u.)	3.47 ± 0.94 [2.99; 3.96] (1–5)	3.55 ± 1.04 [2.85; 4.24] (2–5)	t = -0.219; p = 0.83; ES = -0.08
Sleepiness (a.u.)	3.59 ± 1.54 [2.79; 4.38] (1–7)	3.73 ± 1.35 [2.82; 4.63] (3–7)	t = -0.568; p = 0.57; ES = -0.10
Chronotype score (a.u.)	52.59 ± 7.65 [48.66; 56.52] (35–61)	52.64 ± 5.85 [48.70; 56.57] (45–62)	t = 0.376; p = 0.91; ES = -0.01
Bedtime (hr:min)	22:54 ± 1:36 [22:05; 23:44] (19:22–1:44)	23:38 ± 0:35 [23:15; 00:01] (22:27–00:26)	t = -1.773; p = 0.09; ES = -0.63
Wake up time (hr:min)	7:36 ± 1:46 [6:41; 8:30] (5:41–12:03)	6:01 ± 0:29 [5:41; 6:20] (5:18–6:50)	t = 3.665; p < 0.01; ES = 1.30
Time in bed (hr:min)	8:55 ± 1:01 [8:23; 9:27] (7:42–11:00)	6:22 ± 0:32 [6:01; 6:44] (5:15–7:18)	t = 8.394; p < 0.001; ES = 3.34
Total sleep duration (hr:min)	8:31 ± 0:54 [8:03; 8:59] (7:16–10:47)	6:01 ± 0:34 [5:38; 6:24] (5:02–6:44)	t = 8.878; p < 0.001; ES = 3.46
Latency (min)	17 ± 13 [10; 24] (5–54)	22 ± 19 [9; 34] (6–72)	t = -0.847; p = 0.40; ES = -0.31
Wake after sleep onset (min)	7 ± 29 [-8; 22] (0–118)	0 ± 0 [0; 0] (0–0)	t = 0.799; p = 0.43; ES = 0.34
Efficiency (%)	95.74 ± 4.60 [93.38; 98.11] (80.45–99.23)	94.39 ± 4.84 [91.14; 97.64] (81.20–98.51)	t = 0.712; p = 0.48; ES = 0.29
Number of awakenings (a.u.)	0.06 ± 0.24 [-0.07; 0.18] (0–1)	0 ± 0 [0; 0] (0–0)	t = 0.799; p = 0.43; ES = 0.35
Kicking performance			
Ball velocity (m/s)	25.95 ± 1.78 [25.03; 26.86] (22.79–30.25)	27.45 ± 2.03 [26.09; 28.81] (24.61–31.47)	t = -2.026; p = 0.059; ES = -0.79
Foot velocity (m/s)	18.88 ± 1.19 [18.27; 19.49] (16.48–20.45)	19.33 ± 0.72 [18.84; 19.81] (18.30–20.61)	t = -1.145; p = 0.26; ES = -0.46
Foot/ball velocity ratio (a.u.)	1.41 ± 0.18 [1.32; 1.50] (1.21–1.81)	1.43 ± 0.15 [1.33; 1.53] (1.25–1.79)	t = -0.482; p = 0.63; ES = -0.12
Approach run velocity (m/s)	2.75 ± 0.76 [2.36; 3.14] (1.89–4.54)	2.78 ± 0.85 [2.21; 3.35] (1.70–4.55)	t = -0.806; p = 0.43; ES = -0.04
Mean radial error (m)	2.19 ± 0.52 [1.92; 2.45] (1.56–3.55)	2.09 ± 0.24 [1.93; 2.25] (1.78–2.60)	t = 0.432; p = 0.67; ES = 0.25
Bivariate variable error (m)	3.45 ± 0.47 [3.21; 3.69] (2.69–4.34)	3.27 ± 0.36 [3.02; 3.51] (2.84–3.90)	t = 0.594; p = 0.31; ES = 0.43
Accuracy (m)	4.10 ± 0.56 [3.82; 4.39] (3.27–5.61)	3.88 ± 0.37 [3.64; 4.13] (3.37–4.69)	t = 1.110; p = 0.28; ES = 0.46
Kicks on-target (%)	5.19 ± 5.05 [2.59; 7.79] (0–20.00)	6.82 ± 3.02 [4.79; 4.79] (0–13.33)	t = 0.222; p = 0.83; ES = -0.39

Values are mean ± standard deviation [95% upper; lower confidence limits] (min – max). TST = total sleep duration; ES = Cohen's *d* effect size.

Supplementary online Table 2. ROC outputs concerning the performance of sleep-derived classifiers for distinguishing "best" and "worst" kicking velocity groups.

	***p*-value**	**AUC**	**Standard error**	**Sensitivity**	**Specificity**	**Cut-off**
Ball velocity						
Sleep quality	0.46	0.42	0.11	0.93	0.79	2.50
Sleepiness	0.11	0.68	0.10	0.50	0.14	4.00
Chronotype score	0.15	0.34	0.11	0.29	0.64	54.50
Bedtime	0.23	0.37	0.11	0.50	0.79	22:54
Wake up time	0.14	0.34	0.11	0.21	0.64	6:30
Time in bed	0.29	0.38	0.11	0.93	0.79	6:21
Total sleep duration	0.22	0.36	0.11	0.29	0.57	7:57
Latency	0.45	0.58	0.11	0.57	0.29	15.50
Wake after sleep onset	0.75	0.54	0.11	0.07	0.00	59.00
Efficiency	0.63	0.45	0.11	0.43	0.71	95.94
Number of awakenings	0.75	0.46	0.11	0.00	0.07	0.50
Foot velocity						
Sleep quality	0.18	0.35	0.10	0.00	0.21	4.50
Sleepiness	0.36	0.60	0.11	0.36	0.29	4.00
Chronotype score	0.051	0.28	0.10	0.29	0.64	54.50
Bedtime	0.75	0.46	0.11	0.64	0.86	22:19
Wake up time	0.48	0.58	0.11	0.86	0.57	5:59
Time in bed	0.49	0.58	0.11	0.36	0.07	8:55
Total sleep duration	0.43	0.59	0.11	0.43	0.29	8:15
Latency	0.19	0.35	0.11	0.57	1.00	7.00
Wake after sleep onset	0.75	0.54	0.11	0.07	0.00	59.00
Efficiency	0.14	0.67	0.11	0.64	0.43	96.03
Number of awakenings	0.75	0.46	0.11	0.00	0.07	0.50

Note: AUC, area under the curve.

Supplementary online Table 2 (continued)

	p-value	AUC	Standard error	Sensitivity	Specificity	Cut-off
Foot/ball velocity ratio						
Sleep quality	0.53	0.43	0.11	0.00	0.17	4.50
Sleepiness	0.70	0.54	0.12	0.40	0.28	4.00
Chronotype score	0.65	0.55	0.11	0.90	0.61	48.50
Bedtime	0.81	0.47	0.11	0.90	0.67	22:19
Wake up time	0.98	0.50	0.12	0.70	0.50	6:15
Time in bed	0.67	0.45	0.12	0.40	0.61	7:57
Total sleep duration	0.42	0.41	0.11	0.10	0.33	8:29
Latency	0.10	0.69	0.10	0.90	0.56	9.50
Wake after sleep onset	0.81	0.47	0.11	0.00	0.06	59.00
Efficiency	0.04	0.26	0.09	0.30	0.72	95.94
Number of awakenings	0.67	0.55	0.12	0.10	0.00	0.50
Approach run velocity						
Sleep quality	0.38	0.60	0.11	0.64	0.50	3.50
Sleepiness	0.21	0.36	0.11	0.21	0.43	4.00
Chronotype score	0.52	0.43	0.11	0.14	0.50	57.50
Bedtime	0.78	0.47	0.11	0.21	0.36	23:49
Wake up time	0.65	0.55	0.12	0.79	0.43	6:11
Time in bed	0.78	0.53	0.11	0.57	0.43	8:02
Total sleep duration	0.95	0.51	0.11	0.57	0.50	7:35
Latency	0.15	0.66	0.11	0.64	0.21	15.50
Wake after sleep onset	0.75	0.46	0.11	0.00	0.07	59.00
Efficiency	0.55	0.43	0.11	0.50	0.71	95.66
Number of awakenings	0.75	0.46	0.11	0.00	0.07	0.50

Note: AUC, area under the curve.

Supplementary online Table 3. ROC outputs concerning the performance of sleep-derived classifiers for distinguishing "best" and "worst" kicking ball placement groups.

	***p*-value**	**AUC**	**Standard error**	**Sensitivity**	**Specificity**	**Cut-off**
Mean radial error						
Sleep quality	0.35	0.60	0.11	0.50	0.38	3.50
Sleepiness	0.78	0.47	0.11	1.00	0.88	6.00
Chronotype score	0.13	0.67	0.12	0.67	0.19	51.50
Bedtime	0.68	0.55	0.11	0.58	0.38	23:16
Wake up time	0.17	0.35	0.10	0.08	0.44	5:59
Time in bed	0.46	0.42	0.11	0.17	0.38	6:42
Total sleep duration	0.52	0.43	0.11	0.17	0.44	6:36
Latency	0.58	0.44	0.12	0.50	0.81	21.50
Wake after sleep onset	0.71	0.46	0.11	0.92	1.00	59.00
Efficiency	0.37	0.60	0.12	0.58	0.25	95.66
Number of awakenings	0.71	0.46	0.11	0.92	1.00	0.50
Bivariate variable error						
Sleep quality	0.002	0.84	0.08	0.71	0.14	3.50
Sleepiness	0.30	0.39	0.11	0.57	0.79	4.00
Chronotype score	0.27	0.38	0.11	0.43	0.79	55.50
Bedtime	0.36	0.60	0.11	0.71	0.43	23:38
Wake up time	0.26	0.38	0.11	0.00	0.36	5:51
Time in bed	0.15	0.34	0.10	0.57	0.93	8:49
Total sleep duration	0.12	0.33	0.10	0.21	0.43	6:36
Latency	0.12	0.67	0.11	0.57	0.14	11.50
Wake after sleep onset	0.75	0.46	0.11	0.93	1.00	59.00
Efficiency	0.32	0.39	0.11	0.36	0.64	96.47
Number of awakenings	0.75	0.46	0.11	0.93	1.00	0.50

Note: AUC, area under the curve.

Supplementary online Table 3 (continued)

	***p*-value**	**AUC**	**Standard error**	**Sensitivity**	**Specificity**	**Cut-off**
Accuracy						
Sleep quality	0.14	0.66	0.11	0.57	0.29	3.50
Sleepiness	0.41	0.41	0.11	0.57	0.79	4.00
Chronotype score	0.84	0.52	0.11	0.21	0.07	44.50
Bedtime	0.09	0.69	0.10	0.64	0.29	23:16
Wake up time	0.31	0.39	0.11	0.21	0.50	6:07
Time in bed	0.17	0.35	0.11	0.21	0.57	7:30
Total sleep duration	0.15	0.34	0.11	0.21	0.57	7:00
Latency	0.40	0.59	0.11	0.50	0.21	11.50
Wake after sleep onset	0.75	0.46	0.11	0.93	1.00	59.00
Efficiency	0.63	0.45	0.11	0.50	0.71	97.22
Number of awakenings	0.75	0.46	0.11	0.93	1.00	0.50
Kicks on-target						
Sleep quality	0.23	0.67	0.12	0.80	0.52	3.50
Sleepiness	0.17	0.70	0.13	0.60	0.26	4.00
Chronotype score	0.72	0.55	0.12	1.00	0.61	50.00
Bedtime	0.10	0.26	0.13	0.20	0.65	23:13
Wake up time	0.14	0.29	0.15	0.20	0.65	6:15
Time in bed	0.53	0.59	0.20	0.60	0.13	8:55
Total sleep duration	0.65	0.57	0.20	0.60	0.13	8: 523
Latency	0.24	0.33	0.14	0.20	0.57	13.50
Wake after sleep onset	0.88	0.48	0.14	0.00	0.04	59.00
Efficiency	0.93	0.49	0.18	0.40	0.13	98.70
Number of awakenings	0.49	0.60	0.16	0.20	0.00	0.50

Note: AUC, area under the curve.

Supplementary online Table 4. Direct, indirect and total effects obtained from the mediational models including self-reported/actigraphy-derived sleep measures, estimated maturity and their influence on soccer kicking performance parameters.

	β coefficient	Standard error	Z	*p*-value	CI (95%)
Model A					
Direct	0.6040	0.20	2.99	0.00	0.21 – 1.00
Indirect	0.0189	0.05	0.42	0.68	-0.07 – 0.11
Total	0.3260	0.16	2.01	0.05	0.01 – 0.64
Model B					
Direct	-0.5499	0.22	-2.5	0.01	-0.98 – -0.12
Indirect	0.0049	0.02	0.31	0.76	-0.03 – 0.04
Total	-0.5543	0.22	-2.48	0.01	-0.99 – -0.12
Model C					
Direct	-0.1258	0.07	-1.89	0.06	-0.26 – 0.00
Indirect	-0.0048	0.02	-0.29	0.77	-0.04 – 0.03
Total	-0.1287	0.07	-1.94	0.05	-0.26 – 0.00
Model D					
Direct	0.2323	0.14	1.67	0.10	-0.04 – 0.51
Indirect	0.0033	0.01	0.46	0.65	-0.01 – 0.02
Total	0.2120	0.10	2.12	0.03	0.02 – 0.41
Model E					
Direct	-0.0964	0.06	-1.54	0.12	-0.22 – 0.03
Indirect	-0.0039	0.02	-0.25	0.80	-0.03 – 0.03
Total	-0.1019	0.06	-1.63	0.10	-0.22 – 0.02
Model F					
Direct	-0.5511	0.40	-1.38	0.17	-1.33 – 0.23
Indirect	0.0888	0.08	1.12	0.26	-0.07 – 0.24
Total	-0.4045	0.34	-1.19	0.23	-1.06 – 0.26

Note: CI = confidence interval. Please refer to Figure 4.3 to see each model components.

CHAPTER 5

RELIABILITY OF COMTEMPORARY MARKERLESS SYSTEM APPLIED TO KICKING INVESTIGATION

5. PAPER 4 – Automatic markerless motion detector method against traditional digitisation for 3-dimensional movement kinematic analysis of ball kicking in soccer field context [(5)]

Palucci Vieira, L.H., Santiago, P.R.P., Pinto, A., Aquino, R., Torres, R., & Barbieri, F. A. (2022). Automatic markerless motion detector method against traditional digitisation for 3-dimensional movement kinematic analysis of ball kicking in soccer field context. *International Journal of Environmental Research and Public Health*, *19*(3), 1179. **https://doi.org/10.3390/ijerph19031179**

(5) APPENDIX 5 - editorial explanation allowing reuse of this previously published study in the current thesis

5.1. Abstract

Kicking is a fundamental skill in soccer that often contributes to match outcomes. Lower limb movement features (e.g., joint position and velocity) are determinants of kick performance. However, obtaining kicking kinematics under field conditions generally requires time-consuming manual tracking. The current study aimed to compare a contemporary markerless automatic motion estimation algorithm (OpenPose) with manual digitisation (DVIDEOW software) in obtaining on-field kicking kinematic parameters. An experimental dataset of under-17 players from all outfield positions was used. Kick attempts were performed in an official pitch against a goalkeeper. Four digital video cameras were used to record full-body motion during support and ball contact phases of each kick. Three-dimensional positions of hip, knee, ankle, toe and foot centre-of-mass (CM_{foot}) generally showed no significant differences when computed by automatic as compared to manual tracking (whole kicking movement cycle), while only z-coordinates of knee and calcaneus markers at specific points differed between methods. The resulting time-series matrices of positions (r^2 = 0.94) and velocity signals (r^2 = 0.68) were largely associated (all $p < 0.01$). The mean absolute error of OpenPose motion tracking was 3.49 cm for determining positions (ranging from 2.78 cm (CM_{foot}) to 4.13 cm (dominant hip)) and 1.29 m/s for calculating joint velocity (0.95 m/s (knee) to 1.50 m/s (non-dominant hip)) as compared to reference measures by manual digitisation. Angular range-of-motion showed significant correlations between methods for the ankle (r = 0.59, $p < 0.01$, *large*) and knee joint displacements (r = 0.84, $p < 0.001$, *very large*) but not in the hip (r = 0.04, p = 0.85, *unclear*). Markerless motion tracking (OpenPose) can help to successfully obtain some lower limb position, velocity, and joint angular outputs during kicks performed in a naturally occurring environment.

Keywords: image processing; human estimation; COCO; MPII; deep learning; team sports.

5.2. Introduction

Kicking is a frequent technical action taken in football matches, and achieving high-velocity and accurate targeting standards usually contributes to winning matches [1,2]. Extracting players' movement kinematics data derived from ball kicking, such as passing actions or shooting against goalposts, is arguably important in the coaching process since it assists in identifying and understanding (a) body mechanical factor determinants for performance outputs; (b) practice constraints' (e.g., acute-to-chronic exercise or recovery related) effects on coordination aspects [3]; most importantly, (c) individual weaknesses in need of improvement, thereby allowing the provision of specific feedback to refine movement patterns [4]. Currently, among the tools available to examine kicking movement performance, video analysis originates the most objective and sensitive kinematic metrics, which are not always captured by only visual ratings [5]. In fact, video analysis has been used in some other research fields (e.g., animal displacement detection and analysis), as well as in a range of sports [6–14]. However, while ecologically valid assessment protocols using an on-field multiple-camera setup (such as high-speed action sport cameras [15]) have made it possible to record the three-dimensional and open nature of soccer kicks, flexible/reliable and boosting image processing methods are still required to provide useful information to practitioners in due time [3,16,17].

Traditional excess of the manual digitisation necessary in obtaining body landmark position time-series information is one important issue related to video kinematic investigations of kicking [18–20], which would render as long as half a year of data processing depending on sample sizes [21]. Indeed, manual tracking generally results in the existence of both inter- and intra-operator variability in labelling [22] and is highly dependent on marker sharpness/contrast in relation to the skin and environment [23,24]. Furthermore, game rules do not always allow players to wear objects [25], implying that kick assessment routines should attempt to respect the realities of competition [3]. The latter can also prevent athlete monitoring with foot-mounted sensors [26], or otherwise attaching any apparatus to the player's body may interfere with their normal technique [27–29].

Thus, publicly available markerless motion estimation algorithms seem to be a potential solution in analysing video data and extracting kick kinematics in a likely less time-consuming, more cost-effective, and non-invasive way. For such purposes, advanced computer vision and deep learning techniques (e.g., convolutional neural network (CNN) mask) [30] have been applied whilst the validity of the various contemporary markerless systems is still lacking consensus in research (for a recent review, see Cronin [31]).

To date, results on the performance of a widespread, state-of-the-art open-source pose estimation tool called 'OpenPose' [32] are found for a range of dynamic tasks, including human walking [33], running [34], jumping [35], and ball throwing [36]; this method demonstrated acceptable functioning in two- [33,37] or three-dimensional [34–36] plane analysis (e.g., agreement with measures derived from 'gold-standard' marker-based kinematic systems). Either of these previous experiments assessing movements pertaining to team sports was notably performed indoors in such controlled environments as a laboratory room. To our knowledge, no studies determined its measurement error under field conditions such as a soccer pitch scenario and considering the inclusion of ballistic (explosive) tasks involving object manipulation using the lower limbs such as in ball kicking. Differently from a throw, during kicking actions, one limb is fixed on the ground while another moves in parallel, generating some blocking between these body segments in the camera's view, which can influence tracking effectiveness [31]. Notwithstanding, as this method involves the recognition/estimation of key body points in each image (i.e., video frame) separately, the implementation of tracking strategies represents an important attempt to further improve such a tool in motion analysis, despite the fact that it was almost overlooked in the existing works specifically interested in sports tasks. Additionally, non-controllable aspects comprising lighting, possible mutual occlusions and diversified subject/background configurations may often collectively interfere during image processing in team sport real-world contexts [13,29,38]. Therefore, the purpose of the current preliminary study was to compare traditional frame-by-frame manual and modified OpenPose automatic motion tracking methods in determining soccer kicking movement kinematic parameters in a naturally occurring environment.

5.3. Materials and Methods

5.3.1. Data acquisition

In an official, FIFA-standard, natural grass pitch, four tripod-mounted digital video cameras (240 Hz, 1920 × 1080 pixel; Hero 7/Black Edition, GoPro® GmbH, München, Germany) were distributed perpendicular to each other and 2.5 m laterally to the established kick mark (18 m apart from the midpoint goal line). An experimental dataset (unpublished observations) including six outfield—defenders, midfielders and forwards—U17 academy players was used (16.1 ± 1 years old, 176 ± 6 cm, 71 ± 11 kg). Spherical markers (25 mm diameter) were attached externally on the participant's greater femoral trochanter and also, on the non-dominant side, the lateral malleolus, calcaneus, and distal phalanx of the fifth metatarsal head (dominant limb). As illustrated in Figure 5.1A, kick attempts were performed near the entrance of the penalty area (18 m from the midpoint goal line), and participants were instructed to strike the target's centre (1 × 1 m in both goalpost upper corners) while avoiding a teammate goalkeeper intercepting the ball. A detailed description of the design of the field assessments and the test–retest reliability measures of the task adopted to measure soccer kicking characteristics are both available elsewhere [39]. Following collection, image sequences were transferred to a computer Ubuntu 20.04.2 LTS (Intel i7-8750H (12) @ 2.208GHz; 16GB RAM; Intel Corporation, Santa Clara, USA) with GPU (GeForce GTX 1050 Ti; 4096 MB GDDR5; NVIDIA Corporation, Santa Clara, USA), and 30 kicking attempts were randomly selected (https://www.random.org; accessed on 8 July 2021) for further analysis.

