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Physical high-intensity actions in elite soccer

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THE FACULTY OF EDUCATION AND ARTS

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Summary

Soccer is the most popular sport in the world, played by approximately 275 million people, over 128,000 of whom are registered as professionals (FIFA Professional Football Report, 2019). A soccer match for senior players is scheduled to last 90 minutes (min), consisting of two 45-min halves divided by a 15-min rest period. Two teams compete against one another with the aim of outscoring the opponent. Teams are permitted to have 11 players on the field, consisting of one goalkeeper and 10 outfield players. The outfield players are organized in numerous formations in and out of possession based on tactical instructions from the coach. Performance in soccer is determined by the players' technical, tactical, physiological and psychological/social characteristics. Soccer players who have the ability to cope with the physical demands of the game can utilize their tactical and technical skills more effectively during match play. Understanding the physical demands of soccer is important in order to optimize the training process. Over the years, numerous techniques have been used to determine the physical profile of soccer players. Observations of athletes while they participate in their specific sport may provide useful data on the physiological demands of an activity. These data could have an impact on the training regimen, fitness assessment and selection of players by providing an ergonomic framework for these activities.

The overall objective of this thesis was to investigate the physical demands of elite soccer players, with special focus on high-intensity movements and actions. In order to investigate the overall objective, my colleagues and I wanted to characterize the sprint and acceleration profiles of elite soccer players and investigate whether the number of accelerations constitutes a more precise estimate of match physical performance and performance decline in elite soccer players compared to high-intensity running (HIR) distances, as well as whether small-sided games (SSGs) in training could give a high enough training load for high-intensity movements and actions. Finally, we aimed to obtain knowledge concerning player load using accelerometers and the patterns of player load during matches, and how different soccer-specific high-intensity actions influence physiological, perceptual and accelerometer loads. The main research

objective was assessed through six specific aims and hypotheses related to Study I through Study VI, respectively.

Study I aimed to characterize the sprint and acceleration profiles of elite soccer players across five different player positions in one elite soccer team's match play. In elite players across all positions, we observed fewer accelerations during the second compared to the first half of the matches. Players in lateral positions accelerated more often than those in more central positions. Further, average sprint distances and number of sprints during the match showed no significant differences between the halves, while players in lateral positions covered longer sprint distances.

Study II aimed to obtain new knowledge concerning player load during match play using a combination of tri-axial accelerometer and time-motion analysis. In addition, we aimed to determine acceleration and deceleration profiles of elite soccer players, as well as the contribution of accelerations and decelerations to player load during match play. A novel finding from this study was that in elite soccer players, accelerations contribute to 7–10%, and decelerations to 5–7%, of the total player load across all playing positions during match play. Therefore, in order to obtain a "true workload," accelerations, decelerations (i.e., number, distance, effort) and distance covered at various running speeds must all be included when evaluating a player's total workload during a full soccer game.

Study III investigated the effect of different soccer-specific maximal actions (sprints with and without change of directions [COD], jumps and shots) on physiological (oxygen uptake and heart rate) and perceptual (rating of perceived exertion [RPE]) responses, as well as accelerometer load data. In our evaluation of different soccer-specific maximal actions, the total accelerometer load was lowest in sprint and sprint COD conditions, although the physiological (oxygen uptake and heart rate) and perceptual (RPE) responses were highest in the respective conditions. The order of physiological and perceptual responses of the specific soccer actions from low to high differed from those of the acceleration load, indicating that accelerometer loads are not similar to physiological and perceptual responses.

Study IV explored whether the number of accelerations is a more precise estimate of match physical performance and performance decline in elite soccer players compared to HIR distances. In addition, the study aimed to compare changes in the number of accelerations and HIR distances across playing positions to examine whether the match profiles of the physical performance measures were consistent or demonstrated high interposition variability. This study found a continuous reduction in accelerations over the course of the match and after peak working periods of the match in elite soccer players. Although there are positional differences in the number of accelerations in a match, the positional similarities seem applicable to performance decline both from the start to the end of matches and after the peak periods of each half. Thus, findings from this study suggest that accelerations might be a more stable and sensitive measure of physical performance decline compared to HIR distance in soccer match play.

Study V investigated the patterns of player load in comparison to locomotor variables over moving 5-min windows in an elite soccer team, comparing these patterns between different positions within the same team. By using 5-min moving windows throughout the match, this study found similarities in player load patterns between positions in elite soccer matches. The novel finding is the identification of a clear pattern, consisting of three high-load periods in both halves that are followed by periods with reduced load. The present study did not find similar unambiguous patterns in any of the locomotor variables. The evident pattern in player load indicates a physical "pacing pattern" employed by the team. These "pacing patterns" were relatively similar between positions and occurred at the same time points during the matches over three successive seasons.

Study VI aimed to study whether the physical performance of players (i.e., total distance, HIR distance, sprint distance, number of accelerations and player load) during 4 vs. 4 and 6 vs. 6 SSGs was equivalent to or higher than the physical performance of the most intense periods of match play. The total, HIR and sprint distances were lowest during SSGs, while compared to peak match periods, the number of accelerations was similar in 4 vs. 4 but less than half in 6 vs. 6. Meanwhile, compared to average match data per min, players had twice the number of accelerations during 4 vs. 4 and almost 50% more during 6 vs. 6. Player load during SSGs was somewhat lower than peak match periods and higher than the match mean (which was highest for 4 vs. 4).

This thesis suggest that accelerations may be a more stable and sensitive measure of physical performance decline compared to HIR distance in soccer match play. Time-motion analysis is a useful tool for examining the physiological demands from high-speed activities, but accelerometers may supply information concerning player load from the many discrete actions of a soccer match that may be classified as low-speed activity. Indeed, the present thesis reveals some new factors concerning player load during matches. This thesis also suggests that many high-intensity actions without change in location at the pitch may contribute significantly to player load during matches and training. Player load from accelerometer may function as a complementary tool to investigate player loads during matches and training in addition to other tracking systems. Furthermore, the similarity in player load patterns between both matches and positions in elite soccer competition could indicate a physical "pacing pattern" employed by elite soccer teams. Training with 4 vs. 4 SSGs seems highly valuable to provide the peak demand for accelerations and player load during matches, but neither 4 vs. 4 nor 6 vs. 6 SSGs are close to the HIR or sprint demands during matches.