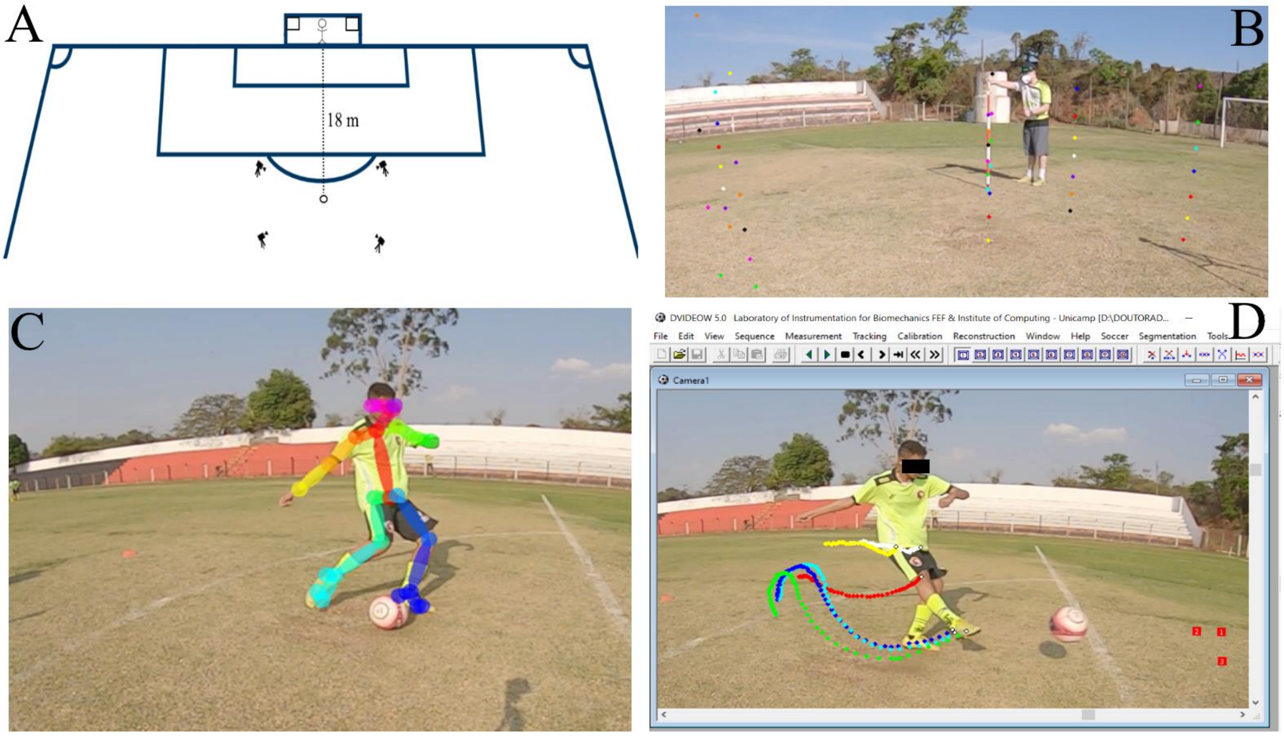

Figure 5.1. Illustration of (A) experimental setup used for data collection, (B) calibration, (C) a given kicking trial digitised using OpenPose markerless system and (D) manual tracking frame by frame.

5.3.2. Motion tracking

5.3.2.1. Manual digitization

Manual frame-by-frame tracking of markers was completed (Figure 5.1D) by a single experienced (>10 years) examiner using the DVIDEOW interface (v.5.0; Laboratory of Instrumentation for Biomechanics & Institute of Computing UNICAMP, Brazil—see Figueroa et al. for more information [40]). This motion tracking method is considered as the reference measurement in the current study. The audio-band feature embedded into the software was employed to synchronise the video cameras before tracking [41]. The image sequences of the same initial and final events and the duration (i.e., number of frames) were inputted in DVIDEOW and OpenPose tracking methods. A common calibration frame containing 49 control points was also defined for both in order to completely cover the kicking area (3.6 × 3.2 × 1.3 m, respectively, in antero-posterior, medio-lateral and vertical directions—Figure 5.1B). Reconstructed calibration points were compared to the reference values entered by the operator to compute a global error.

5.3.2.2. Markerless system

OpenPose is a bottom-up deep-learning-based approach designed to estimate human pose and joint angles. In brief, this approach estimates and encodes the locations (Figure 5.1C) and orientations of the limbs, in addition to the association score between body parts. For this, the method produces confidence maps that encode the location of each body part in the image domain. Then, a set of 2D vector fields of part affinity fields (PAFs) is used to encode both location and information. Next, the PAFs are used to estimate the degree of association between the body parts, which is used to assemble the limbs and thus come up with a full-body pose for all people in the scene. A more detailed description of this method can be found in [32]. Although OpenPose can detect the pose of all people in a scene, a tracking strategy is necessary for associating a set of poses found in the frame t with their respective poses detected in a subsequent frame t + 1. In this work, we proposed a simple tracking strategy that firstly consists of computing the centre of mass of a given pose in the frame t. Then, we associate it with the pose in the frame t + 1 whose centre of mass presents the smallest Euclidean distance. We take advantage of the K-Means algorithm [42] for efficiently computing the pairwise distances between a set of poses found in the frame t and frame t + 1. The source code is freely available for scientific purposes on GitHub repository (https://github.com/allansp84/allansp84-markerless-motion-detection).

5.3.3. Data treatment and measures

In a Matlab® environment (R2019a; MathWorks Inc., Natick, MA, USA), 3-dimensional coordinates were obtained from Direct Linear Transformation (DLT) [43], with previous correction for radial lens distortion [44] caused by the type of action that the sports cameras used. The raw data from both methods were treated with a dual filter fourth-order Butterworth plus rloess [45,46], using a span equal to 0.1 and a cut-off frequency of 25 Hz as smoothing parameters, which were set after a residual analysis. The dependent variables of the current study were determined for all kick attempts using custom-built routines and included: (a) time-series reconstructed 3-dimensional position of each marker; (b) its associated time-series velocity; (c) foot centre-of-mass (CM_{foot}) velocity at impact; (d) angular range of motion (ROM). Velocity outputs were taken from finite central differences using time-series data of the entire attempt duration as input arguments [18]. CM_{foot} velocity at impact was calculated from the three final frames just before ball contact considering the centroid of malleolus, calcaneus, and toe coordinates. Local reference frames and segment centres were defined as per previous studies [21,47]. Joint ROMs were then computed as the difference between the lowest and the highest joint (hip, knee, and ankle) angle values observed in the sagittal plane [47]. Independent variables were the two distinct methods used (DVIDEOW software for manual tracking and OpenPose markerless system) for the digitisation of the kicking motion.

5.3.4. Statistical analysis

The data were time normalised and presented as medians and 95% confidence intervals (CI). Significant differences between methods in time-series analysis were flagged when CIs did not overlap [21,45,48]. Mean absolute error (MAE) was computed according to Equation (1) [36] separately to support phase (1% to 65% of the cycle—starting from the take-off of the kicking limb until complete touchdown of the supporting limb in the last step before impact), contact phase (from 66% to 100% of the cycle, starting immediately following termination of the support phase until foot–ball impact [45]) as well as considering the whole kick cycle. Correlation coefficients were determined (time-series (corrcoef.m Matlab function) and single-point measures (Pearson product-moment (r) and intraclass correlation coefficients—ICC)) to gain insights about the random error and interchangeability of signals obtained among the two methods. For the latter, the statistical significance level was pre-set at $p \leq 0.05$. The correlation values (r, 95% CI) were deemed as being trivial (<0.1), small (>0.1–0.3), moderate (>0.3–0.5), large (>0.5–0.7), very large (>0.7–0.9) or almost perfect (>0.9–1.0). If the resulting CIs overlapped both small positive and negative values, then the correlation was deemed unclear [49]. Shared variance was considered small (r^2 < 0.30), moderate (r^2 > 0.3–0.5) or large (r^2 > 0.50). Ratio limits of agreement (RLOA) were also computed for the non-time-series parameters (joint ROMs and CM_{foot} velocity at impact) as a measure of systematic bias [50]. Finally, effect sizes (ES) assumed as standardised mean differences (Cohen's d) were calculated [51] for each comparison (Equation (2)) and interpreted as trivial (d < 0.2), small (d > 0.2–0.59), moderate ($d \geq$ 0.6–1.19) or large ($d \geq$ 1.2).

$$\mathrm{MAE} = \frac{1}{n}\sum_{i=1}^{n}|d_m(i) - d_a(i)| \quad (1)$$

$$\mathrm{ES}(i) = \frac{M_m(i) - M_a(i)}{\sqrt{\frac{\sigma_m^2(i)+\sigma_a^2(i)}{2}}} \quad (2)$$

Where: d_m = the data point obtained from manual tracking; d_a = the data point obtained from automatic tracking; n = the number of data samples; i = a given frame; M_m = the average obtained from manual tracking; M_a = the average obtained from automatic tracking; σ_m = the standard deviation of the values obtained from manual tracking; σ_a = the standard deviation of values obtained from automatic tracking.

5.4. Results

Figure 5.2 shows the time series of the absolute position data (x, y and z coordinates) of selected markers obtained from OpenPose automatic and DVIDEOW manual tracking methods, while Figure 5.3 contains its three-dimensional resultant velocity observed across the whole kicking movement cycle. Separate figures for all markers/axes are provided in supplementary online material S1. Global calibration errors were 0.9, 1.1 and 1.8 cm, respectively, in the x (antero-posterior), y (medio-lateral) and z (vertical) directions.

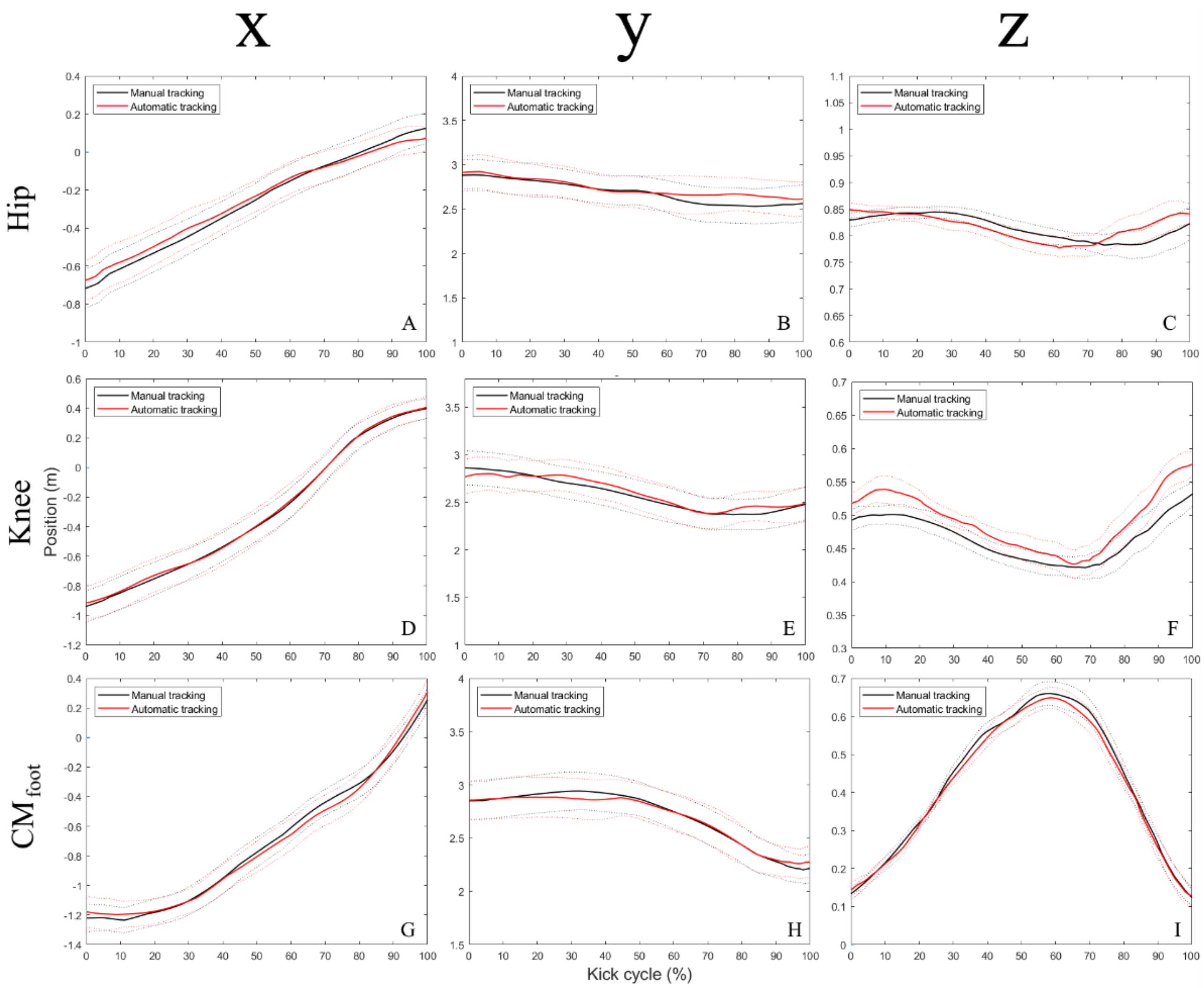

Figure 5.2. Time series containing median values (solid lines) and associated confidence intervals of marker's absolute position (x, antero-posterior; y, medio-lateral; z, vertical) computed across the whole kick movement cycle for both tracking methods (dominant hip x-axis (**A**), dominant hip y-axis (**B**), dominant hip z-axis (**C**), knee x-axis (**D**), knee y-axis (**E**), knee z-axis (**F**), CM_{foot} x-axis (**G**), CM_{foot} y-axis (**H**), CM_{foot} z-axis (**I**).

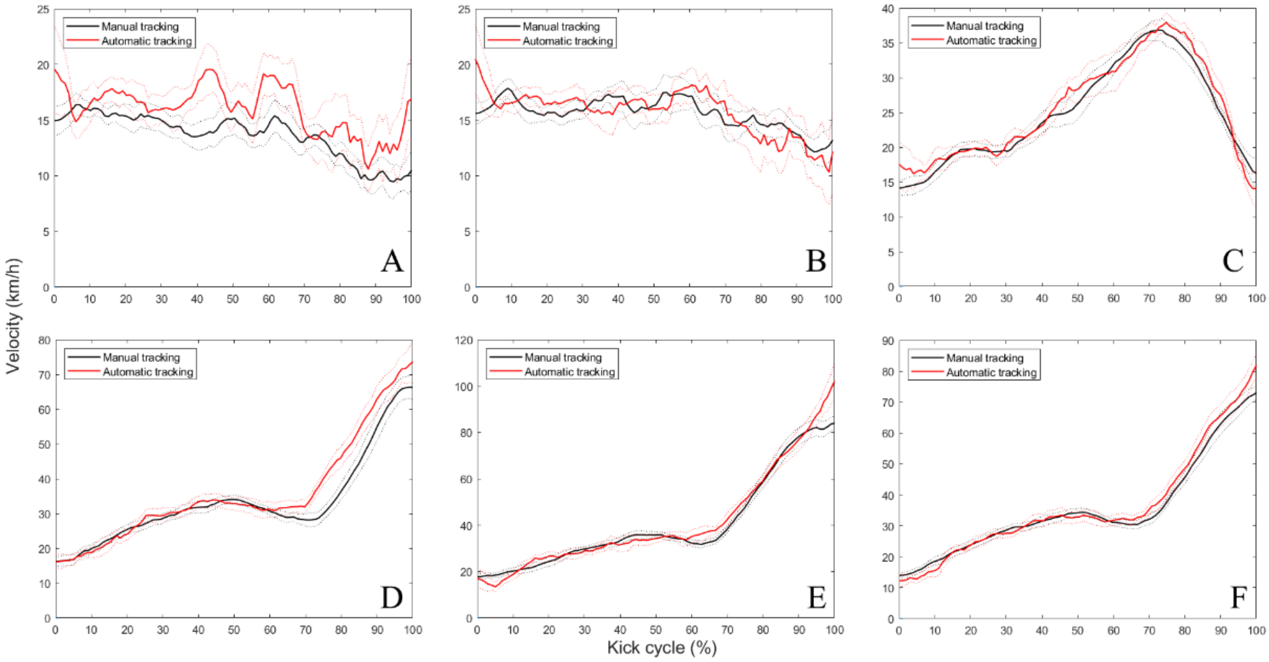

Figure 5.3. Time series containing median values (solid lines) and associated confidence intervals of marker's resultant three-dimensional velocity computed across the whole kick movement cycle for both tracking methods (non-dominant hip (**A**), dominant hip (**B**), knee (**C**), calcaneus (**D**), fifth metatarsal head (**E**) and CM_{foot} (**F**)).

Positional differences were observed between the two methods only in the z-coordinates of the knee (from 6 to 12%; 20% instant and 90 to 100% of kicking movement cycle—Figure 5.2F) and calcaneus markers (from 16 to 18%—Supplementary online material S1, Figure 5.1M). Hip (dominant and non-dominant), ankle, fifth metatarsal head and CM_{foot} (Figure 5.2G–I) showed no significant differences in their three-dimensional positions (x, y or z coordinates), computed by automatic as compared to manual tracking methods, during the whole kicking movement cycle. Overall effect sizes (Table 5.1) were trivial to small for the x coordinates (ES = 0.01 to 0.39 (mean = 0.17)) and y coordinates (ES = 0.06 to 0.32 (mean = 0.14)) and small to large concerning z coordinates (ES = 0.34 to 6.40 (mean = 1.59)).

Table 5.1. Effect sizes (ES) obtained for pairwise comparisons between OpenPose automatic tracking and DVIDEOW manual tracking positional data (x, antero-posterior; y, medio-lateral; z, vertical) and velocity outputs.

Marker	Position									Velocity		
	X-Axis			*Y*-Axis			*Z*-Axis					
	Overall	Min	Max	Overall	Min	Max	Overall	Min	Max	Overall	Min	Max
Non-dominant hip	0.01	−0.14	0.15	−0.10	−0.29	0.11	−0.77	−5.03	4.22	−0.08	−0.25	0.00
Dominant hip	−0.19	−0.34	0.44	−0.32	−0.63	−0.16	1.40	−3.99	6.33	−0.01	−0.11	0.08
Knee	−0.04	−0.39	0.45	−0.15	−0.23	0.00	−6.40	−12.32	−2.78	−0.02	−0.13	0.12
Ankle	−0.39	−0.84	−0.17	−0.15	−0.38	0.05	0.88	−4.71	4.12	0.00	−0.07	0.05
Calcaneus	0.29	−1.07	0.96	0.06	−0.08	0.22	0.75	−4.57	5.50	−0.05	−0.21	0.05
5th metatarsal head	−0.19	−1.71	0.15	−0.10	−0.39	0.05	−0.34	−6.22	1.85	−0.02	−0.11	0.04
CM_{foot}	−0.11	−1.23	0.26	−0.07	−0.23	0.10	0.61	−3.76	2.36	−0.02	−0.11	0.05

Large Moderate Small Trivial

In reference to the marker's velocity outputs, the overall differences between methods were trivial (ES ≤ 0.08 (mean = 0.03)) but reached significance in the non-dominant hip (from 15 to 20%, from 37 to 47%, from 58 to 67%, and from 98 to 100%—Figure 5.3A), dominant hip (from 1 to 2% and 65% instant—Figure 5.3B), calcaneus (from 68 to 90%—Figure 5.3D), fifth metatarsal head (from 5 to 7%, 17% instant, from 64 to 68%, and from 97 to 99%—Figure 5.3E) and CM_{foot} (from 6 to 8%, 71% instant, and from 99 to 100% of kicking movement cycle—Figure 5.3F). Knee showed two separate differences (48% and 97% instants—Figure 5.3C), whilst ankle velocity was similar (supplementary online material S2) between OpenPose automatic and DVIDEOW manual tracking methods (ES ≤ 0.07 (trivial)) across the whole kicking cycle (supplementary online material S3).

Table 5.2. Mean absolute error (MAE) for three-dimensional positions (cm) and resultant velocity (m/s) of each joint derived from comparisons between DVIDEOW manual digitisation and OpenPose automatic tracking algorithm.

Marker	Support Phase					Contact Phase					Whole Kick Cycle				
	X	Y	Z	All	VEL	X	Y	Z	All	VEL	X	Y	Z	All	VEL
Non-dominant hip	2.76	1.86	6.54	3.72	1.42	3.11	2.82	7.03	4.32	1.66	2.88	2.20	6.71	3.93	1.50
Dominant hip	2.65	2.49	5.88	3.67	1.06	3.04	2.91	8.98	4.98	1.29	2.79	2.63	6.96	4.13	1.14
Knee	1.91	2.45	4.40	2.92	0.84	1.91	3.19	3.31	2.80	1.14	1.91	2.71	4.02	2.88	0.95
Ankle	3.29	2.09	5.48	3.62	1.54	3.02	1.99	4.68	3.23	1.06	3.19	2.05	5.20	3.48	1.37
Calcaneus	4.44	2.22	5.47	4.04	1.10	4.62	2.59	3.84	3.68	2.12	4.50	2.35	4.90	3.92	1.45
5th metatarsal head	2.60	1.98	5.59	3.39	1.23	3.40	2.13	3.70	3.08	1.81	2.88	2.03	4.93	3.28	1.43
CM_{foot}	2.50	1.41	4.87	2.93	1.14	2.93	1.41	3.18	2.51	1.24	2.65	1.41	4.28	2.78	1.17
Overall	2.88	2.07	5.46	3.47	1.19	3.15	2.43	4.96	3.51	1.47	2.97	2.20	5.29	3.49	1.29

VEL = resultant 3-dimensional velocity; X = antero-posterior; Y = medio-lateral; Z = vertical directions.

The overall MAEs of the OpenPose motion tracking method as compared to manual digitisation was 3.49 cm for determining positions and 1.29 m/s for calculating markers' velocity (all pooled). In particular (Table 5.2), these values ranged, respectively, from 2.78 cm (CM_{foot}) to 4.13 cm (dominant hip) and 0.95 m/s (knee) to 1.50 m/s (non-dominant hip). ROM showed *large-to-very large* correlations between OpenPose automatic and DVIDEOW manual tracking methods, respectively, for the ankle (r = 0.59 (± 0.40), $p < 0.01$; ICC = 0.47, $p < 0.01$; RLOA = 0.655 ×/÷ 1.758; 1.08 [0.92; 1.24] and 1.41 [1.33; 1.49] rad) and knee joint displacements (r = 0.84 (± 0.08), $p < 0.001$; ICC = 0.82, $p < 0.001$; RLOA = 1.072 ×/÷ 0.323; 1.91 [1.83; 1.99] and 1.86 [1.76; 1.96] rad), but it was *unclear* in the hip (r = 0.04 (± 0.15), $p = 0.85$; ICC = 0.01, $p = 0.48$; RLOA = 0.520 ×/÷ 1.940; 0.86 [0.43; 1.28] and 1.14 [1.08; 1.20] rad), while CM_{foot} velocity at impact showed a moderate correlation (r = 0.48 (± 0.23), $p < 0.01$; ICC = 0.47, $p < 0.01$; RLOA = 1.021 ×/÷ 0.046; 21.57 [20.77; 22.36] and 19.70 [19.04; 20.36] m/s, respectively). Finally, large average shared variances were found among methods in their resulting matrix of position ($r^2 = 0.94$ [0.73; 0.99], all $p < 0.001$) and velocity signals ($r^2 = 0.68$ [0.46; 0.92], all $p < 0.01$).

5.5. Discussion

The current study aimed to compare the OpenPose automatic motion detector method [32] against traditional frame-by-frame manual digitisation (DVIDEOW software) conducted through a relatively flexible interface [40] in determining on-field soccer kicking movement kinematics. Furthermore, a simple tracking algorithm was proposed to overcome the original limitation of OpenPose that provides a set of full-body poses per frame without any tracking information, allowing us to determine the set of poses for a specific person over time. To the extent of our knowledge, no previous work has investigated the reliability aspects of markerless tracking in ball kicking drills. In the following paragraphs, the strengths and weaknesses relating to the application of such advanced tracking methods are discussed—in particular, within the context of kicking kinematics analysis—and recommendations for possible further improvements are also provided.

Manual tracking systems (marker-based) are one of the most common computer methods adopted in measuring the kinematics of soccer kicks to date, despite their possible impractical characteristics. According to the original results obtained, a markerless algorithm can help to successfully obtain lower limb position and velocity outputs during kick tasks performed in an official outdoor pitch. Critical parameters related to kicking effectiveness, such as those derived from knee and ankle joint kinematics, showed acceptable levels of error when computed by the OpenPose algorithm as compared to traditional tracking (i.e., manual frame-by-frame tracking of kick movement features [18,19,52–54]). Conversely, hip motion demonstrated the worst outcomes using this procedure in all of the position, velocity and angular aspects. Notwithstanding, while the accuracy of the x axis and y axis was generally preserved, most sources of uncertainties when using the contemporary tracking tool were likely due to discrepancies identified in the *z*-axis (vertical) coordinates among methods, indicating that advances in the OpenPose motion detector are still necessary, mainly in the hip segment. Regardless, such a markerless system can be helpful for performance-enhancing purposes (training to correct occasional inefficient movements) as well as possible clinical cases (e.g., identifying athletes with potentially excessive plantar flexion amplitude; Tol et al. [55]) owing to the presumable interchangeability of its signals with manual digitisation.

In biomechanical investigations, the validity of the measures is invariably a concern, notably in field testing where non-controllable/unexpected factors usually exist. In a first analysis, the error values found were within the range reported previously by applying OpenPose to other human movements—primarily performed with the lower limbs—which were found to be 2 cm in walking at a comfortable pace [56], about 3–4 cm in walking plus quick jumping conditions [36] and up to 5 cm on average in sprinting bouts [28]. However, variable acquisition frequencies (30 [56], 120 [36] or 240 [35] Hz), number of cameras (one [33], two [34,35,56], five [36] or nine [28]), their positioning (e.g., 1.8 [34], 2.3 [56] or 6.35 m [33] away from the subjects) and recording resolution (640 × 480 [56], 1280 × 720 [35], 1920 × 1080 p [28] or 4K [36]) may constrain such a direct comparison of our results and literature. In general, such previous studies also used experimental setups including cameras with apparently traditional optical systems (e.g., linear field of view) in which no mention was made concerning whether the image sequences were corrected for eventual distortions. Thus, it is plausible to state that action sport cameras were not tested among existing works, which highlights another innovative aspect of the current study. Regardless, these documented results indicate that, similar to that occurring with other biomechanical position monitoring systems [57], uncertainties of OpenPose may be speed dependent. In accordance, we have verified some increases in error values (e.g., average +8.23% and +15.07% in *x*-axis positions and resultant velocities across markers, respectively) from the support to contact phase of kicking (Table 5.2). Of note, distal endpoint kicking velocity increased from ~33–37 km/h in toe-off to 84–102 km/h at the ball contact instant, as exhibited in Figure 5.3E. These sudden changes in velocity could alter the image properties (e.g., might add some blurred pixels), thereby influencing motion estimation [31]. Furthermore, CM_{foot} velocity—a key parameter of performance—showed infrequent but significant systematic bias across time moments of the kicking cycle, including ball impact. Conversely, random error appears to be low given the significant correlations between methods, whilst the RLOA of CM_{foot} velocity at impact is also compatible with previous studies measuring kick velocity [58,59]. In this sense, given the habitual distortion caused by foot–ball impact on the kicking kinematics data, excluding the last few frames of the contact phase is not uncommon [3,45,60] and could also solve this issue despite improvements in the precision of foot detection being mainly required in investigations focused on depicting the full ball-impact phase.

Here, the OpenPose method had superior performance in determining antero-posterior/medio-lateral (respectively, *x* and *y* axis) than vertical (*z* axis) positions (Table 5.1). The same occurred for intermediate-to-distal (knee, ankle, and foot) limb kinematics—position, velocity and angular amplitude—of the contact limb as compared to the proximal joint (hip) involved in the action (Table 5.2). It should be noted that the resulting velocity was slightly impacted by the worse results in the z coordinates/vertical direction that are seemingly cancelled by acceptable functioning in the remaining pair of axes. The strong similarity of signals between methods (e.g., as indicated by r-squared outcomes and also the waveforms—Figures 5.2I and 5.3C) indicates the presence of more systematic rather than random error. This is further illustrated by the significant associations observed from the resulting ROM (knee and ankle) and CM_{foot} velocity outcomes among the two methods. As shown in Figure 5.3, all important events such as continuous knee acceleration throughout the support phase followed by a reversal to deceleration—around 70% of the cycle—concomitantly with the foot acceleration, which is a typical illustration of proximal–distal energy transference during kicks, were correctly identified. The highest discrepancies between automatic and manual tracking in z coordinates might be partly attributed to a concomitant greater global calibration error magnitude that was observed in this specific axis, meaning that uncertainties in the vertical direction are themselves the poorest. Lower precision in obtaining hip movements is also observed elsewhere in squat and locomotion tasks [34,37]. The hip is generally entirely covered by clothing (shorts/t-shirt) [61], with unconstrained portions that are not well fixed to the body, and this probably causes an undefined/more variable pattern of appearance in image sequences, while this is not the case or might be at least reduced in the remaining equipment (socks and clothes) covering the leg and foot segments. In addition to being wider, by the under-17 age, the hips and thighs are also longer [21] as compared to the lower leg, thereby involving image processing of a greater number of pixels, perhaps increasing the complexity in keypoint detection of the former. In the case of kicking assessed using only lateral cameras, given the common path of players in the approach run and subsequent ball flight, issues in markerless tracking can be also attributed to a longer mutual occlusion of hip joints as compared to the knee and ankle—in particular, the overlapped proximal region of both thighs in the image sequences across a substantial trial duration. Taken collectively, it can make the process to precisely detect and track the hip joint more challenging in some instances. Therefore, hip kinematic outcomes of kicking should be interpreted with caution when using OpenPose. The possible advantages of including a camera behind the player trajectory (i.e., posterior view) in addition to a higher sampling frequency should be tested in future research.

Additional limitations are also recognised to this study, which collectively indicate taking caution in any generalisations made. Firstly, given the practical difficulties in conducting repeated measurements within soccer clubs, the cross-sectional design of the present comparative analysis prevents the calculation of minimal detectable differences. Secondly, re-training based on our own dataset characteristics may contribute to further reducing errors arising from possible algorithm false detections [62]. Thirdly, a relatively small sample size was used here to evaluate the performance of a markerless algorithm, despite this not being uncommon, as some published pilot or validation studies have included, for example, only two [36,56], six [63], or a maximum of nine participants [64]. Fourthly, assessment outcomes may fail to replicate actual soccer match demands, possibly limiting the results to only testing routines. Finally, as soccer kicking performance is age dependent, a priori extrapolation of results to senior players may not be warranted.

5.6. Conclusions

In short, empirical evidence provided by the current experiment indicates that the OpenPose tracking method may be a reliable tool with which to evaluate soccer kicking kinematics in youth soccer under grassy pitch conditions, providing compatible data to those obtained from traditional frame-by-frame manual digitisation. In particular, we were more confident in knee and ankle joint preliminary outcomes, whilst hip detections should still be improved to reduce between-methods differences. Markerless motion tracking systems such as OpenPose seem to be a pertinent option to help fill a critical gap currently existing between research and soccer practice, mainly in the analysis of ball kicking skills, since it reduces the time spent in processing the data dramatically, while its precision in computing position and velocity is generally not compromised. Future work is recommended to further check the validity of the proposed method against microtechnology devices or 'gold-standard' marker-based (semi)automatic tracking measures provided by infrared cameras, despite the difficulties in implementing the latter in the "real-world" rather than within a laboratory or indoor artificial turf soccer pitch.

5.7. References

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CHAPTER 6

TEMPORAL DYNAMICS OF KICKING PARAMETERS GIVEN A PLYOMETRIC-BASED WARM-UP ROUTINE

6. PAPER 5 – Post-drop jumps kick potentiation in youth trained soccer players: temporal changes in EMG, kinematics and performance components [(6)]

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6.1. Abstract

Scientific studies testing warm-up routines and their effects on subsequent soccer kicking features are restricted to only-stretching based or unloaded resistance, with no information to date on the possible consequences of priming plyometric efforts as the main conditioning activity (CA). Therefore, this study addressed the possible effects of a warm-up intended to cause postactivation performance enhancement (PAPE) based on traditional prescription (low intensity running and dynamic stretching) followed by conditioning repeated drop-jumps. Also, time-course of PAPE expression in kicking indices was determined over five blocks, before (Pre) and after (immediately, 5, 10 and 15 minutes) CA cessation. Fifteen under-17 soccer players (16 ± 1 years; 2 ± 1 year from peak height velocity) kicked stationary balls from the entrance of the penalty area aiming at square target positioned in their contralateral goalpost upper corner, in each of the five blocks of assessment. All procedures were conducted on-field in habitual training/match time. Kick attempts were monitored using wireless EMG and concomitant video kinematics to obtain limb motion and performance parameters (ball velocity and placement). Some increases in EMG indices were observed between 5 (rectus femoris activation and median frequency) and 10 minutes (biceps femoris median frequency) after CA. Angular velocity of knee extension in 5 minutes was greater than immediately post. Frequency of missed kicks increased immediately and post-15 minutes. Ball speed and other placement-derived indices remained stable from pre to all post-measures. Kicking ball velocity was correlated with vastus lateralis and rectus femoris EMG (integral and RMS). Ball placement was associated with approach run velocity and biceps femoris activation. To conclude, following a traditional warm-up plus conditioning drop-jumps, PAPE effect was observed only in a restricted number of neuromuscular parameters in under-17 players that are not generally converted into acute harm or benefits to movement mechanics and performance responses. Distinct muscle activity indicators may act as determinants to ball velocity and placement in youth soccer. **KEY WORDS**: football; pre pitch-entry; PAPE; plyometric; accuracy; conditioning; neuromechanics.

6.2. Introduction

Postactivation performance enhancement (PAPE)-based techniques have been extensively used among strength and conditioning professionals in applied settings via prescription of conditioning activity (CA) generally ranging from separate or combined submaximal running, stretching, resistance and plyometric exercises (9, 10). The PAPE has been defined as a phenomenon by which acute improvements are observed in muscle performance characteristics (e.g. voluntary force production) or athletic outcomes itself as a result of the musculoskeletal system contractile history (9, 11, 45). Mechanisms contributing to PAPE includes muscle temperature, water content and activation while inhibition aspects comprise fatigue, motion pattern and perseveration (9). Inducing PAPE through plyometric CAs prior to explosive criterion tasks can shows superior positive effects or at least similar to traditional warm-up methods (33, 56, 57). In the context of youth soccer, plyometric exercises have been recognised to induce important chronic functional adaptations, including gains in muscle strength and power, endurance capacity, balance and coordination (7, 48, 49) essentials to overall performance in soccer as well as various of these aspects are in particular determinants to technical outputs such as required in ball kicking (28, 58, 70).

Ball kicking movement requires ballistic contractions of the lower limbs (5). As a consequence, adding some load in CAs to attempt induce PAPE in kicks seems reasonable owing to the fact that it favored acute neuromuscular responses and performance in activities of similar etiology, in both professional senior and young players (e.g. jump and running; (51, 64, 72)). In this sense, previous studies in university and professional players (aged ~19–23 years-old) reported that dynamic stretching/resistance CAs using only bodyweight (BW) (1-5, 22, 43) were sufficient to increase kicking performance in soccer (e.g. hip flexion-extension range-of-motion, knee extension angular velocity and ball velocity). Additional work in children revealed benefits to kicking accuracy (21). These results suggest the manifestation of post-stretching kick potentiation mainly due to priming dynamic stretch-based CAs in boys or senior players. However, warm-up routines in soccer are not restricted only to isolated stretching exercises, there is no information to date in youth (teenager) population and of great importance assessment of neuromuscular activity has been also overlooked in kick attempts (51). This indicates that PAPE mechanisms related to soccer kicking skill lacks scientific support. Furthermore, the experimental studies evaluating PAPE in soccer kicking involved only trials with initial ball position ≤ 11 m from the goalposts, characterised as events with low frequency in real match-play and targets were only centered in the goal plane, which collectively represents kick testing approaches with low external validity (43). To the extent of our knowledge, while long-term training effects of plyometric exercises have been known to be positive (velocity or horizontal distance attained by the ball (12, 49, 53)), the possible acute influence of this mode of CA upon kicking characteristics was never addressed (see for a review in (43)). Notwithstanding, warm-up routines applied to developing players increasingly adopt high-intensity CAs in addition to stretching, based on the assumption that the former can facilitate a PAPE state to a greater degree than traditional methods (62, 64, 72). Yet heavy-loaded CAs generally requires additional load and installations outside the pitch environment, likely implying some associated financial costs and logistic constraints. In addition, they can generate higher immediate fatigue thereby potentially delaying PAPE expression (71). Conversely, those low-intensity ballistic/explosive CAs are possibly preferable in team sports as they are equally capable of causing subsequent recruitment of high-order muscle fibers, evoked force and performance enhancements (16, 33, 37) without the need for specialized external (load) apparatus.

Available studies on PAPE effects in youth still shows conflicting evidence, with acute increases (38), no changes (61) or decreases (18) in motor performance (i.e. running at high-intensity and jumping) have been simultaneously reported. A possible explanation for this discrepancy across studies fell again on the use of an unstandardized intensity across papers (e.g. BW–5RM). Given that youth do not seem to sustain benefits of PAPE to the same magnitude as observed in senior players (32), it is still necessary to clarify whether low-intensity ballistic CAs using own BW (e.g. plyometrics) would be effective to increase kicking performance preparedness in this population, since this mode of exercise originates less muscle by-products which favoured ensuing power performance as compared to heavy-resistance on teenagers soccer players in a preliminary study (57). Most important, to date and regardless of age and CA type no studies determined the temporal expression in terms of kicking performance measures integrating velocity and ball placement analysis given PAPE protocols according to a recent systematic review (43). Determining the time-evolution of criterion task performance following cessation of CA is important to offer knowledge on whether an "optimal" time-moment exist (i.e. when potentiation effects overcome fatigue expression) and how much time intended benefits can persist. Based on such assumptions, the present study aimed to analyse, in youth soccer players, the post-drop jumps kick (unknown) potentiation/depression effects. The time-course of possible changes in neuromuscular, movement kinematics and outcome in soccer kicking after drop-jumps cessation was also determined. Finally, relationships between kicking EMG, kinematics and performance were also examined. The hypothesis was that plyometric-based PAPE protocol would promote positive effects on various kicking components - aiming at a far target - in youth soccer players, by notably enhance muscular readiness and consequent faster movement and ball velocities following 5 minutes of CA termination (33, 56).

6.3. Methods

6.3.1. Participants

Sample size calculation was done a priori (software G*Power© 3.1.9.2, Universität Düsseldorf, Germany) based on results of previous experimental studies from Amiri-Khorasani and collaborators (4, 5), considering positive responses in neuromuscular, mechanics and performance of soccer kicking after dynamic conditioning exercises (i.e. increases in RMS of vastus lateralis and rectus femoris, knee angular and ball velocities; effect size ≥ 0.8). Fifteen under-17 trained soccer players (16.3 ± 0.9 years-old; 64.1 ± 11 kg; 172 ± 9 cm; 2.1 ± 0.7 years from peak height velocity), competing at regional/state level composed the sample (statistical power = 80%; $\alpha = 0.05$). Training background of the players consisted in three to four practice sessions per week (including separate resistance tasks for at least 1 year) and one competition game on weekends. The study followed a cross-sectional design with repeated measures of kicking variables (EMG, kinematics and performance) being collected before and after the execution of the selected warm-up PAPE-based intervention. All procedures were approved by the Institutional Ethics Board (approval number CAAE85994318.3.0000.5398). Players and respective guardians were informed of the benefits and risks of the study prior to signing respectively assent and consent forms, confirming participation as a volunteer.

6.3.2. PAPE protocol

The overall warm-up process lasted approximately 17 minutes across subjects and included three distinct phases: 1) initiation consisting in low-intensity running bout (4 minutes at a 5 km/h pacing) followed by 2) dynamic stretching to the lower limbs (2, 5) and ended with 3) drop-jumps as the main CA prior to performing kicks (14, 16, 37). Velocity of running was controlled using beeps through a pre-defined linear/curvilinear route demarked by cones in the pitch. A dynamic stretching routine was implemented as per previous studies (1-3, 5) and included exercises to stimulate the gastrocnemius, hamstrings, hip extensors, hip flexors, quadriceps and hip adductors. These were performed by the participants in the order stated and alternating between legs within each series. A total of 3 series x 30 s exercising (approximately 15 s in each leg) x 1 cycle of stretch-shortening per second was completed [full description of stretching method available elsewhere (2, 5)]. After finishing stretches, players undertook 5 repetitions of drop jumps with 15 s passive resting intervals between then. In each repetition, the athletes started on top of a box (30 cm height) (47) and were instructed to keep their hands on the waist, step down to the ground and in sequence perform a jump as explosively as possible to attain maximal individual height; notable brake between the descending and ascending phases of drop-jump was not allowed (14, 16, 47).

6.3.3. Kick testing

To determine kick-derived indices, a field testing protocol adapted from (41) was used here. In short, players were asked to kick stationary balls (PENALTY® company – FIFA-stamped, 5 sized, 430 g, 0.7 atm controlled across the experiment) positioned 18 m apart from the midpoint goal line, using the instep portion of the preferred limb with maximal velocity and aiming at the centre of a hollow iron square (1 m^2) target allocated in the contralateral goalpost upper corner. Further details on task constraints (e.g. approach run, justifications and day-to-day reliability) are available elsewhere (41). Three kick attempts (8) interspersed by 40 s rest were given to the players at each of the 5 time-moments they were evaluated. All procedures (warm-up and kick testing) were performed outdoors in an official pitch with natural emerald grass, during the mid-afternoon period of which the participant club generally train/compete.

6.3.4. Dependent measures

EMG. Monitoring of muscular activity was done using a wireless eletromyographic system (Mini Wave Infinity – COMETA© srl, Bareggio, Italy) with bipolar surface electrodes (Ag/AgCl, circled – 2 cm centre-to-centre) attached to the muscles vastus lateralis, rectus femoris and biceps femoris of the preferred limb (4, 28, 34), in accordance with SENIAM guidelines (http://www.seniam.org). Before electrodes fixation, the skin was shaved, sanded and cleaned with alcohol (70%). The EMG signals were collected with an acquisition frequency set at 1000 Hz, gain of 400 times and a 8–500 Hz bandpass filter (28). Subsequently, the data were treated by a 4th-order Butterworth high-pass filter (cut-off frequency = 20 Hz). Kicking attempts were then cropped considering a time-window of interest lasting from -450 ms to ~impact instant based on the identification of vastus lateralis peak activity recorded (13). Thus, for each attempt/muscle the following dependent measures were extracted: (a) median frequency, being defined as the frequency in which the spectral power is divided into two equal parts after the EMG signal passed through the FFT (Fast Fourier Transform) (65); (b) percentage activation, taking the average normalised time-window values by dividing it to the maximal EMG observed for each muscle in each specific attempt (34); (c) root mean square (RMS) and (d) integral (area under the curve) indexes (4, 6).

Movement kinematics. Two digital video cameras (GoPro® model Hero 7, GoPro GmbH, München–Germany) tripod-mounted operating at 240 Hz (1280 x 960 pixel resolution; 1/480 s shutter speed; NTSC and wide field-of-view modes) and synchronized via proprietary remote control were allocated laterally to the initial ball position in order to capture lower limb behaviour and initial ball flight across kick testing. The kick zone was calibrated (3.47 x 3.08 x 1.30 m) using a rigid object resulting in 49 control points. Image sequences were transferred into a laptop computer (Dell Inc., Intel(R) Core™ i7-10510U, Texas–USA) and to automatically obtain time-series position of lower limb keypoints of interest (all derived from the hip, knee, ankle and foot were used), it was applied an updated version of the OpenPose algorithm (42) that showed overall error lower than 35 mm in determining kinematics of soccer kicking of youth-aged players. Combined data from both cameras allowed three-dimensional DLT (Direct Linear Transformation) reconstruction through a custom-built Python 3.8.3 code (Python Software Foundation, Delaware–USA) after radial distortion correction (52). Matrices of position as a function of time were then exported to MATLAB R2019a environment (MathWorks Inc., Natick–USA), linearly extrapolated in 20% after foot-ball impact, treated by a dual filter [Butterworth (cut-off frequency=25 Hz) and rloess (span=0.1)] and then such estimated data following impact was removed from further analysis. Approach run velocity, joint angles in the sagittal plane [and consequent range-of-motion

(ROM)], peak knee angular velocity, foot centre-of-mass (CM_{foot}; obtained from the centroid of ankle, heel and small toe coordinates) linear velocity and leg relative velocity (formally described as CM_{foot} to knee relative velocity at impact) were computed as described elsewhere in (40, 41).

Performance parameters. Ball velocity was taken from its centroid trajectory across the 10 frames following impact with the foot (40), using the image sequences and calibration files as for movement kinematics. The peak ball speed reached among the three trials was then conserved for further analysis. Two additional video cameras having the same model as those above stated, adjusted at 60 Hz sampling frequency (1920 x 1080 pixel resolution and linear field-of-view mode), were tripod-mounted (i) above the goal line in its intersection with penalty area line, to detect the exact moment when the ball entered the goal and (ii) frontally to the goalposts in order to obtain the 2-dimensional position of ball centroid in the DVIDEOW software (52). To provide a calibration frame, goalpost dimensions (7.35 x 2.32 m) and its four extremities were considered as the control points. Thus, for each kick attempt the Euclidean distance between the manually digitised ball centroid and target centre was calculated. This allowed for each time-windows of assessment the subsequent determination of various ball placement measures: mean radial error, bivariate variable error, global accuracy (41, 66, 67), percentage of kicks on-target and the absolute frequency of missed kicks.

6.3.5. Independent variable

Time of data collection was considered as the independent variable in the present study and included kicking measures taken at baseline (Pre) and immediately, 5, 10 and 15 minutes following the cessation of the drop-jump conditioning activity. These 5-minute epochs were chosen considering that three repeated kick attempts of a same block were interspersed with 40 s intervals and to allow at least 3 minutes for passive resting (41) between the execution of the last kick attempt of a given block and the first one pertaining to the subsequent block, a total of 5 minutes were thereby required.