Sammendrag (Summary in Norwegian)

Fotball er den mest populære sporten i verden, spilt av omtrent 275 millioner mennesker, med over 128 000 spillere registrerte som profesjonelle (FIFA Professional Football Report, 2019). En fotballkamp for seniorspillere varer i 90 minutter, bestående av to 45-minutters omganger med en 15-minutters pause mellom omgangene. To lag spiller mot hverandre med sikte på å vinne over motstanderen. Hvert lag har 11 spillere på banen, bestående av en målmann og ti utespillere. Utespillerne er organisert i tallrike formasjoner for angrep og forsvar basert på taktiske instruksjoner fra treneren. Prestasjon i fotball bestemmes av spillernes tekniske, taktiske, fysiologiske og psykologiske/sosiale egenskaper. Fotballspillere som har evnen til å takle de fysiske kravene til spillet kan bruke sine taktiske og tekniske ferdigheter mer effektivt under kamp. Å forstå de fysiske kravene til fotball er viktig for å optimalisere treningsprosessen. Gjennom årene har en rekke måleteknikker blitt brukt for å bestemme den fysiske profilen til fotballspillere. Observasjoner av idrettsutøvere mens de deltar i sin spesifikke idrett kan gi nyttige data om de fysiologiske kravene som stilles til en aktivitet. Disse dataene kan ha en innvirkning på treningsregime, vurdering av fysisk prestasjon og seleksjonen av spillere, og dermed gi et passende rammeverk for kravene i disse idrettene.

Det overordnede intensjonen med denne avhandlingen var å utforske de fysiske kravene til elitefotballspillere med spesiell henblikk til høyintensive bevegelser og aksjoner. For å undersøke den overordnede intensjonen ønsket vi å beskrive sprint- og akselerasjonsprofilene til elitefotball og å undersøke om antall akselerasjoner utgjør et mer presist estimat enn høyhastighetsløp i vurdering av fysisk prestasjonsnedgang hos spillere på dette nivået, samt om småbanespill i trening kan gi stor nok treningsbelastning på høyintensive bevegelser og aksjoner. I tillegg til dette ønsket vi å undersøke spillerbelastningen målt med akselerometer og om denne typen belastning utviklet spesielle mønster i kamp. Videre var hensikten å undersøke hvordan ulike fotballspesifikke høyintensitetsaksjoner påvirker fysiologiske, perseptuelle og akselerometerbelastninger. Seks studier med spesifikke mål og hypoteser ble designet for å undersøke den overordnende intensjonen.

Studie I ønsket å beskrive sprint- og akselerasjonsprofilene til norske elitefotballspillere på tvers av fem forskjellige spillerposisjoner i kamp. Hos spillerne på tvers av alle posisjoner observerte vi færre akselerasjoner i andre omgang sammenlignet med første omgang av kampene. Spillere i kantposisjoner akselererte oftere enn spillere i mer sentrale posisjoner. Videre ble det ikke funnet noen signifikante forskjeller mellom omgangene i gjennomsnittlig sprintdistanse eller antall sprinter i løpet av kampen, men spillere i kantposisjoner tilbakela lengre sprintdistanser.

Studie II ønsket å innhente ny kunnskap om spillerbelastning under kamp ved bruk målinger fra en kombinasjon av akselerometer som måler akselerasjoner i tre akser og et radiobasert sporingssystem for fotball, som måler spillernes endringer i posisjon og hastigheten på denne. I tillegg hadde vi som mål å bestemme akselerasjons- og retardasjonsprofiler for elitefotballspillere, og akselerasjoner og retardasjoner sine bidrag til spillerbelastningen under kamp. Denne studien viste at hos elitefotballspillere på tvers av alle spilleposisjoner bidrar akselerasjoner til 7-10 % og retardasjoner til 5-7 %, av den totale spillerbelastningen under kamp. Derfor, for å oppnå en "ekte spillerbelastning", bør akselerasjoner, retardasjoner (dvs. antall, distanse, innsats), samt distanse tilbakelagt ved ulike løpshastigheter inkluderes når man skal evaluere en spillers totale belastning under fotballkamp.

Studie III undersøkte effekten av ulike fotballspesifikke maksimale aksjoner (sprint med og uten retningsendring (COD), hopp og skudd) på fysiologiske (oksygenopptak, hjertefrekvens) og perseptuelle (vurdering av selvopplevd anstrengelse, RPE) responser, samt akselerometerets belastningsdata. Ved å evaluere forskjellige fotballspesifikke maksimale aksjoner, var den totale akselerometerbelastningen lavest i sprint- og sprint-COD kondisjonene, selv om de fysiologiske (oksygenopptak og hjertefrekvens) og perseptuelle (RPE) responsene var høyest under de respektive kondisjonene. Rekkefølgen fra lav til høy av fysiologiske og perseptuelle responsene for de spesifikke fotballaksjonene var ulik rekkefølgen på belastningen fra akselerometeret, noe som indikerer at belastningen fra akselerometer ikke gir lik respons som fysiologiske og perseptuelle responser.

Studie IV studerte om antall akselerasjoner var et mer presist estimat enn høyhastighets-løpedistanse på både fysisk prestasjon i kamp og eventuell fysisk prestasjonsnedgang hos elitefotballspillere. I tillegg var målet å sammenligne endringer i antall akselerasjoner og høyhastighets-løpedistanse på tvers av spilleposisjoner for å studere om kampprofilene til de fysiske prestasjonsmålene i kamp var konsistente eller viste høy variabilitet mellom posisjoner. Denne studien fant en kontinuerlig reduksjon i akselerasjoner i løpet av kampen og en reduksjon etter perioder med ett høyt antall av akselerasjoner i kampen. Selv om det er posisjonsforskjeller i antall akselerasjoner i en kamp, ser posisjonslikhetene ut til å gjelde både prestasjonsnedgang fra start til slutt av kamper og etter høyintensitetsperioder i hver omgang. Derfor tyder funn fra denne studien på at akselerasjoner kan være ett mer stabilt og sensitivt mål på fysisk prestasjonsnedgang sammenlignet med høyhastighets-løpedistanse i fotballkamp.

Studie V undersøkte mønstrene for spillerbelastning fra akselerometer sammenlignet med bevegelsesvariabler fra et radiobasert sporingssystem for fotball med analyse av suksessive 5-minutters vinduer fra kamp til elitefotbalspiller. I tillegg ble det sammenlignet i hvilken grad disse mønstrene varierte mellom forskjellige posisjoner innen samme lag. Ved å analysere suksessive 5-minutters vinduer gjennom kampen, fant denne studien lignende i spillerbelastningsmønstre fra akselerometeret mellom ulike posisjoner. Det vises ett tydelig mønster som består av tre perioder med høyere belastning i begge omganger, og hvor disse periodene med høyere belastning etterfølges av perioder med redusert belastning. Den nåværende studien fant ikke lignende entydige mønstre på noen av de fysiske variablene fra det radiobaserte sporingssystemet for fotball. Det tydelige mønsteret i spillerbelastning indikerer et fysisk "tempomønster" som dette laget bruker, og disse "tempomønstrene" var relativt like mellom posisjoner og skjedde på samme tidspunkt under kampene over tre påfølgende sesonger.