6.3.6. Statistical analysis

Normality of the data distribution was checked by the Shapiro-Wilk's test, kurtosis, skewness and visual inspection. To obtain reliability estimates, Pearson product-moment (r) and intraclass correlation coefficients (ICC), typical error (TE) and coefficient of variation (CV) were calculated (https://sportsci.org/resource/stats/xrely.xls). For those variables normally distributed, values are presented as mean ± standard deviation. One-way ANOVA with repeated-measures was ran to evaluate the time-course expression (Pre, Post, 5, 10 and 15 minutes) of kicking-derived variables. Fisher's LSD post-hoc was applied for pairwise comparisons. Effect sizes were calculated as the η^2 ($\eta^2 > 0.01$, small; $\eta^2 > 0.06$, moderate; and $\eta^2 > 0.14$, large) and Cohen's *d* ($d > 0.20$, small; $d > 0.50$, moderate; and $d > 0.80$, large) respectively for main effects and pairwise analysis. When normality assumption was violated and logarithmic transformation did not resolved, variables are described as median and interquartile range; Friedman's test was used to evaluate possible time-course changes, accompanied with Dunn's post-hoc test. In this case, effect size for testing main effect was obtained by the Kendall's *W* value ($W > 0.10$, small; $W > 0.30$, moderate and $W \geq 0.50$, large). Spearman's rank-order correlation coefficients (rho) were computed between EMG, kinematics and performance variables derived from soccer kick attempts. GraphPad Prism version 8.2.1 was used (GraphPad Software Inc., San Diego–USA) and the level of statistical significance was pre-set at $p \leq 0.05$.

6.4. Results

6.4.1. Overview and reliability

Table 6.1 shows overall mean and standard deviation values for all collected parameters. Reliability measures computed between repeated kick attempts for EMG, kinematics and performance metrics are also displayed. In general, apart from RMS of the biceps femoris having *poor* reliability (ICC = 0.49 [0.26; 0.72]; $p = 0.04$), EMG parameters showed *moderate* (biceps femoris percentage activation; ICC = 0.50 [0.28; 0.72]; $p < 0.001$) to *good* (median frequency of the vastus lateralis; ICC = 0.82 [0.69; 0.91]; $p < 0.001$) reliability. CVs ranged from 5.45% (percentage activation of the biceps femoris) to 110.69% (integral of the rectus femoris). Lower limb kinematics demonstrated *moderate* (ROM ankle; ICC = 0.54 [0.33; 0.75]; $p < 0.001$) to *excellent* reliability (CM_{foot} velocity; ICC = 0.97 [0.94; 0.99]; $p < 0.001$). There was only one exception of approach run velocity that showed *poor* reliability (ICC = 0.20 [0.01; 0.47]; $p = 0.003$). CM_{foot} velocity showed the lowest CV (4.78%) whilst ROM ankle presented the highest (36.24%). All performance measures related to ball placement in the goal also showed *poor* reliability with high CVs (e.g. bivariate variable error; ICC = -0.05 [-0.17; 0.16]; $p = 0.19$; CV = 35.79%) while peak ball speed had a *good* reliability (ICC = 0.88 [0.79; 0.94]; $p < 0.001$; CV = 3.12%).

Table 6.1. Reliability measures across repeated attempts for muscle activity, kinematics and performance parameters all obtained from kicking (n = 15).

	Overall mean ± SD	**r (90% CI)**	**ICC (90% CI)**	**TE (90% CI)**	**CV (%)**
EMG					
Fmed – VL (Hz)	45.49 ± 30.74	0.81 (0.53 – 0.91)	0.82*** (0.69 – 0.91)	14.21 (12.19 – 17.45)	22.67
Fmed – RF (Hz)	30.89 ± 19.19	0.59 (0.20 – 0.82)	0.56*** (0.35 – 0.76)	13.25 (11.37 – 16.27)	21.32
Fmed – BF (Hz)	47.87 ± 28.47	0.66 (0.33 – 0.86)	0.65*** (0.45 – 0.82)	17.55 (15.07 – 21.56)	23.30
Integral – VL (µV/s)	189.00 ± 202.46	0.76 (0.41 – 0.91)	0.76*** (0.59 – 0.89)	104.62 (87.41 – 133.52)	55.36
Integral – RF (µV/s)	48.72 ± 51.00	0.63 (0.25 – 0.89)	0.68* (0.46 – 0.84)	30.33 (25.36 – 39.02)	110.69
Integral – BF (µV/s)	37.36 ± 27.78	0.69 (0.20 – 0.75)	0.60** (0.39 – 0.79)	18.78 (16.03 – 23.37)	57.80
RMS – VL (mV)	0.21 ± 0.17	0.75 (0.41 – 0.90)	0.64*** (0.42 – 0.82)	0.11 (0.09 – 0.14)	30.48
RMS – RF (mV)	0.19 ± 0.20	0.76 (0.41 – 0.91)	0.76* (0.59 – 0.89)	0.10 (0.09 – 0.13)	104.64
RMS – BF (mV)	0.14 ± 0.12	0.49 (-0.10 – 0.72)	0.49* (0.26 – 0.72)	0.09 (0.08 – 0.11)	81.85
Activation – VL (%)	84.92 ± 9.95	0.83 (0.64 – 0.94)	0.80*** (0.66 – 0.90)	4.83 (4.14 – 5.93)	5.45
Activation – RF (%)	79.20 ± 9.97	0.70 (0.31 – 0.85)	0.70*** (0.53 – 0.85)	5.77 (4.95 – 7.08)	6.63
Activation – BF (%)	83.12 ± 6.90	0.47 (0.08 – 0.76)	0.50*** (0.28 – 0.72)	5.06 (4.34 – 6.22)	5.90
Kinematics					
CM_{foot} vel (m/s)	18.81 ± 6.13	0.97 (0.91 – 0.99)	0.97*** (0.94 – 0.99)	1.20 (1.03 – 1.48)	4.78
Foot/ball speed ratio (a.u.)	1.36 ± 0.23	0.89 (0.70 – 0.96)	0.83*** (0.68 – 0.93)	0.11 (0.09 – 0.14)	8.68
Leg relative vel (m/s)	16.63 ± 3.68	0.77 (0.49 – 0.90)	0.78*** (0.63 – 0.89)	1.88 (1.61 – 2.31)	8.77
Approach run vel (m/s)	2.69 ± 1.13	0.60 (0.22 – 0.82)	0.20** (0.01 – 0.47)	1.03 (0.88 – 1.26)	31.93
Peak knee ang vel (rad/s)	0.54 ± 0.21	0.87 (0.73 – 0.95)	0.85*** (0.73 – 0.93)	0.09 (0.08 – 0.11)	11.67
ROM hip (rad)	1.26 ± 0.52	0.97 (0.93 – 0.99)	0.97*** (0.95 – 0.99)	0.10 (0.09 – 0.12)	6.39
ROM knee (rad)	1.54 ± 0.45	0.96 (0.90 – 0.98)	0.96*** (0.92 – 0.98)	0.10 (0.09 – 0.13)	5.46
ROM ankle (rad)	1.07 ± 0.47	0.55 (0.10 – 0.78)	0.54*** (0.33 – 0.75)	0.34 (0.29 – 0.42)	36.24
Performance					
MRE (m)	1.93 ± 1.03	0.24 (-0.27 – 0.60)	0.13** (-0.04 – 0.40)	0.98 (0.84 – 1.21)	50.64
BVE (m)	2.04 ± 1.25	-0.12 (-0.45 – 0.42)	-0.05 (-0.17 – 0.16)	1.30 (1.11 – 1.60)	35.79
ACCUR (m)	2.90 ± 1.44	0.12 (-0.31 – 0.56)	0.15** (-0.03 – 0.42)	1.37 (1.16 – 1.67)	33.09
Kicks on-target (%)	10.59 ± 18.62	-0.04 (-0.43 – 0.44)	-0.08 (-0.18 – 0.13)	19.19 (16.35 – 23.72)	57.58
Missed kicks (a.u.)	1.83 ± 0.83	-0.05 (-0.46 – 0.37)	-0.03 (-0.15 – 0.20)	0.79 (0.68 – 0.97)	79.28
Peak ball speed (m/s)	28.75 ± 2.72	0.89 (0.67 – 0.94)	0.88*** (0.79 – 0.94)	1.03 (0.88 – 1.26)	3.12

Note: VL, vastus lateralis; RF, rectus femoris; BF, biceps femoris; Fmed, median frequency; RMS, root-mean-square; vel, velocity; ang, angular; MRE, mean radial error; BE, bivariate variable error; ACCUR, accuracy; CI, confidence interval; Pearson product-moment correlation (r), intraclass correlation coefficient (ICC), coefficient of variation (CV) and typical error (TE). Overall data is representative of all blocks of assessment while reliability measures were calculated using data from the first block of kick attempts. * $p \leq 0.05$; ** $p < 0.01$; *** $p < 0.001$.

6.4.2. Time-course of changes in kicking characteristics

6.4.2.1. EMG

Temporal dynamics of muscle activation-derived indices are presented in the Figure 6.1. RM ANOVA indicated a *large* main time effect for the median frequency of the biceps femoris ($F_{(4, 56)}$ = 3.675; p = 0.01; η^2 = 0.208; Figure 6.1(C)). Post hoc analysis indicated that biceps femoris median frequency values peaked at 10 minutes as compared to Pre (percentage, mean absolute difference [CI lower; upper] = +21.18%, 12.87 Hz [0.74; 24.99]; p = 0.04; d = 0.41 [*moderate*]), Post (+35.78%, 21.74 Hz [9.62; 33.86]; p < 0.001; d = 0.73 [*large*]) and 5 minutes (+29.28%, 17.79 Hz [5.67; 29.91]; p < 0.01; d = 0.60 [*moderate*]) time-windows. No main time effects were observed, for any muscle, concerning integral (Figure 6.1 (D)–(F)) and RMS parameters (Supplementary online Figure 1). RM ANOVAs also revealed *moderate* non-significant main time effects concerning the rectus femoris median frequency ($F_{(4, 56)}$ = 1.669; p = 0.17; η^2 = 0.107), percentage activation of rectus femoris ($F_{(4, 56)}$ = 1.813; p = 0.14; η^2 = 0.115) and biceps femoris ($F_{(4, 56)}$ = 1.833; p = 0.14; η^2 = 0.116) despite some significant pairwise differences were noted for such three latter indicators. In particular, percentage activation of rectus femoris (Figure 6.1(H)) at 5 minutes period significantly demonstrated *moderately* superior levels as compared to both Pre (+5.05% [0.75; 9.35]; p = 0.02; d = 0.51) and 15 minutes (+4.87% [0.57; 9.16]; p = 0.03; d = 0.51) time-windows. Rectus femoris median frequency *moderately* declined in the 15 minutes instant compared to the 5 minutes time-moment (-28.91%, -10.60 Hz [-20.56; -0.63]; p = 0.04; d = 0.53; Figure 6.1(B)). Finally, percentage activation of biceps femoris were *moderately* higher in the 10 minutes (+4.19% [0.68; 7.69]; p = 0.02; d = 0.34) and 15 minutes (+3.93% [0.43; 7.43]; p = 0.03; d = 0.53) as compared with the Pre moment (Figure 6.1(I)).

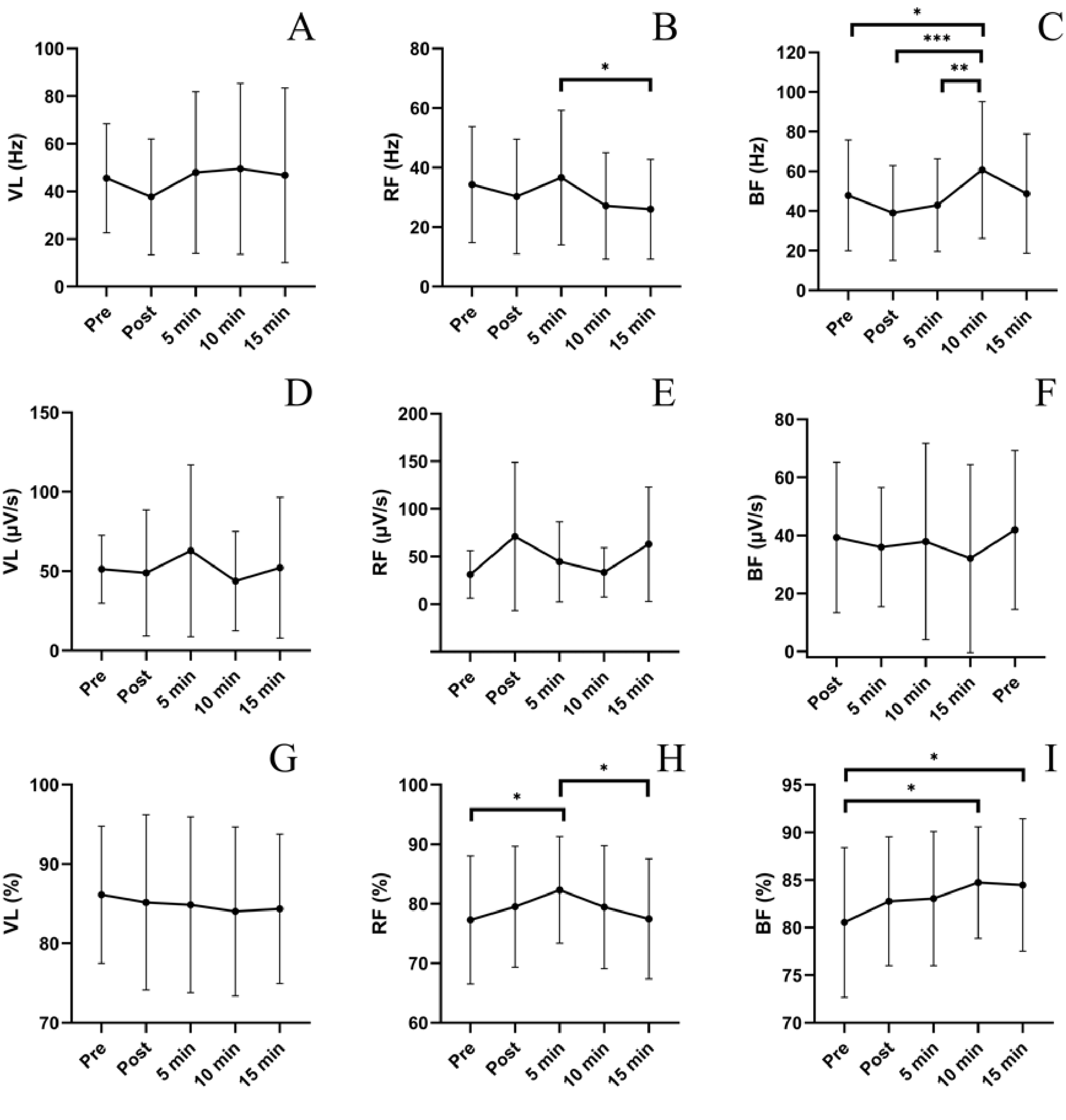

Figure 6.1. EMG indices observed at each time-window of data collection, containing median frequency (top row), integral (middle row) and percentage activation (bottom row) for the vastus lateralis (VL, left column), rectus femoris (RF, middle column) and biceps femoris (BF, right column) muscles of the lower kicking limb. Statistical significance level denoted as: * $p < 0.05$; ** $p < 0.01$; *** $p < 0.001$.

6.4.2.2. Lower limb kinematics

Figure 6.2 contains the results of the lower kicking limb kinematics parameters considered across the various time-windows. ANOVAs or Friedman's test revealed *small*-to-*moderate* non-significant main time effects for all variables in this category (p = 0.16–0.94; η^2 = 0.014–0.111). For example CM_{foot} velocity ($F_{(4, 56)}$ = 0.8742; p = 0.49; η^2 = 0.059 [*small*]; Figure 6.2(A)), CM_{foot} to knee relative velocity ($F_{(4, 56)}$ = 0.1965; p = 0.94; η^2 = 0.014 [*small*]; Figure 6.2(C)) and ROM ankle ($F_{(4, 56)}$ = 0.445; p = 0.78; η^2 = 0.030 [*small*]; Figure 6.2(G)) remained stable over time, from Pre to 15 minutes instant. Knee angular velocity also had *moderate* non-significant main time effects in the ANOVA ($F_{(4, 56)}$ = 1.293 p = 0.28; η^2 = 0.085; Figure 6.2(E)) accompanied by one post-hoc difference. Specifically, knee angular velocity at 5 minutes was *moderately* faster as compared to the Post moment (+13.79%, 0.07 rad/s [0.01; 0.14]; p = 0.03; d = 0.36).

6.4.2.3. Performance measures

Kicking performance indices according to each temporal moment of assessment, before and after the PAPE protocol, are reported in the Figure 6.3. Friedman's test detected a *small* significant main time effect for the frequency of missed kicks ($X^2_{(4)}$ = 12.40; p = 0.01; W = 0.207; Figure 6.3(E)). Pairwise comparisons indicated that there were *largely* more missed kicks immediately Post (+62.14%, 0.87 a.u. [0.32; 1.42]; p = 0.01; d = 1.07) and at 15 minutes time-windows (+47.86%, 0.67 a.u. [0.12; 1.21]; p = 0.01; d = 0.83) when compared to Pre values. No other significant main time effects were found (p = 0.41–0.76), generally accompanied with *small* effect sizes (e.g. ball placement-derived indices excepting missed kicks; W = 0.031–0.066). Examples include the stability across the time regarding the peak ball speed ($F_{(4, 55)}$ = 0.689; p = 0.60; η^2 = 0.101 [*moderate*]; Figure 6.3(F)) and mean radial error ($X^2_{(4)}$ = 1.867; p = 0.76; W = 0.031 [*small*]; Figure 6.3(A)).

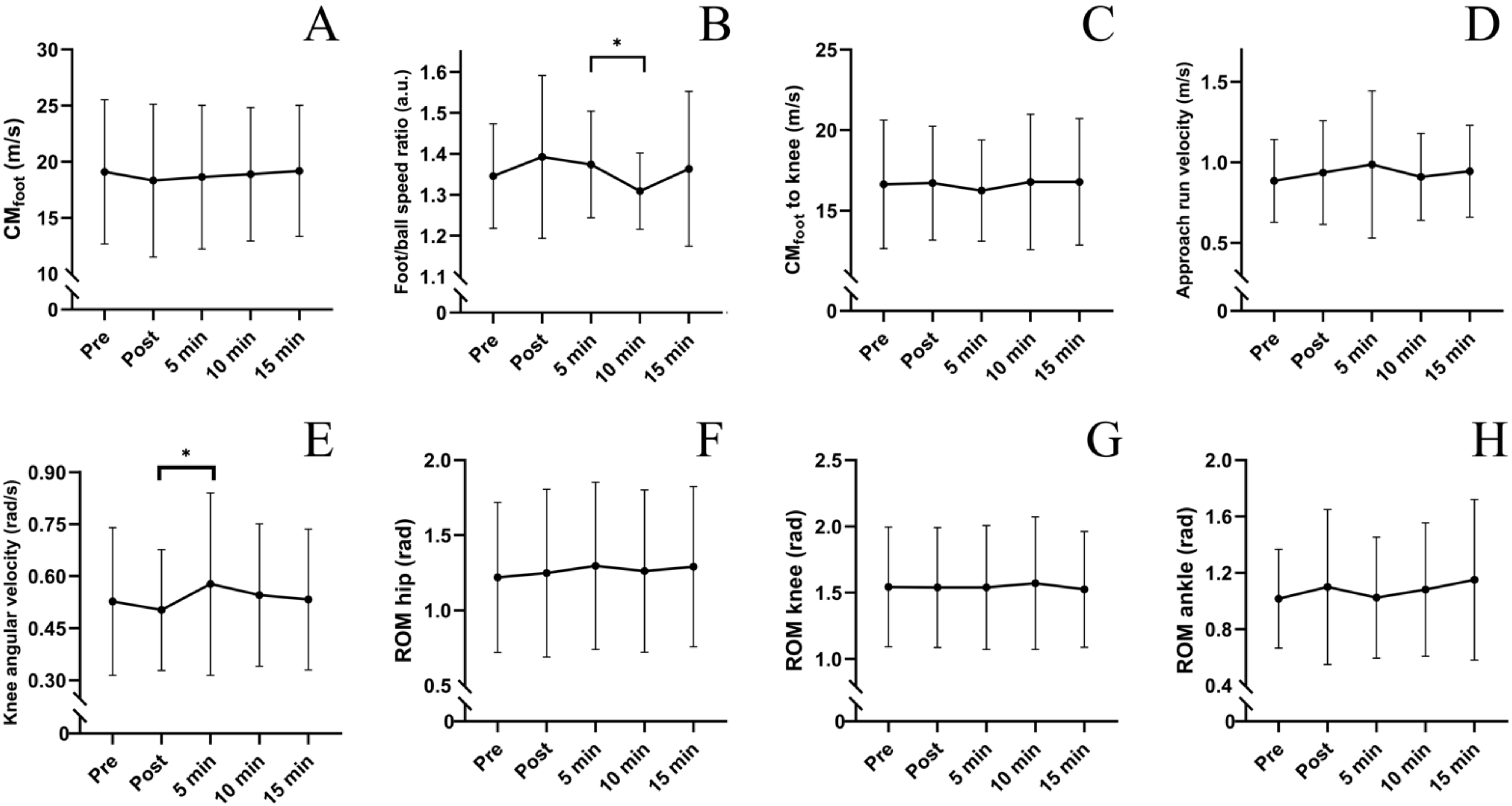

Figure 6.2. Kinematics of the lower kicking limb observed at each time-window of data collection. Statistical significance level denoted as: * $p < 0.05$.

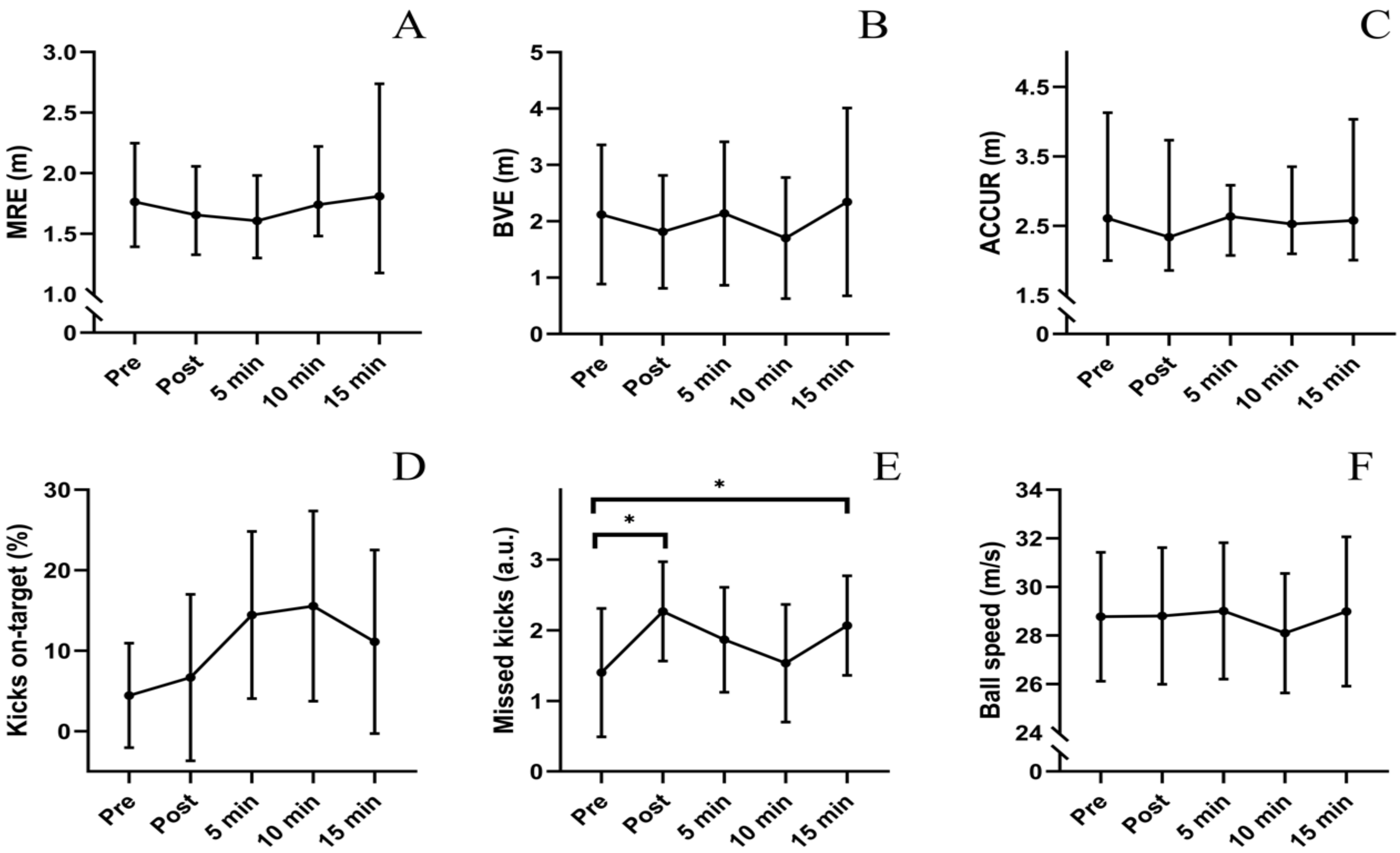

Figure 6.3. Kicking performance components observed at each time-window of data collection. Statistical significance level denoted as: * $p < 0.05$.

6.4.3. Associations between EMG, kinematics and performance

Figure 6.4 is an overview of the magnitudes of relationships tested between all kicking-derived measures (EMG, kinematics and performance) computed in the present study. In particular, approach run velocity was related to mean radial error (rho = 0.23 [0.01; 0.44]; $p = 0.053$) and accuracy (rho = 0.28 [0.05; 0.49]; $p = 0.01$). Frequency of missed kicks was significantly correlated with both ROM hip (rho = 0.26 [0.03; 0.47]; $p = 0.02$) and percentage activation of biceps femoris (rho = 0.27 [0.04; 0.48]; $p = 0.02$). Significant relationships were also observed between peak ball velocity and integral (rho = 0.25 [0.01; 0.47]; $p = 0.049$ and rho = 0.40 [0.15; 0.60]; $p < 0.01$) and RMS (rho = 0.27 [0.02; 0.48]; $p = 0.03$ and rho = 0.43 [0.18; 0.62]; $p = 0.001$) of the vastus lateralis and rectus femoris muscles, respectively. Finally, both median frequency (rho = 0.39–0.51; $p \leq 0.01$ and rho = 0.28–0.49; $p \leq 0.02$) and percentage of activation (rho = 0.28–0.40; $p \leq 0.01$ and rho = 0.39–0.60; $p \leq 0.001$, respectively) of the vastus lateralis and rectus femoris muscles were significantly related to all kinematics parameters computed.

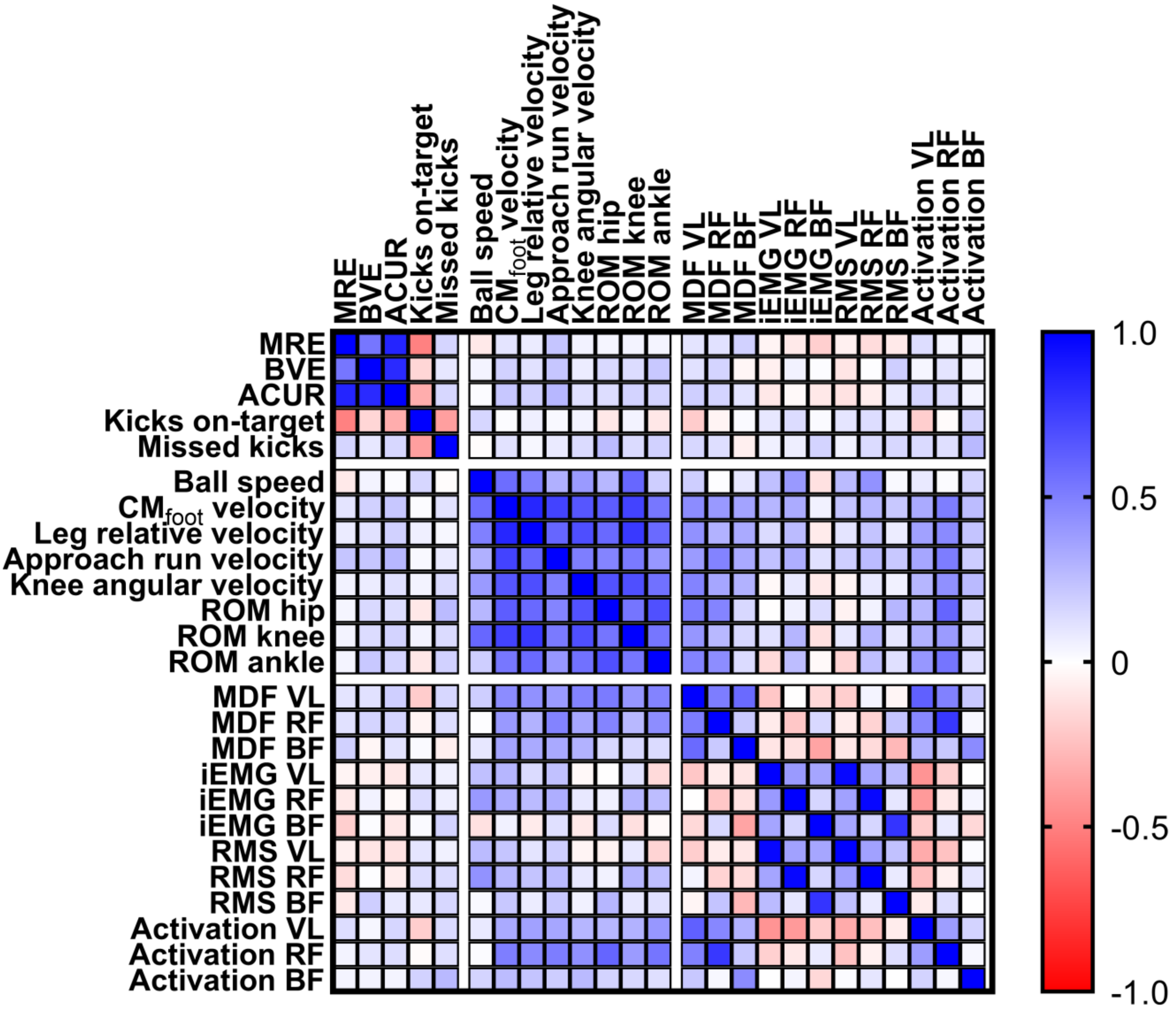

Figure 6.4. Spearman's rank-order correlations observed among EMG, kinematics and performance indices all concomitantly obtained from kicking. Note: MRE, mean radial error; BVE, bivariate variable error; ACUR, accuracy; CM_{foot}, foot centre of mass; ROM, range-of-motion; VL, vastus lateralis; RF, rectus femoris; BF, biceps femoris; MDF, median frequency; iEMG, integral; RMS, root-mean-square.

6.5. Discussion

The objective of the current investigation was to verify the consequences, in youth academy players, the post-drop jumps kick (unknown) potentiation/depression effects. Also, the time-course of possible changes induced by this pre-kick exercise was assessed in reference to neuromuscular, movement and performance (ball placement and velocity) characteristics, immediately after CA cessation until 15 minutes of relative resting. A secondary goal was to explore the possible associations between EMG, kinematics and performance outputs concomitantly collected in kick attempts made from the entrance of penalty area. According to our results, the PAPE protocol based on low-intensity running followed by dynamic stretching plus five drop jumps induced some increases in muscle activity parameters. In particular, these notably occurred 5 minutes (rectus femoris percentage activation and median frequency) up to 10 minutes (biceps femoris median frequency) following CA termination. On the other hand, evidence of post-drop jumps benefits in mechanical features and performance of soccer kicking were both limited. There was only a transient increase in angular velocity of knee extension in 5 minutes while no significant changes happened in ball speed from pre to post-15 minutes. Of note, frequency of missed kicks increased immediately following PAPE and in the last window of assessment. Significant associations were observed amongst kicking movement and ball velocity with distinct EMG parameters derived from the vastus lateralis/rectus femoris (median frequency/percentage activation and integral/RMS, respectively) while ball placement was influenced by the approach run velocity/biceps femoris percentage activation. Below we will discuss the post-drop jumps effects on neuromuscular, kinematics and performance aspects of kicking in the youth sample, that are more evident in the former than in the latter. Explanations to neuro-mechanics-outcome relationships found are also provided.

Including plyometric exercise as drop jumps following a traditional dynamic warm-up routine demonstrated a few benefits to neuromuscular responses during kick actions in youth soccer players. These were observed in rectus femoris and biceps femoris muscles (e.g. median frequencies for both cases and percentage activation in the former). In addition, the peaks in these parameters occurred roughly 5–10 minutes after performing the selected CA. Comparing our results to literature, EMG was slightly lower than college/amateur young adults [RMS of the vastus lateralis: 0.28–0.36 mV (4); rectus femoris percentage activation: 50.9–85.4% (34)] while performance is compatible to data in high-level youth under-16-17s [ball velocity: ~18.41–28.74 m/s (8); successful kicks: 9.52–10.48% (44)]. In reference to neuromuscular responses after protocol intended into potentiate performance, if increases in arousal levels of players and/or in net motoneuron output occurred after warming-up, these may have reflected in increased muscle excitability detected (9). Drop-jumps indeed were shown previously to improve muscle electrical activity responses in explosive (sprint) activities (37, 71). In particular, we observed most frequent increase in median frequency components of EMG signal than in the other parameters computed. It is something that can provide evidence indicating the present PAPE plyometrics protocol caused modifications in quadriceps/hamstrings muscles during kick attempts mainly in the firing rate of motor units (65). As regarding the duration of neuromuscular (limited) effects observed, which lasted here from 5 up to 10 minutes following drop jumps, despite partly in agreement to ranges supported in existing meta-analyses (19, 59, 69), this time-frame is shorter than the typical interval separating the end of a warm-up and performance in the real-world (63) thereby implying that a post/re-warm-up practice (24, 59, 68) could be necessary when plyometric mode of pre-pitch entry exercise are prescribed in youth soccer. Thus, the effectiveness of performing drop jumps aiming at acutely improve subsequent kicking skill in developing players is not warranted given the scanty/transient task-related muscle activity improvements found.

Aside from the enhancements encountered in some EMG features as above mentioned, kick mechanics and performance such as ball velocity was almost unchanged post-drop jumps. There are three possible explanations to these unexpected findings; two based on previous work and one supported by our experiment data (i.e. EMG-performance relationships). Firstly, drop jumps were not always beneficial in scientific publications to subsequent performance as some demonstrated that its effects in explosive actions can be very short (≤ 2 min) (14) or adding no additional benefits as compared to using only dynamic warm-up exercises in youth engaged in after-school soccer practice (20). Despite in adult athletes drop-jumps was probed to induce both PAP/PAPE (16), recently in the context of female youth soccer, contractile responses indicative of PAP following CAs were also not translated to players lower limb power performance (46). Here only one exception existed in reference to a faster knee extension angular velocity at 5 minutes time-window and this may be attributed in part to increases in muscle (i.e. rectus femoris) electrical activity. Second, under-17 players are recognised to have not yet a mature kick movement pattern. By this age, players are still developing kinematics features associated to a proficient kick motion. This is evidenced in comparisons with the nearest older age-group under-20, which in turn presents skilled behaviour compatible to senior players (40, 66). Thus, in addition to the notion that teenagers appear not able to sustain PAPE effects as concerning power-dependent tasks given the reduced number/training status of type-II muscle fibers (23, 32, 36), their possible ongoing kick technique refinements may have influenced on the utilization of a few benefits (e.g. those neuromuscular) provided by traditional warm-up plus conditioning drop jumps.

To appraise the temporally unchanged ball velocity output, there is a third and most plausible reason considering solely the data gathered in the current investigation. According to the correlation analysis, movement characteristics were related to EMG median frequency. Ball velocity showed no significant correlations with this parameter, instead demonstrated associations to RMS and integral recorded in the two selected quadriceps muscles (Figure 6.4). In fact, weak correlations were also observed between high-density EMG median frequency of tibialis anterior muscle and associated force output (17). While median frequency of EMG signal notably reflects the velocity of electrical input transmission (60), RMS and integral components prominently represents mainly the amplitude of neural discharges (6). As a consequence, we provide preliminary evidence that kicking ball velocity in youth soccer players is more dependent upon the intensity rather than velocity of the electric signal propagation. Even owing to the fact that CM_{foot} velocity was also directly influence here by the median frequencies of quadriceps contraction during kick attempts, and distal end-point kinematics has been demonstrated as the most important parameter to subsequent ball flight characteristics (e.g. strong foot-ball velocity relationships regardless of age) (27, 39, 70) our data illustrate that it seems necessary an optimal magnitude of muscle activation levels (kinetics) to sustain transmission of momentum from foot to ball at impact instant and thus assist development of high ball velocity instead of solely movement velocity (kinematics). Hence, post-drop jump soccer kicking potentiation was purely neuromuscular in the present youth population, being little translated into mechanical and performance enhancements in developing under-17 players. This is due to the drop-jumps likely improved motor unit firing rates but not the amplitude of muscle activity, and this is an emergent aspect determinant to obtain faster ball velocity in youth soccer.

It is noteworthy that the absolute frequency of missed kicks (i.e. outside goalposts) significantly raised immediately after the cessation of CA as well as following 15 minutes. This indicates that drop jumps possibly induced youth players into a temporary state of fatigue right after the CA repetitions, then the number of missed kicks decreased (5 to 10 minutes) and worsened latter again. Indeed, simultaneous expression of potentiation and fatigue can coexist at a certain time-windows following CA (10, 25, 50), and this relation is time-dependent but not in a linear form (roughly U-shaped); PAPE effects are generally depressed right after CAs (i.e. augmented transient fatigue; (30)) and could dissipate following long lasting rest intervals (55). Notwithstanding, soccer kick is also often difficult to be fully predicted given its highly variable nature either in official competition matches or even using controlled testing conditions (8, 31, 67) that would render analysis of ‘true’ intervention effects uncertain, i.e. casting doubts on whether an observed kicking output across time-moments is result of PAPE protocol or undesired/involuntary adjustments in players motor behaviour occur across kick attempts even with standardised instructions. It is illustrated by various components of kicking including EMG (integral in all muscles, biceps and rectus femoris RMS), kinematics (approach run velocity and ROM ankle) and performance (all ball placement-derived indices) showing large CVs exceeding 30% (15).

Several additional limitations are recognised to the present findings. This includes the fact that, due to logistics, a fixed drop jump height was used while individualised drop box based on highest player reactive strength index maximize performance gains in youth soccer players (47). Despite well documented practical limitations to compute advanced kick features under match conditions (43), environmental constraints such as distance to the nearest opposition player, sight of goal and offensive pitch zone influences on kicking effectiveness (54) thus potentially limiting transference of our findings to actual game-play. Furthermore, even that influence of playing position on kicking performance observed in senior is less evident in youth soccer (29, 35), future analysis of PAPE effects according to positional role are warranted. To increase external validity, including specific ubiquitous exercises into the warm-up routine prior to measuring performance (e.g. small-sided games) are also recommended to future research (43). Finally, using other sampling windows (e.g. assessments interspaced by 2 minutes) could be pertinent to fully depict temporal changes in kicking performance while reduces the time that players keep resting passively.

6.6. Practical applications

In youth under-17 players, a traditional warm-up routine consisting in low-intensity running followed dynamic stretching exercises in addition to five repetition drop jumps may immediately impair targeting ability in kick attempts made from the entrance of penalty area whilst a long period of relative inactive (15 minutes) also had similar effect. The best window at which neuromuscular functioning (firing rate or electric signal propagation velocity but not amplitude) improves slightly falls into 5 until 10 minutes after conditioning activity termination. Considering the limited transference of such transient gains in muscle activity to mechanical and performance outputs related to kicking ability, prescription of dynamic stretches plus drop-jumps with primary intention to cause PAPE in this skill is therefore questionable in developing teenagers. Kicking velocity in youth soccer players was demonstrated at first time to be dependent upon amplitude of intrinsic muscle contractions parameters rather than being strictly related to firing rate/velocity of electrical discharge. A robust inverse linear relationship exists between ball velocity and chance of a goalkeeper block the shot (26). Thus, while this was not the case in the protocol analysed here, priming exercises that promote substantial increases in amplitude characteristics of quadriceps EMG signal are of particular interest to obtain faster kicks which in turn are linked to a greater likelihood of success.

6.7. References

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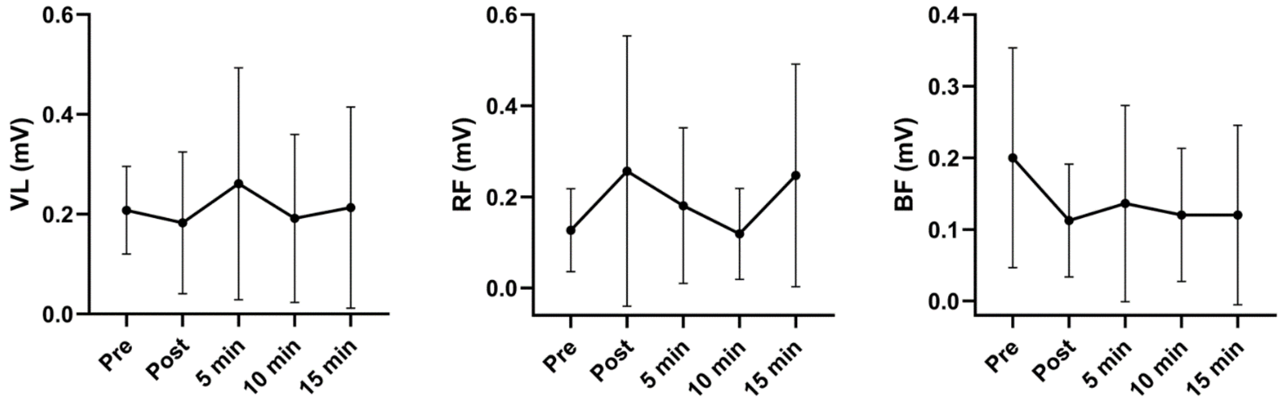

Supplementary online Figure 1. EMG RMS for the vastus lateralis (VL, left), rectus femoris (RF, middle) and biceps femoris (BF, right) muscles of the lower kicking limb.

CHAPTER 7

INDUCED COOLING IN ATTEMPT TO RECOVER KICKING PERFORMANCE AFTER REPEATED INTENSE EXERCISE

7. PAPER 6 – Recovery of kicking kinematics and performance following intermittent high-intensity running bouts in young soccer players: can a local cooling intervention help? [(7)]

Palucci Vieira, L.H., Carling, C., Kalva-Filho, C.A., Santinelli, F.B., Velluto, L.A.G., da Silva, J.P., Kellis, E., Barbieri, F.A. (n.d.). Recovery of kicking kinematics and performance following intermittent high-intensity running bouts in young soccer players: can a local cooling intervention help? *medRxiv*. [preprint]. **https://doi.org/10.1101/2022.03.05.22271957**

[(7)] This paper will be submitted for possible publication in the Journal of Sports Sciences

7.1. Abstract

Repeated high-intensity running (RHIR) exercise is known to affect central and peripheral functioning. Declines in RHIR performance are exacerbated by environmental heat stress. Accordingly, the use of post-exercise cooling strategies (COOL) is recommended as it may assist recovery. The present study aimed to investigate, in a hot environment (> 30ºC), the effects of local COOL following RHIR on indices of soccer kicking movement and performance in youth soccer. Fifteen academy under-17 players (16.27 ± 0.86 years-old; all post-PHV), acting as their own controls, participated. In #Experiment 1, players completed an all-out RHIR protocol (10 x 30 m bouts interspersed with 30 s intervals). In #Experiment 2, the same players performed the same running protocol under two conditions, 1) 5 minutes of COOL where ice packs were applied to the quadriceps and hamstrings regions and, 2) a control condition involving only passive resting. In both experiments, perceptual measures [ratings of perceived exertion (RPE), pain and recovery], thigh temperature and kick-derived video kinematics (hip, knee, ankle and foot) and performance (ball speed and placement) were collected at baseline and post exercise and intervention. In the first experiment, RHIR led to moderate-to-large increases ($p < 0.03$) in RPE ($d = 4.08$), ankle eversion/inversion angle ($d = 0.78$) and mean radial error ($d = 1.50$) and small-to-large decreases ($p < 0.04$) in recovery ($d = -1.83$) and average/peak ball speeds ($d = -0.42$–-0.36). In the second experiment RPE ($p < 0.01$; Kendall's $W = 0.30$) and mean radial error ($p = 0.057$; $\eta^2 = 0.234$) increased only post-control. Significant small declines in ball speed were also observed only post-control ($p < 0.05$; $d = 0.35$). Post-intervention CM_{foot} velocity was moderately faster in COOL as compared to control ($p = 0.04$; $d = 0.60$). RHIR acutely impaired kicking movement, ball speed and placement in youth soccer players. However, a short period of local cryotherapy may be beneficial in counteracting declines in indices of kicking performance in hot environment.

Keywords: Cryotherapy, heat environment, 3-dimensional kinematics, technique, accuracy, football.