Studie VI ønsket å studere om den fysiske prestasjonen til spillere (dvs. total distanse, høyhastighets-løpedistanse, sprintdistanse, antall akselerasjoner og spillerbelastning fra akselerometer) under 4 mot 4 og 6 mot 6 småbanespill var tilsvarende som eller høyere enn den fysiske belastningen av de mest intense periodene med kamp. Totaldistanse og høyhastighets-løpedistanse og distanse av spurter var lavest under småbanespill, mens antallet akselerasjoner var likt i 4 mot 4 småbanespill og de høyeste periodene i kamp, men bare nesten halvparten i 6 mot 6 småbanespill. Sammenlignet med gjennomsnittlige kampdata per min, hadde spillerne det dobbelte antall akselerasjoner i 4 mot 4 småbanespill og nesten 50 % høyere i 6 mot 6 småbanespill. Spillerbelastningen fra akselerometer under småbanespill var noe lavere enn de høyeste periodene fra kamp, men høyere enn gjennomsnittet fra kamp.

Denne avhandlingen antyder at akselerasjoner kan være et mer stabilt og sensitivt mål på fysisk prestasjonsnedgang sammenlignet med høyhastighets-løpedistanse i kamp. Radiobaserte sporingssystem for fotball er nyttige verktøy for å se på de fysiologiske kravene fra bevegelser som innebærer høy hastighet, men akselerometre kan gi informasjon om spillerbelastning fra de mange diskrete handlingene i en fotballkamp, som kan ikke nødvendigvis innebærer høy hastighet. Denne avhandlingen avslører noen nye faktorer angående spillernes kampbelastning, og at mange høyintensitetsaksjoner som skjer uten at spillerne endrer plassering på banen likevel kan være et betydelig bidrag til spillerbelastningen fra kamp og trening. Spillerbelastning fra akselerometer kan fungere som et komplementært verktøy i tillegg til sporingssystemer for fotball for å undersøke spillerbelastningen under kamper og trening. Likheten i spillerbelastningsmønstre mellom både kamper og posisjoner i elitefotball, kan indikere et fysisk "tempomønster" brukt av laget. Trening med 4 vs. 4 småbanespill virker ser ut til å dekke de maksimale kampkravene som stilles til akselerasjoner og spillerbelastning fra akselerometer, men verken 4 vs. 4 eller 6 vs. 6 småbanespill er i nærheten av kravene til høyhastighets-løpedistanse eller sprint under kamper.

Abbreviations

FIFA	Fédération Internationale de Football Association, the international governing body of association soccer, beach soccer and futsal.
Min	Minute
VO_{2max}	Maximal oxygen uptake
ATP	Adenosin triphosphate
PCr	Phosphocreatine, also known as creatine phosphate
Sec	Second
GPS	Global Positioning System
LPM	Local Positioning Measurement system
MEMS	Micro-electromechanical systems
HIR	High-intensity running
SSG	Small-sided games
4 vs. 4	Small-sided soccer games with 4 players (excluding keeper) on each team
6 vs. 6	Small-sided soccer games with 6 players (excluding keeper) on each team
UEFA	Union of European Football Associations
LSB	Least Significant Bit, the smallest interval that can be detected
km/h	Kilometer per hour
m/s^2	meters per second squared

List of figures and tables

List of papers

The original articles included in this thesis are listed below and are referred to by their roman numerals.

Paper I Ingebrigtsen, J. (JI), Dalen, T. (TD) , Hjelde, G. H. (GHH), Drust, B. (BD) and Wisløff, U. (UW) (2015). Acceleration and sprint profiles of a professional elite football team in match play. *European Journal of Sport Science* 15(2): 101-110.

Authors contribution: Conceptualization (TD, JI, UW); methodology (TD, JI, UW); validation (TD, JI, UW); formal analysis (TD, JI); investigation (TD, JI, GHH); data curation (TD, JI, GHH); writing—original draft preparation (TD, JI); writing—review and editing (TD, JI, BD, GHH, UW); visualization (TD, JI); supervision (TD, JI, UW); project administration (TD, JI, UW).

Paper II Dalen, T. (TD), Ingebrigtsen, J. (JI), Ettema, G. (GE), Hjelde, G. H. (GHH) and Wisløff, U. (UW) (2016). Player load, acceleration, and deceleration during forty-five competitive matches of elite soccer. *Journal of Strength & Conditioning Research* 30(2): 351-359.

Authors contribution: Conceptualization (TD, JI, UW); methodology (TD, JI, UW); validation (TD, JI, UW); formal analysis (TD, JI); investigation (TD, JI, GHH); data curation (TD, JI, GHH); writing—original draft preparation (TD, JI); writing—review and editing (TD, JI, GE, GHH, UW); visualization (TD, JI); supervision (TD, JI, UW); project administration (TD, JI, UW).

Paper III Dalen, T. (TD), Øverås, Ø. (ØØ), van den Tillaar, R. (RvdT), Welde, B (BW). and von Heimburg, E. D. (EDvH) (2018). Influence of different soccer-specific maximal actions on physiological, perceptual and accelerometer measurement loads. *Open Access Journal of Sports Medicine* 9: 107-114.

Authors contribution: Conceptualization (TD, ØØ, EDvH); methodology (TD, ØØ, RvdT, BW, EDvH); validation (TD, ØØ, EDvH); formal analysis (TD, ØØ, RvdT); investigation (TD, ØØ); data curation (TD, ØØ); writing—original draft preparation (TD, ØØ); writing—review and editing (TD, ØØ, RvdT, BW, EDvH); visualization (TD); supervision (TD); project administration (TD).

Paper IV Dalen, T. (TD), Lorås, H. (HL), Hjelde, G. H. (GHH), Kjøsnes, T. N. (TNK) and Wisløff, U. (UW) (2019). Accelerations – a new approach to quantify physical performance decline in male elite soccer? *European Journal of Sport Science* 19(8): 1015-1023.

Authors contribution: Conceptualization (TD, HL, UW); methodology (TD, HL, UW); validation (TD, HL, UW); formal analysis (TD, HL); investigation (TD, HL, GHH, TNK); data curation (TD, HL, GHH, TNK); writing—original draft preparation (TD, HL); writing—review and editing (TD, HL, GHH, TNK, UW); visualization (TD, HL); supervision (TD, HL, UW); project administration (TD, HL, UW).

Paper V Dalen, T. (TD), Aune, T. K. (TKA), Hjelde, G. H. (GHH), Ettema, G. (GE), Sandbakk, Ø. (ØS) and McGhie, D. (DMcG) (2020). Player load in male elite soccer: Comparisons of patterns between matches and positions. *PLoS One* 15(9): e0239162.

Authors contribution: Conceptualization (TD,ØS,DMcG); methodology (TD, ØS, DMcG); validation (TD, ØS, DMcG); formal analysis (TD, DMcG); investigation (TD, GHH, DMcG); data curation (TD, GHH, DMcG); writing—original draft preparation (TD, DMcG); writing—review and editing (TD, TKA, GE, GHH, ØS, DMcG); visualization (TD, DMcG); supervision (TD); project administration (TD).

Paper VI Dalen, T. (TD), Sandmæl, R. S. (SRS), Stevens T.G.A. (TGAS), Hjelde, G.H. (GHH), Kjøsnes T.N. (TNK) and Wisløff U. (UW) (2021). Differences in Acceleration and High-Intensity Activities Between Small-Sided Games and Peak Periods of Official Matches in Elite Soccer Players. *Journal of Strength & Conditioning Research* 35(7):2018-2024.

Authors contribution: Conceptualization (TD, SRS, UW); methodology (TD, SRS, TGAS, UW); validation (TD, SRS, TGAS, UW); formal analysis (TD, SRS, TGAS); investigation (TD, SRS, TGAS, GHH, TNK); data curation (TD, SRS, TGAS, GHH, TNK); writing—original draft preparation (TD); writing—review and editing (TD, SRS, TGAS, GHH, TNK, UW); visualization (TD, SRS,TGAS); supervision (TD, UW); project administration (TD, UW).

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1 Introduction

Soccer is the most popular sport in the world, played by approximately 275 million people, over 128,000 of whom are registered as professionals (FIFA Professional Football Report, 2019). A soccer match for senior players is scheduled to last 90 minutes (min), consisting of two 45-min halves divided by a 15-min rest period. Two teams compete against one another with the aim of outscoring the opponent. Teams are permitted to have 11 players on the field, consisting of one goalkeeper and 10 outfield players. The outfield players are organized in numerous formations in and out of possession based on tactical instructions from the coach. Performance in soccer is determined by the players' technical, tactical, physiological and psychological/social characteristics [1]. Soccer players who have the ability to cope with the physical demands of the game can utilize their tactical and technical skills more effectively during match play [2, 3]. Understanding the physical demands of soccer is important in order to optimize the training process. Over the years, numerous techniques have been used to determine the physical profile of soccer players. Observations of athletes while they participate in their specific sport may provide useful data on the physiological demands of an activity [4]. These data could have an impact on the training regimen, fitness assessment and selection of players by providing an ergonomic framework for these activities [5-7].

1.1 Review of the literature

1.1.1 Energetic contribution in soccer

Soccer incorporates frequent fluctuations between high and low intensity, where the individuals' activity profiles are highly variable and include an element of self-pacing, since decision-making about opportunities to become engaged in play dictates the individual's activities [5]. Since less than 2% of players' total distance in a match occurs while in possession of the ball, self-pacing choices to become engaged in the play are made almost continuously and reflect the self-imposition of physical stress by the players [5]. Soccer players require a high level of aerobic fitness in order to generate and maintain power output during repeated high-intensity efforts, as well as for rapid recovery between efforts [8]. This separates soccer from sports in which continuous exercise is performed at either very high or moderate intensity during the entire event. As a consequence, the acyclic, intermittent nature of soccer makes the physiological demands more complex than in individual sports with continuous movements [1]. Soccer is regarded primarily as an aerobic sport including frequent bouts of activity with varying intensity [9]. Due to the nature of soccer competition, which entails up to 1,000 movement changes during a match, expressing game intensity merely as an average over 90 min, or for each half, would lead to loss of specific information [8]. Bangsbo (1994) proposed that physical demands in soccer are closely related to players' physical capacity, which can be divided into four main categories: 1) the ability to perform prolonged intermittent exercise, 2) the ability to exercise at high intensity, 3) the ability to sprint and 4) the ability to develop a high power output in single match situations such as kicking, tackling and jumping [1]. Analyses of soccer matches indicate that the length of the match and the high-intensity actions observed outline the importance of both the aerobic and anaerobic energy systems throughout the game [10]. Ideally, both systems provide players with the energy demanded to perform all types of movements required during a high-level soccer match.

Maximal oxygen uptake (VO_{2max}) is one of the most commonly used indicators of aerobic metabolism and power, as it is taken to represent the cardiorespiratory fitness of an individual [11]. VO_{2max} is usually measured in mL O_2 per kilogram per min (mL/kg/min) using direct gas exchange measurements during a maximal exercise test. As VO_{2max} is not always achieved, the peak measurement is often provided instead. The average oxygen uptake during a soccer match is estimated to be around 70% of VO_{2max} [1, 10]. Since it is difficult to measure oxygen uptake during real soccer games, the values for oxygen uptake are often based on heart rate values and their relationship with oxygen uptake during simulated soccer drills in laboratory, where factors like hyperthermia, dehydration and stress are taken into consideration [1, 10]. For soccer players, maximal aerobic power is important for the ability to play for 90 min, and for the recovery between the short bouts of high-intensity exercise [12-14]. However, due to the discrepancies in the activity patterns and the underlying physiology associated with soccer match play, VO_{2max} is not a sensitive enough measure for physical performance in soccer [12].

The average work intensity in a soccer match is close to the anaerobic threshold, normally ranging between 80% and 90% of maximal heart rate [8, 10]. The concentration of blood lactate is often used as a measure of anaerobic lactacid energy production in soccer. In soccer matches, players have periods of high-intensity activities where accumulation of lactate takes place. Mean blood lactate concentrations of 2–10 mmol/L have been observed during soccer games [10, 15]. However, one study found a low correlation between muscle lactate concentration and blood lactate concentration during an intense repeated intermittent test [16]. The rather high blood lactate that appears in soccer, therefore, may not be due to lactate production in a single action during a game, but represent an accumulated response to a number of high-intensity activities [15]. However, with respect to soccer, the lactate threshold does not appear to be strongly related to physical performance during match play or to performance during an intermittent field test [12, 17]. Degradation of creatine phosphate (PCr), and to a lesser extent stored adenosin triphosphate (ATP), provides a considerable amount of energy during periods of high intensity during a match [1, 14, 18]. PCr is rapidly resynthesized during periods of rest or during low-intensity exercise, and therefore PCr concentration probably fluctuates continuously during a game as a result of the intermittent nature of soccer activities [18]. In addition, PCr has an important function as an energy buffer, supplying phosphate for the synthesis of ATP through the creatine kinase reaction during rapid elevations in exercise intensity [18]. Speed and sprints are important components of soccer, as the ability to accelerate and run fast may relate to important outcomes of the game. As for energy supply, the difference seems to lie in whether players perform a single sprint or multiple sprints [13, 14]. The energy necessary for a single brief sprint (less than 10 seconds [sec]) is derived from anaerobic pathways by means of intramuscular PCr and anaerobic glycolysis. PCr is particularly important where a high rate of ATP utilization and resynthesis is required, for example in activities with repeated high-intensity actions [14]. After a single maximal sprint of 6 sec, PCr stores can be reduced to 35–55% of resting values [19, 20]. However, Dawson et al. (1997) found that PCr stores were recovered to about 70% of resting concentration

30 sec after a 6-sec maximal sprint. In repeated high-intensity actions (e.g., sprints), the recovery times generally do not exceed 60 sec, and therefore ATP/PCr stores may only be partially restored before the onset of subsequent high-intensity action [20]. Anaerobic glycolysis is shown to supply approximately 40% of total energy during a single 6-sec sprint, and there is a reported eight-fold decrease in the absolute ATP production from anaerobic glycolysis from the first to the last of 10 repetitions of 6-sec maximal sprints, interspersed with 30-sec recovery periods [14, 19]. There is an increased physical demand during multiple sprints compared to a single sprint, as muscle pH must normalize and PCr and ATP must be resynthesized between sprints [12]. The contribution from aerobic energy systems to total energy expenditure is limited during a single sprint but increases to contribute to as much as 40% of the total energy supply in the fifth and final repetition of a repeated sprint exercise [14]. In addition, the aerobic energy system plays an important role in the recovery periods between sprints, as aerobic glycolysis is central to resynthesize PCr stores and remove lactate within muscles during recovery from bouts of high-intensity intermittent exercise [12, 21].