7.2. Introduction

In young soccer players, accumulated fatigue is manifestly observed over the course of matches. This is illustrated by an increase in players' ratings of perceived exertion (RPE) and a concomitant reduction in running outputs during the second half (Aslan et al., 2012). Although the majority of in-game activities (~75–82%) are performed in the 'low intensity' domain (< 13 km/h; Buchheit et al. (2010a)), the repeated execution of high-intensity running bouts (Buchheit et al., 2010b) is associated with substantial acute increases in both perceived effort (Brocherie et al., 2015; Sánchez-Sánchez et al., 2014) and sensations of pain (Monks et al., 2017). These can be linked to impairments in neuromechanical responses, explained by either central or peripheral fatigue factors (Brocherie et al., 2015; Goodall et al., 2015; Perrey et al., 2010). In studies using protocols to simulate the running loads commonly found in official matches, including intermittent high-intensity activities, also identified declines in indices of kicking performance (Palucci Vieira et al., 2021b; Russell et al., 2011; Sánchez-Sánchez et al., 2014), notably in senior players. In contrast, there is only limited evidence level regarding the magnitude of the effects of repeated high-intensity exercise on kicking performance in youth populations [for a review: (Palucci Vieira et al., 2021b)].

In an attempt to accelerate recovery processes during/following exercise, cooling interventions are frequently utilised and their beneficial effects are seemingly amplified in hot environments (Bongers et al., 2015). For example, following exercise, cooling may have a transient analgesic effect aiding reduction of swelling and muscle pain and lowering RPE values (Bleakley et al., 2012; Duffield et al., 2013) thus facilitating the execution of subsequent movement/physical effort (Fischer et al., 2009). Some studies have demonstrated short-to-long-term beneficial effects of cooling on running outputs in soccer players notably post-match–periods of fixture congestion–or during the half-time interval (Buchheit et al., 2011; Duffield et al., 2013). However, the literature generally shows that cooling techniques can exert acute negative effects on motor performance immediately after an intervention. These effects include severe declines in lower limb power-dependent activities (e.g. jumping and running at maximal speed) and goal-directed technical skills (Bleakley et al., 2012; Tyler et al., 2015; Wassinger et al., 2007). Longer cooling treatment times utilised in the majority of interventions (e.g. up to 20 minutes) can notably be an issue (Bleakley et al., 2012). As such, a shift to using shorter cryotherapy durations is arguably necessary (Egaña et al., 2019; Fischer et al., 2009; Peiffer et al., 2010) as well as having practical implications. Notably, preliminary evidence in both individual and team sport athletes has shown that rapid post-exercise cooling (≤ 5 minutes) may reduce the negative effects of exercise on power development (Egaña et al., 2019; Peiffer et al., 2010) or at least not impair peripheral blood flow, muscle temperature and motor responses (Fischer et al., 2009; Thorsson et al., 1985; Zemke et al., 1998).

It is clear from the above discussion that recovery-related strategies are necessary in effectively re-establishing explosive performance following intense physical exercise demands (e.g. repeated high-intensity running). Yet, the potential benefits of recovery methods including cooling techniques that are ubiquitously used in soccer contexts on kicking parameters are still unknown (Palucci Vieira et al., 2021b). Local application of ice packs has previously demonstrated positive effects in reducing perceived pain (Algafly and George, 2007), improving thermal and recovery sensations (Wiewelhove et al., 2020) and even assisting the power response of lower limbs in a heat stress experimental condition (Castle et al., 2006). The rolling substitute policy used in youth soccer tournaments played in hot climatic conditions could notably benefit from this mode of cooling to help alleviate game-related load demands in substitute players on pitch entry. To the extent of our knowledge however, the lack of information related to the effects of recovery treatments such as cooling strategies is even greater in relation to soccer technical skills. A recent systematic review has identified a lack of studies investigating the influence of cooling specifically in goal-directed skills, particularly in soccer kicking performance, and notably where concomitant demands for precision and velocity are required (Palucci Vieira et al., 2021b). Thus, the aim of the present study was to verify, under conditions of thermal (heat) stress (temperature > 30ºC; Girard et al. (2015)), the effects of local cooling following intermittent high-intensity efforts on kicking movement kinematics and performance in young soccer players. We hypothesized that an all-out running exercise in the heat would generate acute reductions in ball kicking movement and outcomes, and notably velocity outputs. We then expected that the subsequent application of ice pack during a short period (5 minutes) would favour youth soccer players perceived well-being (e.g. sensations of recovery, pain and exertion) while not negatively interfering with kick movement or performance recovery after intense exercise in the heat.

7.3. Materials and methods

7.3.1. Participants

Fifteen youth players participated (16.27 ± 0.86 years-old; 2.12 ± 0.71 years from peak height velocity; 64.14 ± 10.98 kg; 172 ± 9 cm). All procedures were approved by the local Human Research Ethics Committee (protocol #2650204; CAAE85994318.3.0000.5398) and Brazilian Clinical Trials Registry ReBEC (http://www.ensaiosclinicos.gov.br/; included in the network of WHO primary registries) under number RBR-8prx2m. In #Experiment 1 which tested exercise-induced changes in kicking parameters, a subsample of 13 players was evaluated. This was considered to be the required sample size estimated owing to the expected declines in kicking performance following general intermittent high-intensity exercise mode (effect size = 0.92; power = 85% and α = 0.05) [data from a systematic review by Palucci Vieira et al. (2021b)]. In #Experiment 2 which evaluated the effects of the recovery intervention, all 15 players were evaluated to meet the a priori required sample size based on the assumption that ice would affect motor skills precision (effect size = 0.86; power = 80% and α = 0.05) (Wassinger et al., 2007) and/or global performance in immediately subsequent sports-related tasks (average effect size = 0.83; data from systematic review by Bleakley et al. (2012)). Sample size estimations for each experiment were obtained using G*Power© v.3.1.9.2 environment (Universität Düsseldorf, Germany). The players were invited from the under-17 age-group of a club that competes at state standard in Brazil (1st place in São Paulo Interior League 2020 edition). Both youth athletes and their legal guardians signed respectively approved assent and consent forms to allow participation.

7.3.2. Experimental design

In #Experiment 1, a pre-post paired test design was used, in order to analyse the impact of the running exercise protocol on measures of kicking performance. Players were firstly asked to perform a standardised 15-minute warm-up (dynamic stretching, jogging and submaximal kicks). Thereafter, they performed a running protocol involving high-intensity intermittent exercise (see below). Immediately prior to and at end of this exercise stimuli, players undertook a kicking protocol that allowed monitoring of lower limb movement mechanics and performance.

In #Experiment 2, a repeated measures pre-post testing design was adopted, randomised and counterbalanced between data collection days, where subjects acted as their own controls. After completing the same warm-up and running protocol as in Experiment 1, each participant was assigned to one of the 2 experimental conditions [control or 5 minutes cooling (COOL)] on two separate days, 24–26 hours apart. All subjects performed the kick testing protocol before commencing the running exercise in a rested state and immediately following the post-exercise intervention with COOL or control (5 minutes of passive recovery).

Both experiments were performed on an official FIFA-standard natural grass soccer pitch in the presence of sunlight during afternoon period (between ~14:30–17:30 h). The recorded environmental temperature and relative humidity (provided by an automatic station of Centro de Meteorologia de Bauru, Local Meteorological Research Institute IPMet–UNESP–Bauru–Brazil; https://www.ipmetradar.com.br/) in Experiment 1 were respectively 36.67 ± 3.3ºC [32–41ºC] and 26.70 ± 8.78% [15.10–35.90%]; in Experiment 2 35.5 ± 2.8ºC [33.37–38.67ºC] and 20.2 ± 7.5%

[15.12–28.8%] (control condition) and 33.8 ± 4.6ºC [30.59–39.09ºC] and 21.0 ± 7% [14.82–28.55%] (COOL condition).

7.3.3. Kick testing collection and data processing

The kick testing protocol adopted was based on that employed in a previous study (Palucci Vieira et al., 2022b). In brief, the participants were asked to perform instep kicks, 18 m from the midpoint goal line, using FIFA-approved stationary balls (PENALTY® brand, 5-sized, 70 cm diameter, 430 g weight, and air pressure kept at 0.7 atm). Kicks were performed at maximal velocity and aimed at the centre of a 1 x 1 m target fixated in the contralateral goalpost upper corner. The approach run was constrained to 3.5 m and 45 degrees, with a 40 s passive rest interval between repeated attempts within the same block. Differences to the original protocol included: trying to increase standardization as much as possible between the two proposed intervention conditions as well across the time-moments, no goalkeeper was used, and three kick attempts were allowed per block (time-moment).

Body motion and ball displacement immediately after kicking were recorded using two digital video cameras fixed on tripods (GoPro Hero 7 Black Edition, GoPro GmbH, München–Germany), sampling at 240 frames/s [wide field-of-view (FOV) mode; 1280 x 960 pixel; 1/480 s shutter speed], were turned on and synchronised via remote control (Smart Remote GoPro). The cameras were positioned laterally around the kick mark (2.5 m) so that their focus had ~90 degrees between them. Afterwards, video files from data collections were downloaded onto a laptop computer (DELL INSPIRON 5590; Dell Inc., Texas–USA). The OpenPose markerless motion detector method in addition to a tracking algorithm previously validated to evaluate ball kicking action (Palucci Vieira et al., 2022c) were used to automatically extract 2-dimensional screen coordinates of seven keypoints derived from the hip (preferred and non-preferred), knee, ankle and foot regions (measurement error = 3.49 cm and 1.29 m/s; Palucci Vieira et al. (2022c)). A calibration frame was defined using 49 reference points with absolute 3-dimensional coordinates known (4.11 x 4.05 x 1.30 m). Following tracking and appropriate correction of the radial distortion (Rossi et al., 2015), screen coordinates of both cameras were inputted in a specific Python 3.8.3 algorithm (Python Software Foundation, Delaware–USA) to run 3-dimensional Direct Linear Transformation (DLT) reconstruction. Time-series positional data was then extrapolated following impact (20%) and smoothed (dual filter 4th-order Butterworth/rloess) in MATLAB software (R2019a MathWorks Inc., Natick–USA). Residual analysis helped define filtering parameters (cut-off frequency=25 Hz and span=0.1, respectively). After treatment, extrapolation was then removed. Custom-built routines were written to obtain linear velocities (non-preferred hip, CM_{foot} and CM_{foot} to knee relative), angular (i) joint displacement (ankle plantarflexion/dorsiflexion and eversion/inversion at impact) (ii) range-of-motion (hip and knee flexion/extension) and (ii) peak knee extension velocity. These were computed using local reference frames of joints and segments as described elsewhere (Palucci Vieira et al., 2021a; Palucci Vieira et al., 2022a).

In an attempt to compute ball speed metrics, the ball centroid was manually tracked by the DVIDEOW kinematic system (Rossi et al., 2015), using image sequences from both cameras, considering 10 available airborne frames after the foot contacted the stationary ball. To determine resultant post-impact ball speed, its horizontal and vertical components were calculated from the first derivative of linear and quadratic (second derivative = -9.81 m/s^2) regression lines, respectively (Nunome et al., 2006). Mean and maximal values for ball speed across each block of three kicks were retained for further analysis.

To obtain ball placement-derived indices, two cameras sampling at 60 frames/s (GoPro Hero 7 Black Edition, GoPro GmbH; 1920 x 1080 pixel, linear FOV) were placed one in front of the goal (~23 m apart) and another above the goal line. A calibration frame was defined considering all goalpost upper/lower extremities (four reference points; 7.35 x 2.32 m). The 2-dimensional coordinates of the ball centre at the moment it crossed the goal line were obtained using the same software and similar procedures as for ball speed digitisation. The Euclidean distance between the ball and target centre coordinates was calculated for each kick attempt. Taking the three repeated kick attempts within a same given block, the mean radial error (average ball-target distance), bivariate variable error (square root of the sum of standard deviation squared derived from x- and y-coordinates of the ball) and overall accuracy (a compound of the two previous measures) were computed using specific equations as described elsewhere (Vieira et al., 2018) where Euclidean distances and 2-dimensional coordinates of ball and target centre were adopted as input parameters.

7.3.4. Running protocol

To simulate repeated high-intensity running efforts that players frequently undertake during soccer training and testing, a protocol including 10 “all-out” running bouts x 30 m distance each, interspersed by a recovery period of 30 s was conducted. In particular , the player ran for 25 s at low intensity back to the starting line, ensuring 4–5 s of passive resting before performing the next sprint repetition (Buchheit and Mendez-Villanueva, 2014). In young soccer players of various ages, this RHIR model has previously demonstrated good construct validity for predicting in-game running performance (Buchheit et al., 2010a). Standardised (“go, go, go …”), constant and strong verbal encouragement was provided during each effort. The time to complete each bout was recorded by a single experienced examiner using a digital manual stopwatch (LIVEUP® SPORTS, Paraná–Brazil; 1/100 s sensitivity).

7.3.5. Ice application

At the end of the running exercise, the participants performed the cooling protocol (COOL condition). They were asked to sit on the substitutes bench pitch-side near to where the kicking and running protocols took place. A licensed physical therapist tightly covered the quadriceps and hamstrings of the participant’s preferred lower limb using plastic wrapping paper, respectively with two thin plastic bags (20 x 40 cm), approximately 1/3 filled with cubed ice; these were maintained constantly over muscle sites for 5 minutes (Algafly and George, 2007; Fischer et al., 2009). During the ice application, participants kept their treatment leg comfortably extended on an auxiliary chair at a height slightly lower than the bench on which they were sitting.

7.3.6. Perceptual measures

Before the beginning (Pre), immediately following the running cessation (post-RHIR) and intervention or control conditions (Post), measures referring to ratings of perceived exertion were collected, using the 0–10 Borg scale (Foster, 1998); subjective perception of pain, using a 10-point Likert scale (0 = no soreness and 10 = very, very sore) (Pointon et al., 2011) and perception of recovery, based on another 10-point Likert scale (0 = very poorly recovered/extremely tired and 10 = very well recovered/highly energetic) (Paul et al., 2019). The skin surface temperature, at the midpoint of the thigh, was also determined at these same time-moments by a single examiner using an infrared manual thermometer (precision = ± 0.2ºC; capture range = 0–60ºC; model YRK-002A – HC260, Multilaser Industrial S.A., São Paulo–Brazil).

7.3.7. Statistical analysis

Statistical tests were performed in IBM Statistical Package for the Social Sciences v.25 (IBM Corp. ©, Armonk–USA) with an alpha level set at $p \leq 0.05$ for determining significance unless otherwise stated. Data normality was firstly assessed using the Shapiro-Wilk's test. If data was flagged as non-normal, then kurtosis, skewness and frequency plots were checked. If log-transformation was not efficient, non-parametric versions of tests were used. In #Experiment 1, Student's t test for dependent samples was used to compare measures pre- and post-RHIR. Effect size for paired comparisons was obtained using Cohen's *d* where $d > 0.20$ (small), > 0.50 (medium), and > 0.80 (large). In #Experiment 2, Student's t test or Wilcoxon signed-rank test was employed to obtain estimates of reliability of the responses to the running protocol between testing days/conditions. As in the case where the latter was necessary, r effect size ($r = z/\sqrt{N}$) was calculated and interpreted as r > 0.10 (small), > 0.30 (moderate) and ≥ 0.50 (large). Intraclass correlation coefficients (ICC), typical error (TE) and coefficient of variation (CV) were also computed using a specific Microsoft Excel (Microsoft Corp., Redmond–USA) spreadsheet (x.rely.xls, available on https://sportsci.org/). Finally, to compare the two distinct recovery interventions, 2 (time: pre, post) x 2 (condition: Control, COOL) repeated measures ANOVAs were run with Bonferroni adjustment to the alpha level in post-hoc comparisons. Partial eta-squared (η^2) was taken as effect size for main effects and deemed as $\eta^2 > 0.01$ (small), > 0.06 (moderate), and > 0.15 (large). When necessary, Friedman's two-way ANOVA by ranks was used, also with post-hoc significance adjusted by dividing alpha level to the number of multiple comparisons performed. Kendall's *W* effect size for main effect was determined and considered as $W > 0.10$ (small), > 0.30 (moderate) and ≥ 0.50 (large).

7.4. Results

7.4.1. **#Experiment 1**

7.4.1.1. Intense running exercise, perceptual measures and kicking outputs

The repeated high-intensity running protocol led to a significant *large* increase in ratings of perceived exertion (percentage difference, mean/median absolute difference [CI lower; upper] = +659.74%, 4 a.u. [3; 9]; $p < 0.01$) and a *large* decrease in perception of recovery (-40.47%, 3.62 a.u. [1.66; 5.57]; $p < 0.01$). A *large* significant increase in mean radial error was observed (Table 7.1) following the exercise protocol (+34.90%, 0.67 m [0.10; 1.25]; $p = 0.03$). There was also a *large* non-significant increase in accuracy (+18.12%, 0.50 m [0.14; 1.14]; $p = 0.11$). *Small* significant declines occurred in average (-3.14%, 0.89 m/s [0.06; 1.73]; $p = 0.04$) and peak ball speed values (-3.94%, 1.18 m/s [0.15; 2.21]; $p = 0.03$). Ankle eversion/inversion angle of the kicking limb at impact *moderately* increased after the running protocol (+257.14%, 0.18 rad [0.04; 0.33]; $p < 0.02$).

7.4.2. **#Experiment 2**

7.4.2.1. Running protocol reliability

Table 7.2 presents performance indices observed in the running protocol, statistical outcomes from comparisons of these indicators between distinct intervention conditions as well as their concordance. No significant differences were identified for any of the parameters (i.e. MT, WT, BT, TT and DEC) when players performed Control or COOL conditions (p = 0.17 to 0.43, *small* effect sizes, -0.34 to 0.38). Running outputs exhibited *moderate*-to-*good* reliability (ICCs = 0.50–0.88; $p \leq 0.04$) between the two conditions with the exception of DEC (ICC = -0.43; p = 0.95). CVs ranged between 2.93% (TT) to maximal 5.87% (BT) while a substantially higher value was observed for DEC (CV = 40.66%).

Table 7.1. Effects of repeated high-intensity running bouts (RHIR) on perceptual measures and kicking performance indices (n = 13).

	Pre-RHIR	Post-RHIR	*p*-value	ES [90% CL] – rating
RPE (a.u.)	0.77±1.17*	5.85±2.54	0.006	4.08 [2.96; 5.19] – large
Pain (a.u.)	1.31±0.48	1.54±0.78	0.337	0.45 [-0.35; 1.25] – small
Recovery (a.u.)	8.92±1.85*	5.31±1.89	0.002	-1.83 [-2.64; -1.02] – large
Thigh temperature (ºC)	35.88±0.73	36.22±0.34	0.066	0.49 [0.08; 0.90] – small
Mean radial error (m)	1.92±0.42*	2.59±0.67	0.025	1.50 [0.46; 2.54] – large
Bivariate variable error (m)	1.86±0.59	1.79±0.95	0.764	0.12 [-0.82; 0.58] – trivial
Accuracy (m)	2.76±0.51	3.26±1.10	0.113	0.93 [-0.04; 1.90] – large
Average ball speed (m/s)	28.70±2.30*	27.80±1.19	0.038	-0.36 [-0.64; -0.09] – small
Peak ball speed (m/s)	29.68±2.64*	28.51±2.05	0.029	-0.42 [-0.72; -0.12] – small
CM_{foot} velocity (m/s)	23.88±6.55	24.39±8.27	0.224	0.07 [-0.21; 0.36] – trivial
CM_{foot} to knee relative velocity (m/s)	17.59±3.42	18.49±3.89	0.274	0.24 [-0.14; 0.63] – small
Non-preferred hip velocity (m/s)	10.51±3.19	11.41±4.65	0.244	0.27 [-0.12; 0.65] – small
Peak knee angular velocity (rad/s)	0.53±0.18	0.57±0.22	0.497	0.17 [-0.27; 0.61] – small
ROM hip (rad)	1.30±0.47	1.37±0.49	0.161	0.13 [-0.05; 0.30] – trivial
ROM knee (rad)	1.54±0.46	1.57±0.46	0.229	0.06 [-0.03; 0.14] – trivial
Plantarflexion/dorsiflexion at impact (rad)	-0.54±0.47	-0.54±0.43	0.968	0.00 [-0.13; 0.14] – trivial
Eversion/inversion angle at impact (rad)	-0.07±0.22*	0.11±0.15	0.019	0.78 [0.27; 1.30] – moderate

Note: RPE, ratings of perceived exertion; ROM, range-of-motion; ES, effect size (Cohen's *d*); CL, confidence limits. *significant difference when comparing Pre- vs Post-RHIR at $p \leq 0.05$ level.

Table 7.2. Characterisation of performance indices in the repeated high-intensity running bouts for each condition with reliability measures for responses computed between conditions (n = 15).

	Mean ± SD	Comparison statistics	ICC (90% CI)	TE (90% CI)	CV (%)
MT (s)	Control: 5.02 ± 0.41 COOL: 4.94 ± 0.38	$t_{(14)} = 1.458$; $p = 0.17$; $d = 0.20$	0.88*** (0.73 – 0.95)	0.15 (0.11 – 0.21)	3.01
WT (s)	Control: 5.35 ± 0.45 COOL: 5.28 ± 0.42	Z = -0.796; $p = 0.43$; r = -0.15	0.74** (0.46 – 0.89)	0.24 (0.18 – 0.34)	4.51
BT (s)	Control: 4.67 ± 0.35 COOL: 4.53 ± 0.38	$t_{(14)} = 1.410$; $p = 0.18$; $d = 0.38$	0.50* (0.09 – 0.76)	0.27 (0.20 – 0.39)	5.87
TT (s)	Control: 50.17 ± 4.06 COOL: 49.39 ± 3.82	$t_{(14)} = 1.458$; $p = 0.17$; $d = 0.20$	0.88*** (0.73 – 0.95)	1.46 (1.12 – 2.13)	2.93
DEC (%)	Control: 12.53 ± 4.64 COOL: 14.09 ± 4.48	$t_{(14)} = -0.887$; $p = 0.39$; $d = -0.34$	-0.43 (-0.72 – 0.01)	5.41 (4.16 – 7.89)	40.66

Note: TM, mean time; WT, worst time; BT, best time; TT, total time; DEC, percentage of velocity in the RSA protocol; SD, standard deviation; CI, confidence interval; intraclass correlation coefficient (ICC), typical error (TE) and coefficient of variation (CV). Statistical significance: * $p \leq 0.05$; ** $p < 0.01$; *** $p < 0.001$.

7.4.2.2. Recovery treatment effects

Perceptual measures and skin temperature are presented in Figure 7.1. Responses were similar at baseline (Pre) between the two experimental conditions (p = 1.00; r = 0.02 to 0.38). Friedman's test showed a significant *moderate* main effect for RPE ($X^2_{(3)}$ = 13.408; p = 0.004; Kendall's W = 0.30; Figure 7.1(A)). Pairwise comparisons revealed *largely* increased RPE in the Post- as compared to Pre-Control (+484.85%, 1 a.u. [0; 3]; p = 0.02; r = 0.69) whilst RPE was similar across moments in the COOL condition (+75.00%, 0 a.u. [0; 2]; p = 1.00; r = 0.35 [*moderate*]). Friedman's test also detected a *large* main effect for thigh temperature ($X^2_{(3)}$ = 25.711; p < 0.001; Kendall's W = 0.57; Figure 7.1(D)). Pairwise comparisons indicated a *large* decline following COOL as compared to pre-COOL (-8.59%, 3.3 ºC [2.4; 4]; p < 0.001; r = 0.88). Thigh temperature was *largely* lower in the COOL as compared to Control at Post moment (-9.09%, 3.2 ºC [2.0; 3.7]; p = 0.002; r = 0.88). A main effect in Friedman's test also occurred regarding the perceived Recovery ($X^2_{(3)}$ = 11.057; p = 0.011; Kendall's W = 0.25 [*small*]; Figure 7.1(C)); however pairwise comparisons lacked statistical significance (e.g. Pre- vs. Post-Control; -23.85%, 1 a.u. [0; 4]; p = 0.08; r = -0.65 [*large*]).

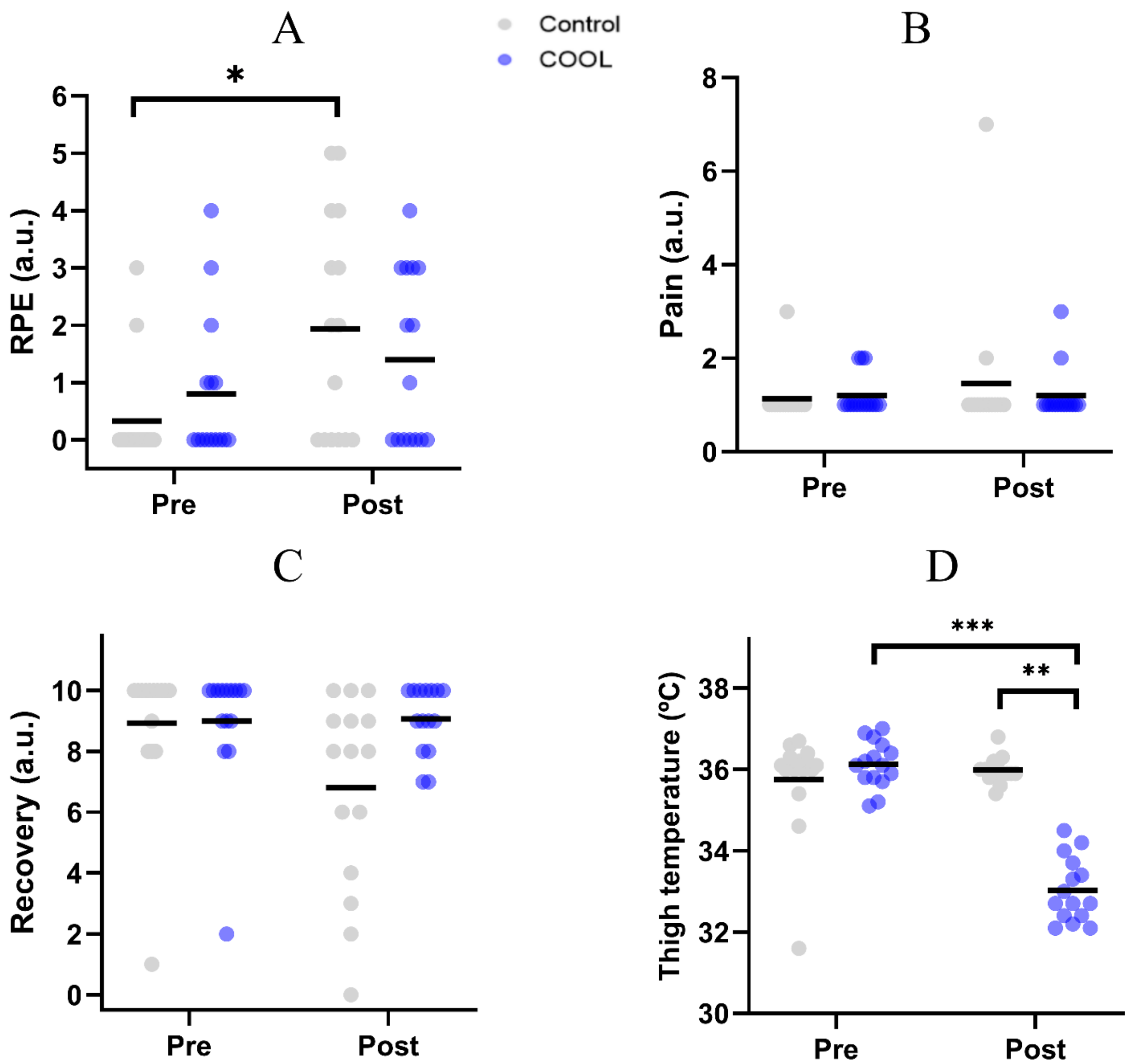

Figure 7.1. Perceptual measures and skin temperature according to time-moments and conditions. * $p \leq 0.05$; ** $p < 0.01$; *** $p < 0.001$.

Kicking ball placement-derived indices (mean radial error, bivariate variable error and overall accuracy) and ball speed (average and peak) across the experiment are shown respectively in Figure 7.2 and Figure 7.3. These parameters did not differ at baseline when comparing Control and COOL conditions (p = 0.39–0.78; d = 0.11–0.36 and p = 0.47–0.78; d = 0.10–0.29 respectively). There was a *large* main Time × Condition interactive effect of borderline significance concerning mean radial error ($F_{(1, 14)} = 4.286$; $p = 0.057$; $\eta^2 = 0.234$). Pairwise comparisons indicated a *large* significant increase in mean radial error after Control condition as compared to baseline (+50.26%, 0.97 m [0.40; 1.54]; p = 0.003; d = -1.12) while no significant pre-post variations existed in COOL intervention (+12.44%, 0.24 m [-0.43; 0.91]; p = 0.45; d = -0.25 [*small*]).

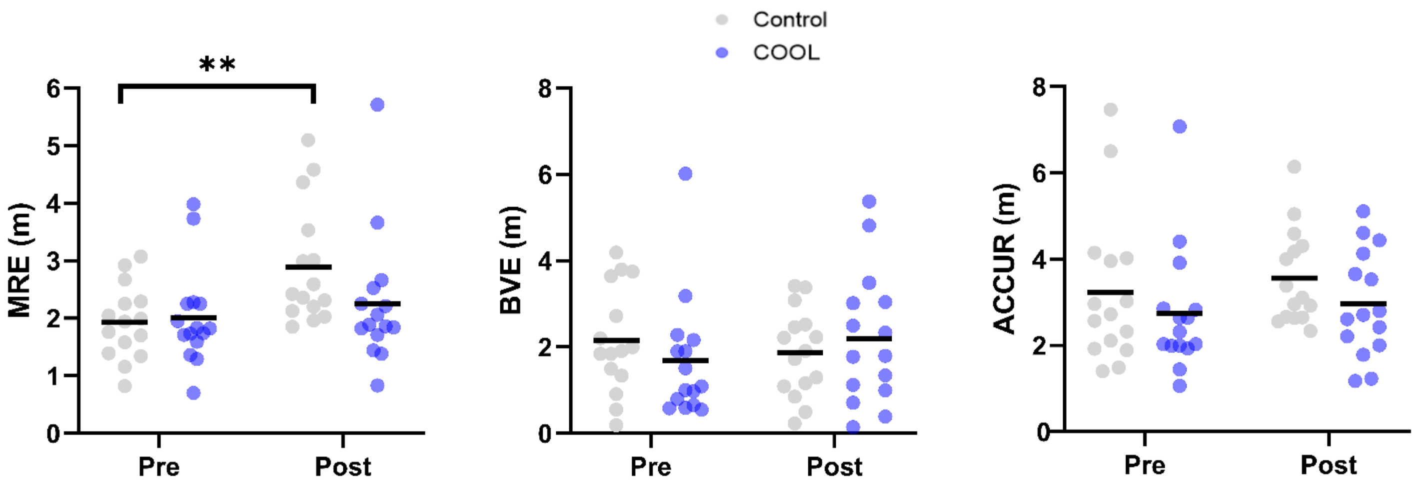

Figure 7.2. Ball placement-derived indices according to time-moments and conditions. ** p < 0.01.

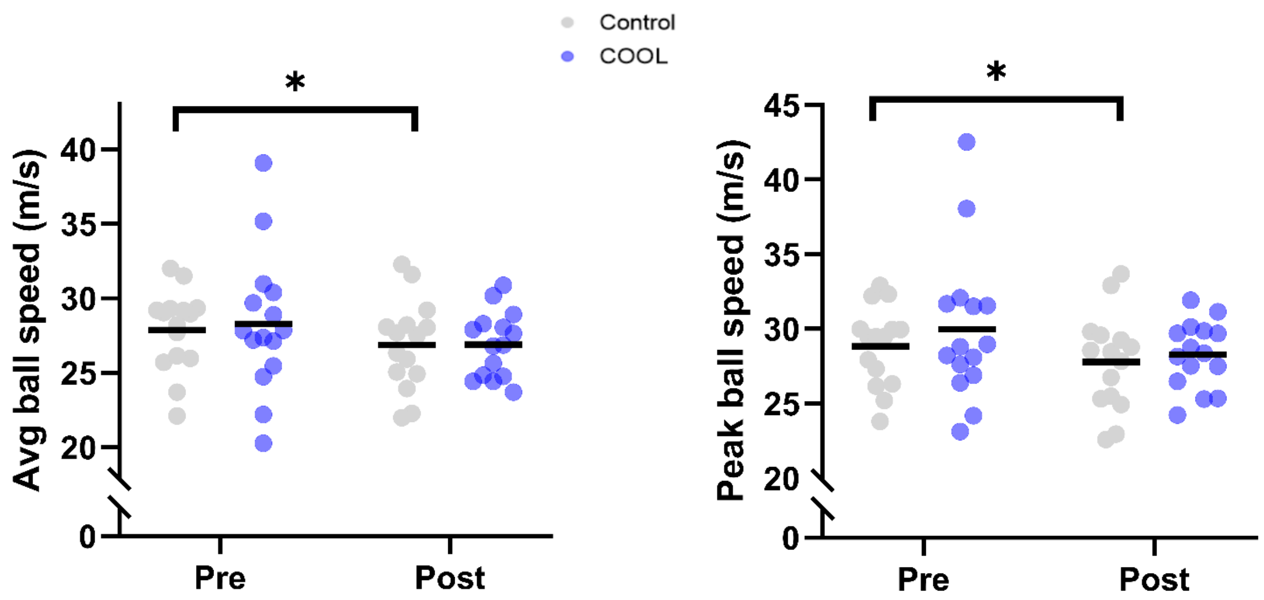

Figure 7.3. Ball speed indices [average (Avg) and maximal (peak)] according to time-moments and conditions. * $p \leq 0.05$; ** p < 0.01.

No significant *small* Time × Condition effects were found for ball speed (average: $F_{(1, 14)}$ = 0.126; p = 0.73; η^2 = 0.009; peak: $F_{(1, 14)}$ = 0.394; p = 0.54; η^2 = 0.027). Separate *large* Time effects were significant for both average ($F_{(1, 14)}$ = 6.649; p = 0.02; η^2 = 0.322) and peak ball speed ($F_{(1, 14)}$ = 6.580; p = 0.02; η^2 = 0.322). Pairwise comparisons revealed significant *small* declines (both d = 0.35) in ball speed following the Control condition (average: -3.62%, -1.01 m/s [-1.95; -0.06]; p = 0.04 and peak: -3.57%, -1.04 m/s [-1.89; -0.18]; p = 0.02) but in COOL condition (average: -4.92%, -1.40 m/s [-3.38; 0.59]; p = 0.15; d = 0.38 and peak: -5.67%, -1.70 m/s [-3.83; 0.42]; p = 0.11; d = 0.44).

Regarding the movement kinematics (Figure 7.4), in general the measures also showed no between-condition differences at baseline (p = 0.14–0.84; d = 0.02–0.42). One exception occurred for the value of ankle eversion angle at impact (main Time × Condition effect: $F_{(1, 14)}$ = 5.339; p = 0.04; η^2 = 0.276 [*large*]), which had a significant pairwise difference among conditions in the Pre (355.56%, -0.32 rad [-0.58; -0.06]; p = 0.02; d = 1.02 [*large*]) but this was not the case in the Post-intervention (33.33%, 0.01 rad [-0.26; 0.29]; p = 0.91; d = -0.06 [*trivial*]; Figure 7.4(H)). Finally, there was a *large* main Time × Condition interactive effect in reference to CM_{foot} velocity ($F_{(1, 14)}$ = 6.538; p = 0.02; η^2 = 0.318). In particular CM_{foot} velocity was *moderately* faster in the COOL as compared to Control in the Post-intervention moment (+21.85%, 4.61 m/s [0.14; 9.08]; p = 0.04; d = 0.60; Figure 7.4(A)).

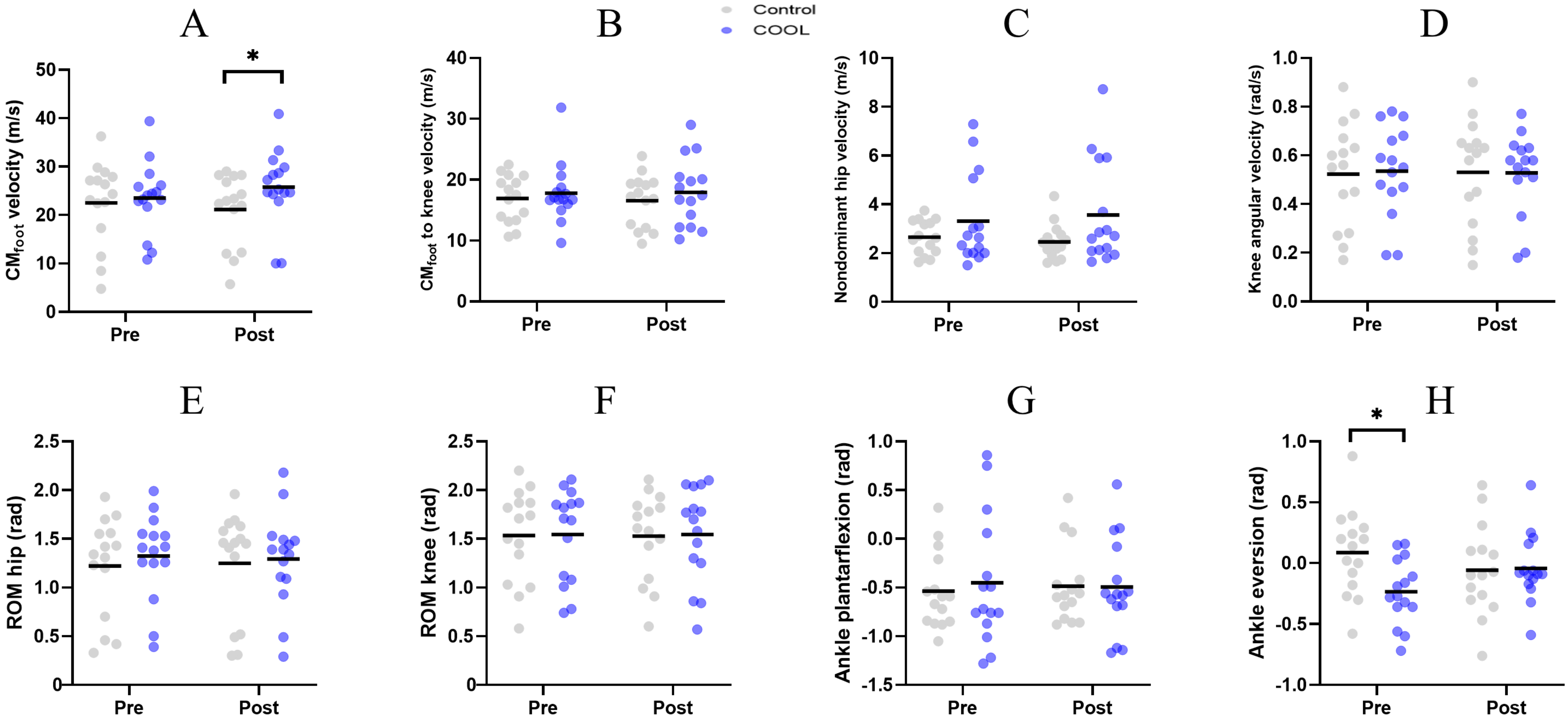

Figure 7.4. Kinematics of the lower contact limb according to time-moments and conditions. * $p \leq 0.05$.

7.5. Discussion

The main purposes of the present investigation were to investigate, in youth soccer players and under an environmental stressor (hot temperature) condition (i) whether repeated high-intensity running (RHIR) efforts immediately modify subsequent kinematics and performance (ball placement and velocity) outputs in kick attempts performed from the edge of penalty area and (ii) the effectiveness of applying a brief local cooling pack (COOL) on the thigh as a potential recovery intervention following this type of locomotor exercise and its consequences on kicking measures. Our first hypothesis was rejected since the intense exercise provoked negative changes notably in ball placement aspects of kicking ability (inducing kicks generally farther from the target in goalpost upper corners) while ball speed was affected to a small extent. Conversely and partly in line with our second hypothesis, the use of 5-minutes COOL following RHIR bouts promoted benefits in perceptual measures (internal load), kinematics (CM_{foot}) and performance (both ball placement and velocity indicators) of soccer kick attempts as compared to the control condition. Hereinafter, we discuss the transient negative impact of RHIR exercise and the ergogenic effects provided by COOL during the acute recovery phase, emphasizing the distinct responses of kicking components to both exercise/cool-down.

In general, RHIR bouts impaired both kinematics and performance components of soccer kicking in youth under-17 players. These include distal mechanics of contact limb as illustrated by modification of ankle eversion to inversion pattern at foot-ball impact moment. In addition, mean radial error substantially increased following the running protocol potentially performance. Recent related research has notably shown that greater ankle inversion is associated to higher mean radial error in kick attempts from entrance of penalty area (Palucci Vieira et al., 2022a). Ball speed verified in the present experiment was within the range (22–32 m/s) of age-matched players (Nunome et al., 2006; Vieira et al., 2018) while the mean radial error was slightly greater than in penalty trials or 15-m kicks (0.90–1.50 m; (Russell et al., 2011; Vieira et al., 2018)). According to a recent review on the topic (Palucci Vieira et al., 2021b) only two studies assessing the acute impact of RHIR mode of exercise on subsequent kicking aspects of youth soccer currently exist. Non-significant (trivial-to-large) exercise effects on accuracy were previously verified but no concomitantly information on kicking velocity was provided (Gharbi et al., 2017; Masmoudi et al., 2016). Of note, these works were conducted in players mean aged 14.6 years-old, that certainly fell in the circum-PHV stage (Buchheit and Mendez-Villanueva, 2013) while the present players were all post-PHV. More mature players perform faster bouts than developing pre/circum-PHV peers in repeated sprints of equalized volume (Selmi et al., 2020). Consequently, the impaired ball placement ability following RHIR efforts verified in the current investigation in youth aged under-17 but not in under-15s in literature can be potentially attributed to a superior disturbance in homeostasis experienced in the former due to their higher intense locomotor output profiles. Notwithstanding, kick task constraints as attempts performed 6.1 m apart from a small-dimension (2.44 x 1.22 m) goal/target aiming only its centre (Gharbi et al., 2017; Masmoudi et al., 2016) prevents such a direct comparison to our results or otherwise could question whether prior evidence of no changes on ball placement ability in youth soccer following RHIR is due to low-challenging kick testing demands. Our findings are in accordance with those of Rampinini et al. (2008) who verified impaired short passing performance in youth players following RHIR that attempted to reproduce most demanding phase of matches (10 x 40 m with one change-of-direction). Importantly, exercising with RHIR in addition to a heat condition are recognised to cause central neurotransmission deficits and a drop in muscle activity (Goodall et al., 2015; Meeusen et al., 2006; Perrey et al., 2010), both determinant aspects to proficiency in targeting the ball when kicking (Palucci Vieira et al., 2022a; Palucci Vieira et al., 2021b). To summarize, intense and consecutive running bouts (e.g. match-play worst case scenarios) could impair soccer kicking in youth under-17 age-group, mainly the ability of players placing the ball in the goalpost upper corners.

It is necessary to highlight a discrepant behaviour of kicking velocity and ball placement responses to the exercise whilst recovery intervention effect was similar for both aspects. In fact central and peripheral signalling paths/measures responsible for kick accuracy and velocity are not the same (Palucci Vieira et al., 2022a), which a priori help justify differences. However, exercise-related fatigue affects to a similar extent the functioning of brain regions/waves determinants for ball speed (frontal theta) and placement (occipital alpha) (Baumeister et al., 2012) meaning that the problem could be more at limb level. Evidence that vastus lateralis RMS may be unchanged as a function of repeated sprints execution and have fast recovery has been provided (Billaut and Basset, 2007). EMG amplitude indices such as RMS and integral were recently demonstrated to affect ball speed in teenagers (unpublished observations from our laboratory). Also, biceps femoris activity that is related to ball placement in youth soccer seems more consistently modified by repeated intense bouts across studies (Hautier et al., 2000; Timmins et al., 2014; Zarrouk et al., 2012) given the high strain on the hamstrings during decelerations separating RHIR efforts. On the other hand, there is a strong linear relation amongst kicking ball speed and chance of goal attempt to become blocked (Palucci Vieira et al., 2021b). Whether players intrinsically adopted a possible strategy of trying to maintain the velocity output under fatigue, with impaired control (e.g. ankle joint) this may have resulted in worst ball placement following RHIR.

Aside from a worst ball placement induced by RHIR, it is necessary to highlight that reductions in ball speed due to this mode of exercise although significant were small and does not surpass minimal detectable difference (~1.27 m/s; Palucci Vieira et al. (2022b)). Even though such little reductions caused by separate RHIR efforts, official competition demands induced moderate-to-large declines in post-match ball speed elsewhere in youth from all playing positions (Izquierdo et al., 2020). This reinforces the potential role of COOL in practice to prevent this picture given the ergogenic effects it had on foot and ball velocities according to our analysis. Notwithstanding, while technological or logistic difficult still exist limiting collection of advanced kicking technique features during real-world events, simulated game-play running demands (e.g. RHIR efforts) seems a pertinent strategy (Palucci Vieira et al., 2021b; Rampinini et al., 2008; Sánchez-Sánchez et al., 2014). In this sense, according to existing reviews (Lopes-Silva et al., 2019; Paul and Nassis, 2015), the day-to-day repeatability of the specific on-field RHIR protocol used has not been determined before this experiment; a single study with similar sprint number/larger course (10 x 40 m; no mention to environmental condition) including youth elite European soccer players age-matched to our sample reported only average bout duration as a reference parameter (r = 0.94), such that it do not always reflect various components of repeated sprints performance (e.g. lack of average-best bouts association). Here the 10 x 30 m RHIR model showed consistent outcomes between distinct experimental conditions in the heat also in peak, worst and accumulated effort durations in addition to no between-day statistically significant differences in all measures (indicative of low random and systematic bias, respectively), thereby providing preliminary evidence at first time supporting global reproducibility of a specific tool to South American academy players.