Several studies have investigated the physical and physiological demands of elite soccer players based on distance covered by running at different intensities during a match [7, 22-24]. However, many of these soccer-specific movements can cause high physical stress on the players, even though the distance and/or the speed are low [25, 26]. While the energy used to travel a fixed distance during continuous exercise is independent of the velocity of the movement, this relationship does not hold under the conditions of locomotion that apply during soccer matches [26]. The energy expenditure throughout a match would be grossly underestimated if it was calculated only from distance covered and did not account for the frequent changes in velocity and direction of motion [23, 26]. Therefore, understanding the physical demands of soccer requires accurate and objective quantification of the players' match activities [27-30].

1.1.2 Time-motion analysis and microtechnology devices

Team sport player tracking systems are available in a variety of technologies across three broad categories: 1) camera-based visual recognition systems, 2) global positioning systems (GPS) and 3) local position measurement (LPM) [31]. Multi-camera systems do not interfere with the players, whereas GPS and LPM systems require the players to wear a device. Visual systems have the advantage of being able to track all players, whereas signal-based systems are limited to the player(s) wearing the device. Visual or LPM systems require permanent or temporary installation at the arena, whereas satellite systems require no additional equipment. GPS is a satellite-based navigational technology originally devised for military purposes [32]. GPS technology is now used in team sports settings all over the world to provide sport scientists, coaches and trainers with comprehensive and real-time analyses of on-field player performance during competitions and training. Unlike GPS systems, where the devices are passive receivers of signals from satellites, LPM systems work by emitted signals from the wearables to local receivers, which do the actual triangulation [33]. The development of these GPS and LPM devices have also led to the integration of other microtechnology sensors within these devices. These inertial sensors, which include gyroscopes, magnetometers and accelerometers, are collectively called micro-electromechanical systems (MEMS) [34-36]. The devices that make use of tri-axial accelerometers are highly responsive motion sensors to record acceleration of body movement in three dimensions: anteroposterior, mediolateral and vertical. Such accelerometer-derived measurements make it possible to provide a valid count of collisions [37] and other specific parameters such as player load and body load impact developed from specific algorithms [38-41]. Team sport tracking systems and microtechnology devices are now commonly used in elite soccer to provide a comprehensive picture to both coaches and researchers of the external load experienced by players during both training and matches [42, 43]. Measuring player movement with these systems makes it possible to objectively quantify levels of physical stress on individual players, examine competition performances, assess different positional workloads, establish training intensities and monitor changes in physical demands [32]. The use of these kinds of systems has advanced our understanding of position-specific work rate profiles and the physical requirements of soccer players [23, 44, 45].

1.1.3 *Descriptive studies: Typical demand during matches of low- and medium-intensity locomotion*

Although there are some differences in results, analyses of activities during soccer matches have shown that elite soccer players normally cover a distance of 9–13 km during a match [5, 46-48]. This has been determined using different methodological approaches. However, the total distance covered is within the same range irrespective of the data collection and analysis method used [5]. Moreover, it has been an established practice to use the total distance covered as a surrogate measure of energy expenditure, given the relationship between total distance and mechanical work output [4, 31]. However, based on metabolic analysis of intermittent activity, the energy demands of intermittent activities are underestimated if it is assumed that movement is executed at a constant speed [31]. Soccer activities seldom occur at constant speed, and analyses of differences in running speed and distance do not take into account other essential elements of soccer that, together, appear several hundred times in each match, such as accelerations and decelerations with different magnitude, duration and starting speed, kicking and passing the ball, tackling, jumping and turning [1, 6]. Therefore, the assumption that variables based on the total distance covered are indicative of energy demands in team sport activity is not warranted [31]. Although the distance covered in the second half of a match is typically found to be less than in the first half, the difference is only about 200 m of the total 9–13 km [30, 49, 50]. According to Carling (2013), such a decline in total distance, which is around 3.5 ± 1.9%, might not reflect a relevant change in match physical performance [51].

The activity in soccer is characterized by prolonged intermittent exercise interspersed with periods of maximal or close to maximal effort exercises [44], although the majority of the game is played within low to moderate intensities [52]. Data from Bangsbo (1994) show that elite players stand, walk and perform low-intensity activities such as jogging, low-speed running and backwards running for 17%, 40% and 35% of the total time, respectively [1]. This means that for these players, more than 90% of the match consists of low-intensity activities. More recent studies from the 2018 FIFA World Cup support earlier findings regarding the percentage distribution of low-intensity activities, with more than 90% of the total time in the locomotor category of less than 15 km/h [53]. Nonetheless, high-intensity efforts are critical for the outcome of the matches, as they relate to the elements that are key to the final match result, such as movements to win the ball or going past a defending player [10, 54].

1.1.4 High-intensity running and sprinting

Although high-intensity running (HIR) and sprinting together account for only approximately 10% of total distance covered during a match, they are generally considered to be important components of soccer performance by both researchers and practitioners [7, 54]. Moreover, straight sprinting has been found to be the single most frequent action in goal situations performed by either the scoring player or the assisting one [55]. Like many other measures of soccer performance, HIR and sprinting are not stable properties, but are subject to variation between matches [56]. Some researchers have suggested that HIR distance is a valid measure of physical performance due to its strong relationship with training status [57]. Unfortunately, several different speed thresholds have been used to define when HIR begins in the different tracking systems. These speed thresholds normally range from 14.4 km/h [58] to 19.8 km/h [59]. Moreover, similar threshold differences have also been reported for the definitions of sprints [60, 61] as well as time spent in the different speed zones in order to be considered HIR or sprints. These differences in thresholds and cut-offs are important to consider when evaluating the results from different studies and for calculations of physical demands of high-intensity activity in soccer.