One key finding of the present analysis was that a cooling intervention using the application of ice pack on the quadriceps/hamstrings across following RHIR performed in the heat reduced the perception of effort while seemingly preventing negative consequences such as worst ball placement, CM_{foot} and ball speed declines as observed in the control condition–passive resting during a time-matched period–but not in the COOL condition. There was a trend represented by non-significant (p = 0.08) large-sized decrease in perceived recovery during post-control while this was not the case in COOL condition. Among the mechanisms possible acting, a forceful reduction in local temperature can have counteracted declines in neuromuscular output observed under heat (Matsuura et al., 2015). Another aspect to appraise these results is that a 5-min induced COOL, despite promoting substantial decreases in skin (Figure 7.1) and subcutaneous temperatures (Myrer et al., 1997), it can cause limited decline in intramuscular temperature as compared to the rested state (e.g. ~0.64ºC; Zemke et al. (1998)). This is important owing to the strong relationship between declines in muscle temperature and lower limb (sprint) performance (Mohr et al., 2004). Locomotor outputs have been indirect markers related to kicking quality in youth (Sporiš et al., 2007), meaning that likely exist shared mechanisms responsible by those explosive actions and if it hold true, an exacerbated muscle temperature drop may lead also into kick deficits. In a meta-analysis, the effectiveness of a commonly used COOL mode namely cold-water immersion was reported to similarly alleviate RPE but had no meaningful effects in power performance in teenagers (Murray and Cardinale, 2015). Also, long periods (e.g. 2 x 15 min) of ice pack maintenance following interval sprints session are recognised to cause bionegative adaptations such as decreased anabolic response in youth team sport athletes (Nemet et al., 2009). Taken together to our results, the premise that COOL has a time-dependent effect on ensuing performance (Bleakley et al., 2012; Fischer et al., 2009; Peiffer et al., 2009) seems well supported as a brief cooling intervention was effective in some instances–especially concerning ball placement–or at least not damaged kicking outputs whilst attenuated exercise effort and recovery perceptions. Thus, we provide evidence for the first time that a short-term local ice pack application following RHIR may assist players in produce subsequent kicks with a greater likelihood of success than resting passively, ameliorating exercise-induced fatigue consequences in skilled performance in a youth soccer context.

Innovative characteristics of the present investigation include empirical testing of whether COOL has benefits to recover (intense) exercise-induced kicking performance loss under heat stress, which fills an important knowledge gap with potential to modify current practices (Bleakley et al., 2012; Palucci Vieira et al., 2021b). Conversely, there are various caveats that should be made which collectively may limits generalizability of this study findings. We have expected that RHIR would promote an acute increase pain sensation while COOL act in its recovery and this was not confirmed since the post-exercise perception of pain was similar to baseline levels. The lack of an extended familiarization of players with such monitoring tool is arguably one of the reasons or otherwise it reflects only a general state of pain and thus scales that compute local muscle soreness are recommended. Advanced measures of body temperature (e.g. infrared thermography) were lacking making unclear the actual physiological impact of COOL treatment over whole working muscles group. When designing the task, we opted to avoid opposition players contesting kicks in an attempt to reduce potential undesirable inter-trial/condition variability interfering with the treatment effects. Despite increasing experimental control, this approach greatly reduces the external validity. Finally, it is yet to be determined the extent to which findings observed in the present investigations are transferable to other intervention format (e.g. cooling chamber), task conditions such as penalty kicks and crowded competition environments.

7.6. Conclusions

Repeated high-intensity running bouts acutely affect soccer kicking performance in youth academy players. Ankle kinematic adjustments at foot-ball impact instant and consequent ball placement are notably impaired following this mode of exercise while kicking velocity aspects are impacted to a small extent. A protocol consisting in 10 x 30 m running efforts interspersed by 30 s intervals is a reliable method in a hot environment, consistent in day-to-day basis. Rather than providing a passive resting period, including 5 minutes of two ice packs applied respectively to the quadriceps and hamstrings muscles of contact limb may favour recovery of wellbeing aspects and overall soccer kicking parameters. Thus, short-term cryotherapy plays an important role in counteracting fatigue-related declines experienced by youth under-17 players in terms of kicking outputs following repeated high-intensity running efforts in the heat.

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CHAPTER 8

EPILOGUE

8. IMPACT OF THIS RESEARCH AND FUTURE PERSPECTIVES

8.1. Introduction

The current thesis investigated both internal individual constraints (brain activity and chronotype/sleep-derived indices) and short-term practical interventions (plyometric-based warm-up and post-exercise cooling) and their role on soccer kicking performance characteristics in youth academy under-17 players. The intentional sample of studies participated in state-level tournaments in a geographical location with remarkable competitiveness (AQUINO et al., 2016; LOTURCO et al., 2015; PALUCCI VIEIRA et al., 2018, 2019b). Experimental studies were all conducted on-field despite the number of challenges and non-controllable aspects of a naturally occurring environment.

Attempts were made to advance from basic to applied research designs in a programme that have resulted in a systematic and critical review of scientific literature investigating warm-up routines, exercise-induced effects and recovery-related consequences on kicking ability, one technical note that evaluated performance of contemporary markerless system to obtain kicking kinematics, two observational and two intervention studies to directly determine respectively the influence of individual constraints and effects of short-term practical interventions.

Evidence gathered here may benefit scientific community and soccer practice since critical input arising from co-workers of distinct expertise in soccer technical performance (academic research and elite world-level practitioner) was also considered when preparing the series of papers presented. Below, there is a short re-statement of literatures gaps that motivated the thesis followed by concluding remarks respectively for the role of (i) internal individual constraints - Section 8.2, (ii) short-term practical interventions - Section 8.3 and (iii) critique/advances regarding techniques to evaluate kicking action - Section 8.4. Finally, recommendations to future investigations are given in Section 8.5 in addition to a theoretical model illustrating the form that results can be useful in a joint manner ultimately to aid improve soccer performance.

8.2. Brain waves, chronotype and sleep influences soccer kicking performance

Internal individual constraints: Aside from simple anthropometrics, estimated maturity and fitness measures (MALINA et al., 2005; WONG et al., 2009; LÓPEZ-SEGOVIA et al., 2015), the influence of internal individual constraints on the soccer kicking performance has been little investigated in youth soccer. Here two studies were proposed to further knowledge on this area considering evaluation of possible associations amongst kicking parameters, complex measures of brain activity (PAPER 2) and perceived/actual sleep-derived indices (PAPER 3). Original data is presented regarding the interactions explored in the PAPER 2 (N = 24) between EEG signals, lower limb movement kinematics and kicking outcomes. Previous studies on the field of sports performance provided evidence only on the associations between the extreme factors (i.e. EEG-outcome; CHUANG et al., 2013; CHRISTIE et al., 2017; PLUTA et al., 2018; THARAWADEEPIMUK & WONGSAWAT, 2017). Thus, a conceptual advance is obtained by describing at first time (Figure 3.8) the possible path to which central inputs control motor system peripheral components and consequent performance (velocity) expression. Following on, the PAPER 3 (N = 28), that included the same sample as in the first experimental study and four additional players from the participant club, evaluated whether inter-individual sleep experienced in the prior night to testing influence ensuing kicking performance features. Literature has investigated only the acute effects of total sleep deprivation condition on soccer kicking ability (MEHRDAD et al., 2012; PALLESEN et al. 2017). In this study chronotype scale score, perceived and actigraphy-derived sleep measures were collected. Of note, the verified influence of low chronotype scale score (toward evening preference), poor perceived sleep quality and latter wake up time linked to worst subsequent kicking ball placement indicates that monitoring night behaviour/sleep could prevent for suboptimal performance occurrences (PALUCCI VIEIRA et al., 2022a).

In particular, the key conclusions of this topic are the following:

- In youth players, brain regions and EEG signal frequencies that control ball velocity and placement in the soccer kicking action are not the same;

- Inter-individual occipital alpha waves prior to approach run is determinant to subsequent effectiveness in targeting the ball in the goalpost upper corners;
- Frontal theta power just before foot-ball impact play a role in motor adjustments (ankle joint) and consequent kicking ball velocity;
- Ball velocity seems robust to oscillations in overall sleep behaviour during the immediately previous night and sleep duration has a limited acute impact on both inter-individual ball velocity and its placement;
- Simple methods to obtain player chronotype (H&O questionnaire; BENEDITO-SILVA et al., 1990) and acute sleep quality (1-very poor, 2-poor, 3-average, 4-good, 5-very good) are associated to subsequent kicking ball placement performance.

8.3. Plyometric activity do not acutely enhance kick while cooling assist post-exercise recovery

Short-term practical interventions: In the light of the comprehensive systematic and critical review (PALUCCI VIEIRA et al., 2021a) that is a pertinent starting point to design applied research in sport sciences (BISHOP, 2008; CARLING, 2012), it was possible to identify that scientific investigations concerned to address effects of warm-up routines upon subsequent soccer kicking performance characteristics were restricted to running activity followed by isolated stretching modalities, unloaded strength stimuli or a simple game-specific task (AMIRI-KHORASANI et al., 2011; GELEN, 2010; McMORRIS et al., 2006); plyometric conditioning activities were not previously tested despite presenting long-term beneficial effects in youth soccer performance components, including kicks (BEDOYA; MILTENBERGER, & LOPEZ, 2015; CAMPO et al., 2009; RAMÍREZ-CAMPILLO et al., 2014, 2015; SÁEZ de VILLARREAL et al., 2015) as well as its ballistic nature that match at least in part biomechanical demands of kick. The PAPER 5 was therefore conceived to assess the time-course of changes in muscle activity (EMG), lower limb motion and kicking outcomes due to drop jumps-based PAPE protocol (N = 15) and determine the neuro-mechanics-performance relationships of soccer kicking. Throughout it is highlighted that the selected warm-up routine increased preparedness in a few neuromuscular responses but that does not directly enhanced ball velocity or placement indices.

While there is notably lack of research dedicated to understanding pre-pitch entry strategies and their effects on subsequent kicking performance, exercise-induced consequences and recovery prescriptions have been addressed to a greater extent (see Figure 2.4). However, repeated high-intensity efforts represents in particular an important portion of game-play activities in youth soccer (BUCHHEIT et al., 2010; SERPIELLO et al., 2018). Collated results through the so called best evidence synthesis method for reviews indicated that information is limited as regarding the relation of such exercise mode and ensuing kicking outputs. Most important, existing reports of effects derived from (i) exercising with repeated sprints or (ii) post-exercise ergogenic aids kick are not representative to a hot environment (ABT; ZHOU, & WEATHERBY, 1998; RUSSELL; BENTON, & KINGSLEY, 2012; STEVENSON et al., 2017), that is a phenomenon experienced in a range of geographical locations/phase of the season. Cooling techniques are ubiquitously used to attempt accelerate post-exercise recovery in soccer, especially in the heat, yet influences on soccer kicking aspects was never an object of analysis (PALUCCI VIEIRA et al., 2021a). To obtain empirical data on this direction, PAPER 6 (N = 15) evaluated the effectiveness of applying cooling (ice packs) to recover kicking kinematics and performance following repeated high-intensity running bouts, using a heat (environment) stress paradigm. The same sample of the prior study participated.

The specific practical applications derived from the interventions studies are as follows:

- A simulated pre-pitch entry warm-up strategy based on low-intensity running followed by dynamic stretching plus five drop jumps is ineffective in promoting acute performance (ball velocity and placement) improvements to youth players;
- A few neuromuscular (EMG) and almost nothing mechanical benefits are observed ~5–10 minutes following cessation of drop jump repetitions, and such limited increases in muscle preparedness–firing rate–are not transferred to kicking outcomes;

- The frequency of missed kicks increase immediately after performing the dynamic stretching+drop jumps warming-up routine;
- Under a high environmental temperature (> 30ºC), exercise like repeated high intensity running bouts acutely impair notably kicking ball placement;
- Ice packs applied during 5 minutes following repeated sprint efforts in the quadriceps and hamstrings promoted superior ergogenic effects to the soccer kicking when compared to passive resting.

8.4. Methodological and critique contributions

Theoretical evidence and advances in methods: Before commencing the experiments of the present thesis, it was identified that previous literature reviews concerned with data collection and analysis methods applied to soccer kick testing were published more than 10 years ago (ALI, 2011; KELLIS & KATIS, 2007; LEES et al., 2010; RUSSELL & KINGSLEY, 2011; SHAN & ZHANG, 2011; YOUNG & RATH, 2011). As a consequence, a decision was made to provide also an updated critical appraisal on these methodological aspects (e.g. constraints related to kicking testing and data acquisition methods) of the scientific peer-reviewed articles included (n = 52), resulting in a systematic plus critical review of literature evaluating acute effects of interventions ranging from warm-up routines, exercise-induced effects and recovery-related strategies (PAPER 1). This theoretical study elucidated a need for better resemblance between kick testing constraints and competition demands while suggesting directives (Section 2.5.1) on how to deal with the identified issues (PALUCCI VIEIRA et al., 2021a). These were took into account here in the present experimental papers (match-derived distance from initial ball position to the goal line, targets in the goalpost upper corners and presence of an opponent goalkeeper in some of them; e.g. Section 4.3.2). A test-retest analysis indicated that the reliability outcomes in the proposed protocol (fully described in Section 4.4.1) is compatible to previous one (ALI et al., 2007; BERJAN BACVAREVIC et al., 2012; RUSSELL; BENTON, & KINGSLEY, 2010) and owing to its game-like features emerge as a pertinent option to test kicking performance in youth soccer, in particular aged under-17. Notwithstanding, obtaining soccer kick kinematics under field conditions has been invariable linked to labour-intensive methods for processing image sequences such as manual tracking (LEES; KERSHAW, & MOURA, 2005; BARRIS & BUTTON, 2008; PALUCCI VIEIRA et al., 2021a). Here, there is a further contribution to technologies currently available that can assist reduce the time spent processing time-series of ball kicking movement. OpenPose markerless tracking was compared to manual digitisation (PAPER 4; PALUCCI VIEIRA et al., 2022b) in a subsample of previous interventions experiments (N = 6). Also, trying to overcome the original limitation of this multi-person detection tool, a simple tracking algorithm was proposed in PAPER 4 (Section 5.3.2.2) which (i) takes OpenPose data as inputs and then compute centre of mass for various poses in the image (if multiple are identified) at each instant t; (ii) associate it with the pose in the frame t+1 whose centre of mass presents the smallest Euclidean distance–K-Means assisted compute pairwise distances; (iii) output set of poses for a specific person over the duration of the trial.

In sum, the portion of the thesis concerned to methodological aspects of kick assessment/processing methods also resulted in some key-points:

- Inclusion of kicks over medium-to-long distances to the goalpost, opponents (defenders/goalkeeper) attempting to block attempts, and a greater variety of targets (e.g. positioned in the goalpost corners) have been systematically overlooked in kick testing procedures;
- Using video kinematics to reconstruct ball placement when it crosses goal line is increasing, but notational-based methods still predominate despite uncertainties regarding their reliability, objectivity and sensitivity (RUSSELL & KINGSLEY, 2011);

- Radar technology is the most frequent choice to measure ball velocity in scientific literature while reporting validity of such method against gold standard 3-dimensional measures is lacking;
- To date, results regarding the effects of actual soccer match-play (11 versus 11) demands upon kicking performance are inconclusive;
- OpenPose markerless system aligned to a simple K-means-based tracking algorithm appears as a pertinent solution to obtain almost the same information than those derived from manual digitisation, in a dramatically shorter time frame.

8.5. Theoretical model integrating evidence and directions for future research

While there is a range of new e noteworthy conclusions where some may have a direct impact on current research/practices, based on theoretical and empirical studies conducted over a four-year doctorate programme and these were aforementioned in details, several limitations were also recognised and wrote across papers presented in this Thesis. This imply that study designs could use this information to direct efforts toward pertinent questions. Aiming at expand information relating brain dynamics and soccer kick motion, future investigations are arguably necessary to compute connectivity and source metrics. Again, given the observational and cross-sectional nature of the sleep analysis employed here, direct practical implications may be limited implying a need of replication studies to evaluate multiple-night within-individual variations in sleep and concomitant kick performance testing data. PAPE-based strategies should encompass also game-specific activities such as technical-tactical exercises commonly adopted in pre-pitch entry prescriptions. The beneficial effects of rapid cryotherapy following intense exercise need to be tested also in other kick types (e.g. penalty attempts). Continuous development in technology (e.g. wireless EEG micro-electrodes, markerless kinematic systems and automatic match event detection algorithms) may offer opportunities to gather advanced in-game neuropsychophysiological and biomechanical data related to kick motion in soccer.

Finally, the Figure 8.1 contains a sequence of possible integrated steps that may be used in practice to assist improve or prevent declines in soccer kicking performance of youth players. These directives were directly derived from the empirical data obtained in the experimental studies of this Thesis and are organised according to a temporal perspective. Future studies are warranted to determine the impact of the provided recommendations in such model on the player's responses during competition, in particular match-related shooting statistics or continuous performance data.

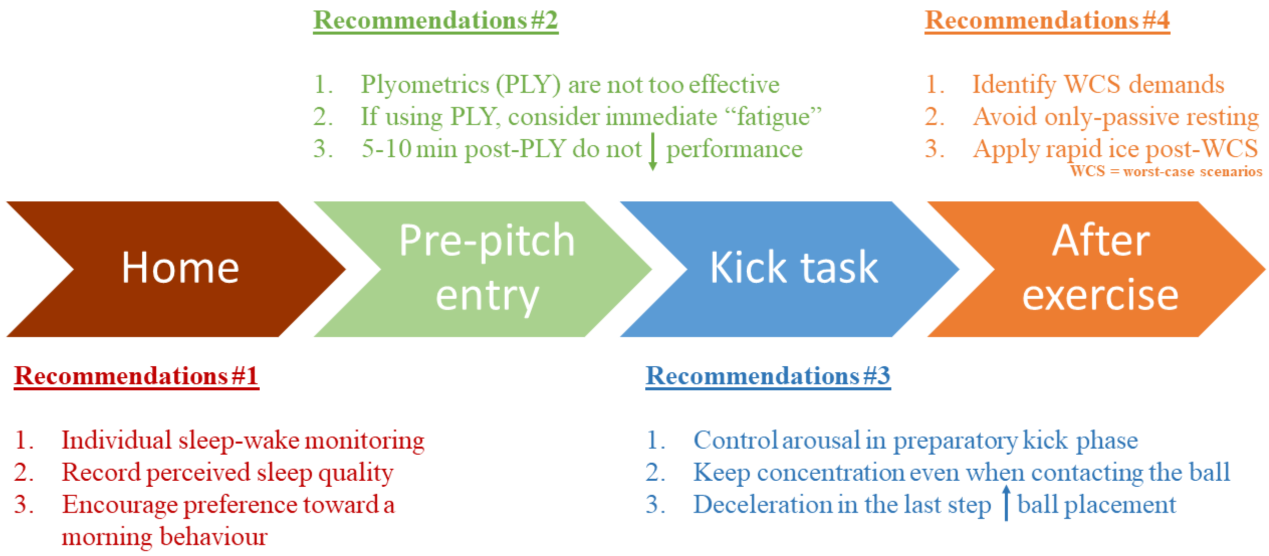

Figure 8.1. Model integrating evidence gathered across experimental studies conducted in the current Thesis.

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APPENDIX 1. RESEARCH ETHICS COMMITTEE APPROVAL

UNESP - FACULDADE DE CIÊNCIAS CAMPUS BAURU - JÚLIO DE MESQUITA FILHO

PARECER CONSUBSTANCIADO DO CEP

DADOS DO PROJETO DE PESQUISA

Título da Pesquisa: INFLUÊNCIA DA QUALIDADE DO SONO, POTENCIALIZAÇÃO PÓS-ATIVAÇÃO E IMERSÃO EM ÁGUA GELADA NA MECÂNICA DE MOVIMENTO E DESEMPENHO DO CHUTE EM JOVENS JOGADORES DE FUTEBOL

Pesquisador: Luiz Henrique Palucci Vieira

Área Temática:

Versão: 2

CAAE: 85994318.3.0000.5398

Instituição Proponente: UNIVERSIDADE ESTADUAL PAULISTA JULIO DE MESQUITA FILHO

Patrocinador Principal: Financiamento Próprio

DADOS DO PARECER

Número do Parecer: 2.650.204

Apresentação do Projeto:

A hipótese deste estudo é que jogadores com baixa qualidade/quantidade de sono apresentarão diminuição na atividade cortical, mudanças na mecânica do movimento e pior desempenho no chute do que pares que apresentam alta qualidade/quantidade de sono.

Objetivo da Pesquisa:

Verificar quais são os fatores pessoais e contextuais que contribuem para um bom desempenho do chute em jovens jogadores.

Avaliação dos Riscos e Benefícios:

Os riscos são relativamente pequenos, limitando-se aos comuns decorrentes da prática esportiva. Como benefício, será possível informar treinadores e professores de futebol sobre as estratégias para possivelmente aprimorar o desempenho do chute neste esporte de equipe.

Comentários e Considerações sobre a Pesquisa:

Pretende-se responder qual a influencia da tríade aquecimento–exercício–recuperação na mecânica do movimento e no desempenho do chute no futebol.

Considerações sobre os Termos de apresentação obrigatória:

O TCLE e o TALE apresentam uma linguagem um pouco erudita para os seus destinatários, mas se

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preocupa em esclarecer os termos técnicos e apresenta todas as necessárias informações.

Recomendações:

Nada a recomendar

Conclusões ou Pendências e Lista de Inadequações:

Nada a observar.

Considerações Finais a critério do CEP:

Projeto considerado aprovado por estar em conformidade com os parâmetros legais, metodológicos e éticos analisados pelo colegiado deste CEP.

Este parecer foi elaborado baseado nos documentos abaixo relacionados:

Tipo Documento	Arquivo	Postagem	Autor	Situação
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Parecer Anterior	Lista_alteracoes.pdf	17/04/2018 16:39:51	Luiz Henrique Palucci Vieira	Aceito
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Situação do Parecer:

Aprovado

Necessita Apreciação da CONEP:

Não

BAURU, 11 de Maio de 2018

Assinado por:
Mário Lázaro Camargo
(Coordenador)

Endereço: Av. Luiz Edmundo Carrijo Coube, nº 14-01
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