Studies from soccer have found that match running demands are influenced by a multitude of contextual factors [56]. Elite-level players from the top Italian league and European Champions League perform more HIR and sprinting than (relatively) lower-level players from the top Danish league [7]. However, in the top Spanish league, no differences were found between successful and less successful teams in the two highest velocity zones [62]. In Brazilian soccer, players from lower ranked divisions were found to demonstrate greater physical demands, for instance with more high-intensity efforts, than players from the upper divisions [63]. In contrast to this finding from Brazil, Bradley et al. (2010) found that domestic and international players from the highest ranked leagues in the world performed about 40% more HIR efforts than elite and domestic players from Danish and Swedish leagues, although the authors highlighted that different tracking technologies could be one of the reasons for the differences between leagues [30].

HIR and sprinting performance could also be influenced by different playing formation systems. Bradley et al. (2011) found that the general match activity profiles did not differ considerably between soccer players playing in three different formation systems (4-4-2, 4-3-3 and 4-5-1) played by teams of similar standing in the English Premier League [64]. These findings are in contrast to findings from Brazilian soccer, where greater match running performance values were reported for 4-3-3 formations than 4-4-2 formations [63]. In the study from the English Premier League, Bradley et al. also found similar HIR distance across formations, although they revealed a difference in HIR distance between formations when the team was in possession, with greater distance covered in 4-4-2 and 4-3-3 than in 4-5-1 [64]. Teams playing in 4-5-1 formation engaged in more very HIR than the other formations when the team was not in possession. The authors suggest that these differences in very HIR might reflect the attacking and defensive characteristics essential to these three common playing formations, with the 4-5-1 formation being a more defensive system with a larger number of players performing a defensive role and occupying a smaller area on the field [64]. Physical performance in high-intensity activities across playing positions could also be dependent on the playing formation employed. For instance, attackers in 4-3-3 and defenders in 4-4-2 performed more HIR than in the other formations [64].

Previous research has shown that the physical demands of players are dependent on their position in the team, and that variations in the physical demands are related to the demands specific to playing position [65-67]. The general results are that central defenders cover the least HIR and sprinting distance throughout a soccer match [47, 60, 64, 68, 69]. With regard to the other positions, there are differences between studies. Bradley and Noakes found midfielders in the English Premier League to have the most HIR, followed by full-backs and attackers, and that this applied even if the teams won or lost by a large margin [60]. Further, studies have found wide midfielders to cover the greatest HIR and sprinting distance in both Brazilian and English leagues, at different performance levels and independent of playing formation [30, 47, 54, 60, 68]. In addition, Gregson et al. (2010) found that the largest variation in high-speed activities tends to be among the central players, and suggested that the central players are most susceptible to differences in the overall intensity of the game and the tactics employed by the coach [47]. The same authors also found that this variability to some extent was influenced by the team having possession of the ball as well as seasonal changes, and that players do not reproduce consistent high-speed activity profiles across games over time [47].

1.1.5 Accelerations and decelerations

A potentially relevant, albeit less studied, physical performance-related component of soccer matches is the number of accelerations and decelerations a player performs throughout a match. Movements with accelerations are more energetically demanding than constant velocity running [25, 26]. Even at a low running speed, a high metabolic load is imposed on a soccer player during accelerations [25, 26]. Decelerations are just as common as accelerations in soccer and therefore also contribute significantly to players' load during match play. Maintaining accelerations and decelerations is highly important for soccer performance, as a soccer match may contain as much as eight times more accelerations than sprints [30, 70]. Additionally, a sustained competition schedule across several days has been shown to lead to a decrease in accelerations in youth international players, while high-speed running distance remained unaffected [71]. Akenhead et al. (2013) demonstrated that the number of accelerations was compromised following periods of peak activity [72]. In this study, the peak acceleration period was on average 148% of the mean, and the number of accelerations in the following 5-min period was on average 10% lower than the mean. Furthermore, Riboli et al. (2021) showed that the peak acceleration and deceleration for 1 min showed four times higher locomotor requirement than the demands for the whole match (90 min) [73].

Previous studies have suggested that inter- and intra-individual variability is smaller for accelerations compared to distance-related measures [47, 51]. Acceleration and deceleration profiles have also been shown to be significantly affected by the time periods between matches, with reduction in both high and maximal acceleration and deceleration during congested periods compared to non-congested periods [74]. In examining the change in the amount of accelerations and decelerations as a match progresses, Newans et al. (2019) identified that both moderate and high accelerations and decelerations displayed a negative decay curve [75], with the largest decrease from the first to the second 15-min period of each half. These findings regarding acceleration and deceleration decrements throughout a match are similar to findings from other studies [59, 71, 72]. These results suggest that the number of accelerations is a more sensitive measure and a better predictor of players' inability to keep the physical performance constant throughout the match compared to high-speed and sprint running distances [71, 72].

1.1.6 Player load

Time-motion analyses have provided an accurate and objective quantification of players' activities, therefore improving our understanding of the physical demands in soccer [30, 76, 77]. However, measurements of different locomotor classifications or speed zones may be insensitive to the totality of mechanical stresses common to team sports. Tri-axial accelerometers provide complementary information to time-motion analysis for understanding player load during matches and training [23, 41], as they record the acceleration of body movement in three dimensions, which better estimates the players' physical exertion. Therefore, manufacturers of GPS and LPM systems have incorporated high-resolution tri-axial accelerometers as a measure of player load. Such analyses have proven useful for valid quantification of the physical demands in soccer [78-80], in which various estimations of player load have been regarded as acceptable measures of external load and largely correlated to players' physiological and perceptual responses to training [39, 81]. A number of soccer-specific movements can cause significant physical stress on the players, even though the distance covered and the running speed are low. Using tri-axial accelerometers, such activities can be counted and classified, but an objective measure of the load from these activities has not been developed. Therefore, there may be a potential for underestimating the external loads during a soccer match when only considering results from time-motion analysis [82].

Tri-axial accelerometers have proven useful for quantifying physical activity in a variety of populations, but also to quantify the physical and physiological demands in Australian football [83, 84] and basketball [85]. Although soccer matches most likely will have a larger distance covered by high-speed runs compared to training, these results suggest additional monitoring tools are necessary to fully understand the external load during training and match play. Thus, the players' tactical roles and available space on the pitch will not only influence the number and distance of high-intensity actions the players are involved in, but also in what way different positions achieve total load in matches. Time-motion analysis alone may thus underestimate the player load because discrete, high-intensity actions in soccer often do not include running at high velocity or change in location on the pitch [41].

1.2 Summary of knowledge gaps

Even though a large number of studies present the physical and physiological demands of elite soccer players on the basis of distance covered by running at different intensities, these analyses do not necessarily take into account certain essential elements of soccer that, together, appear several hundred times in each match, such as kicking and passing the ball, tackling, jumping and turning. Two-dimensional systems compute expended energy only when the players travel from one location to another, with sprinting normally classified as the most strenuous movement [44, 47]. This may cause underestimation of the total energy expenditure, as several of the players' high-intensity movements are made without changes in location on the pitch [23]. Many of the typical soccer activities have therefore been neglected, as a number of previous studies only examine activities measured by distance and speed variables. Another important factor concerning player load is movements with acceleration and deceleration. Earlier quantifications of accelerations in soccer have demonstrated a three- to eight-fold greater number of accelerations than sprints [30, 70]. A relatively underexamined factor in terms of investigating match physical performance of accelerations and decelerations in soccer is the different positions of players. Although several studies have investigated positional differences in HIR distance during soccer match play, the findings conflict as to whether specific positions have a more systematic decrement in HIR distance compared to other positions throughout a soccer match [54, 60, 66, 86, 87]. Various studies have described differences between small-sided game (SSG) formats [88, 89]. However, there are fewer studies investigating whether the physical performance of SSGs coincides with the peak periods of official matches. Moreover, there is a lack of studies investigating the differences between SSGs and official matches using the same tracking system and with a sampling rate high enough to obtain valid data on changes in accelerations.

Several studies have investigated accelerometer load and used tri-axial accelerometers as an additional part of their GPS or radio-based systems for performance analyses in team sports. Examples of systems that have been evaluated include GPSport, Catapult and ZXY Sport Tracking. However, to the best of my knowledge, there are no studies using accelerometer loads in combination with physiological and perceptual measurements in order to specify the demand of these fast, discrete, maximal actions in soccer. Also, the within-match player load based on three-dimensional movement analyses has been investigated using a standardized soccer simulation with 15-min standardized activity blocks [40]. However, to understand in more detail how teams and individual players distribute their player load and related locomotor activities throughout soccer matches, the same factors need to be analyzed over shorter time periods than 15-min blocks. Since analyses based on predefined periods cannot provide information about the actual peaks and troughs in the analysis of patterns throughout a match, moving windows is a potential solution, providing more accurate information about player load and locomotor variables (total distance, acceleration, deceleration, HIR and sprint). More instantaneous analyses of player load and the corresponding activities during soccer matches would logically show variable "pacing" influenced by factors such as tactical elements, player position and the level of the opponents.

1.3 Aims and hypotheses

The overall aim of this thesis was to investigate the physical demands of elite soccer players, with special focus on high-intensity movements and actions. Further, my colleagues and I wanted to investigate whether the number of accelerations constitutes a more precise estimate of match physical performance and performance decline in elite soccer players compared to HIR distances and whether SSGs in training could give a high enough training load for high-intensity movements and actions. Finally, we aimed to obtain knowledge concerning player load from accelerometers and the patterns of player load during matches, and how different soccer-specific high-intensity actions influence physiological, perceptual and accelerometer loads.

The main aim was assessed through six specific aims and hypotheses related to Study I through Study VI, respectively.

1.3.1 Specific aims and hypotheses were:

1) To characterize the sprint and acceleration profiles of elite soccer players across lateral or central positions in one elite soccer team's match play.

   We hypothesized that elite players would sprint and accelerate more during the first half compared to the second half, and we expected to see players in lateral positions sprinting longer distances and accelerating more often compared to players in the central positions.

2) To obtain new knowledge concerning player load during match play using a combination of tri-axial accelerometer and time-motion analysis. In addition, we aimed to determine acceleration and deceleration profiles of elite soccer players, as well as the contribution of accelerations and decelerations to player load during match play.

3) To study the effect of different soccer-specific maximal actions (sprints with and without change of directions [COD], jumps and shots) on physiological (oxygen uptake and heart rate) and perceptual (rating of perceived exertion) responses, as well as accelerometer load data.

   We hypothesized that accelerometer load, physiological response and perceptual response would increase with the discrete maximal actions, but that accelerometer load would be underestimated in conditions with high-speed activities (sprint and sprint COD). In addition, it was hypothesized that sprint and sprint COD would *have the highest values in physiological and perceptual responses because of the higher percentage of time spent in maximal activity during these conditions.*

4) To study whether the number of accelerations is a more precise estimate of match physical performance and performance decline in elite soccer players compared to HIR distances. In addition, the study aimed to compare changes in the number of accelerations and HIR distances across playing positions to examine whether the match profiles of the physical performance measures were consistent or demonstrated high interposition variability.

   We hypothesized that accelerations would be a better predictor of performance decline compared to HIR distance based on findings of less variability in the number of accelerations between different periods of the match.

5) To study the patterns of player load in comparison to locomotor variables over moving 5-min windows in an elite soccer team and to compare these patterns between different positions within the same team.

   We hypothesized that using moving windows would be a potential solution for investigating patterns, providing more accurate information about player load and locomotor variables.

6) To study whether the physical performance of players (i.e., total distance, HIR distance, sprint distance, number of accelerations and player load) during 4 vs. 4 and 6 vs. 6 SSGs was equivalent to or higher than the physical performance of the most intense periods of match play.

   We hypothesized that SSGs would have values of accelerations and player load similar to peak periods of official matches. Furthermore, based on earlier studies comparing different playing area dimensions, we hypothesized that HIR and sprint distances would be less in SSGs compared to peak periods of matches.

2 Methods

This thesis presents data from six published studies, in which data were collected between 2009 and 2016. Data for Study III were collected from moderately to well-trained male soccer players, whereas subjects in the rest of the studies were elite male soccer players.

Data for Studies I, II, III and IV were collected from home matches of a Norwegian elite soccer team; Study I consists of data from one season and Studies II, IV and V consist of data from three seasons. Study VI contains data from both training and matches from one season. The moderately to well-trained male soccer players in Study III performed the experimental protocol before the start of the season.

2.1 Subjects

The subjects who volunteered to participate in this project were male elite soccer players competing at the highest level in Norway or, in Study III, male sport science students. The data in Studies IV and V were collected at the same time and from the same players. Some players participated in more than one study, but they were still classified as one subject per study. The basic characteristics of the subjects in each study are displayed in Table 1. As Study III used data from sport science students, the positions were not applicable for that sample.

Table 1. Basic characteristics of the study populations.

		Position							
Study	**n**	**CD**	**ED**	**CM**	**EM**	**ATT**	**Age**	**Height (cm)**	**Weight (kg)**
I	15	3	4	2	4	2	26.5 ± 4.9	NC	NC
II	38	8	9	9	7	5	25.7 ± 5.3	NC	NC
III	10	NA	NA	NA	NA	NA	25.0 ± 2.7	179 ± 5.4	78.3 ± 7.4
IV_& V*	39	8	6	6	11	8	25.5 ± 4.2	184 ± 6.6	78.9 ± 7.4
VI	26	4	5	8	5	4	24.9 ± 4.2	182 ± 5.0	76.3 ± 6.1

*Abbreviations: NA, Not applicable; NC, Not collected; CD, Central defender; ED, External defender; CM, Central midfielder; EM, External midfielder; ATT, Attacker; *, Studies IV and V collected data from the same players and matches.*

2.2 Experimental approach

Data from professional male elite soccer players were collected using a fully automatic sport tracking system (ZXY Sport Tracking AS, ChyronHego Nasdaq, Trondheim, Norway) based on novel RadioEye™ technology to evaluate match performances over one season (Studies I and VI) or three seasons (Studies II, IV and V).

In Study I, a total of 15 players across five positions were included in order to characterize the sprint and acceleration profiles of male elite soccer match play (goalkeepers were excluded). Movements of all players were observed, but to avoid indirect comparisons with playing time, only data from players completing an entire match were used ($n_{matches} = 15$). The selected games were every domestic league home game of one full season, all played on grass surface.

In order to evaluate new perspectives about player load and acceleration and deceleration profiles, Study II used the same sport tracking system to assess match performances of male elite soccer players over three full seasons ($n_{matches} = 45$). Total player load, player load from accelerations and decelerations and number of accelerations and decelerations were analyzed for each half of the match to identify and investigate differences between the various player positions. Movements of all players were observed, but to avoid indirect comparisons with playing time, only data from players completing an entire match were used. The selected games were every domestic league home game over three full seasons, all played on grass surface.

Study III used a repeated within-subject design in which each subject was tested on five occasions on different days to compare the effect of various soccer-specific maximal actions (continuous run, sprint, sprint with change of direction, jump and shot) on physiological (oxygen uptake and heart rate) and perceptual (rating of perceived exhaustion) responses and accelerometer load. Four of the tests consisted of different series of maximal actions carried out sequentially; however, all five tests had a distance of 900 m and lasted 5 min, thus achieving a mean speed of 3 m/s for all five tests. Continuous submaximal running was chosen as the baseline condition test for comparison with the four maximal action tests.

Studies IV and V used data from domestic home games ($n_{matches}$ = 34) over three full seasons (2012–2014) of male elite soccer players. Only data from players completing an entire match were used. The selected games were every domestic league home game over three full seasons, all played on grass surface. To construct an analysis for the time-scale of a match for all players, the mean number of accelerations and HIR distances were summed for each consecutive (moving) 5-min period, beginning with the first 5 min of the game. The second 5-min period begins with the second minute and lasts to the sixth minute, and so on. These 5-min periods were used to find the players' peak periods. The peak period represents the 5 min that contain the highest value of acceleration and distance covered by HIR in each half of every game and is specific for each of the monitored players for each half of every game.

The same dataset and type of analyses from moving 5-min windows used in Study IV were also used in Study V to explore patterns of player load and to compare these patterns between different positions within the same team in male elite soccer matches, as well as with locomotor variables. To better provide information about the actual peaks and troughs, analyses based on moving windows were conducted on player load and locomotor variables (total distance, acceleration, deceleration, HIR and sprint).

Study VI investigated physical performance variables (total distance, HIR distance, sprint distance, number of accelerations and player load) of elite male soccer players from a total of 18 home matches and 11 training sessions with 4 vs. 4 and 6 vs. 6 SSGs during the 2015–2016 season. Only data from players who completed the whole training session were included. In the analyses of matches, only players who started the match and played for least 60 min were included. For the matches, both mean values and peak 5-min values were calculated. For each player and for each variable, the most intense period was the peak 5-min intensity, which was selected using a 5-min moving window. This period represents those 5 min which contain the highest value of the variable in a game and is specific for each monitored player. Physical performance variables were investigated in all SSGs and expressed as average intensity (performance per minute of play).

2.3 Instruments and materials

2.3.1 Time-motion analysis system (Studies I-II, IV-VI)

In these studies, we used a tracking system where every player movement was continuously monitored by small body-worn sensors. Data were transferred by microwave radio channel to 10 RadioEye™ sensors (ZXY Sport Tracking, ChyronHego, Trondheim, Norway) mounted in the team's home arena. Player movement was registered at 20 Hz for all studies on elite soccer players. Test-retest reliability of the sport tracking system was collected in a controlled on-field track and indicated good agreement between the test and the retest for x- and y-position data as well as for the data of the total distance covered (see Study I).

2.3.2 Locomotor categories

The following locomotor categories were selected: walking (from 0 to 7.1 km/h), jogging (from 7.2 to 14.3 km/h), running (from 14.4 to 19.7 km/h), high-speed running (from 19.8 to 25.2 km/h) and sprinting ($\geqslant$ 25.2 km/h). To be counted in each speed zone, the player needed to stay in that speed zone for at least one second. The speed thresholds applied for each locomotor category were similar to those most commonly used and reported in previous studies [30, 54, 58, 65].

2.3.3 Accelerations and decelerations

Accelerations and decelerations were defined by four event markers by the ZXY Sport Tracking system. First, the start of the acceleration or deceleration event was marked using a minimum limit of 1 m/s^2. Second, to be counted, the acceleration or deceleration event had to reach a minimum of 2 m/s^2. Third, the acceleration or deceleration event had to remain above the 2 m/s^2 limit for at least 0.5 sec. Finally, the duration of the acceleration or deceleration event was measured from the start until the acceleration or deceleration fell below the minimum limit of 1 m/s^2.

2.3.4 Player load

Player load in ZXY Sport Tracking was based on acceleration measures from tri-axial accelerometer sensors that were placed at each player's lumbar spine. The sensor was mounted in a specially designed belt wrapped tightly around the waist. The accelerometer registers data at 20 Hz and has a sensitivity of 184 μg/LSB, with a static noise of 1 mg. The signal was high-pass filtered to avoid the acceleration of gravity (9.81 m/s^2) from being included in the final calculations. Ultimately, player load was calculated and presented as a downscaled (divided by 800) value of the square sum of the high-pass filtered accelerometer values for the respective axes (X, Y and Z) by the equation $(X^2 + Y^2 + Z^2)/800$. Thus, the player load value is the downscaled square of the player's absolute acceleration.

2.3.5 Measurements of physiological and perceptual responses and accelerometer load (Study III)

Oxygen uptake was measured using the Metamax II metabolic cart (Cortex Biophysics, GmbH, Leipzig, Germany) portable metabolic analyzer, with the instrument's breathing valve (Triple V) mounted on the face mask. A standard two-point gas calibration procedure against ambient air and a commercial gas of known concentrations of O_2 (16.00%) and CO_2 (4.00%) was performed each morning after a 30-min instrument warm-up period. Ambient air measurements were also carried out before each test. The flow transducer was calibrated using a 3-L high-precision calibration syringe (Calibration syringe D, SensorMedics, Yorba Linda, CA, USA) before each test. The Metamax II has been validated, and the oxygen uptake reported by this analyzer was precisely measured within subjects [90]. The Metamax II portable oxygen analyzer was mounted in a small backpack on the subject's back and tightened with a belt at the chest and above the hip level and used to measure oxygen uptake. The complete instrument, including batteries, weighed 1.3 kg. Oxygen uptake in this study was expressed as mL/kg/min.

To register subjective perceived exertion, Borg's Rating of Perceived Exertion (RPE) scale was used [91, 92], with the subject instructed to report an overall feeling of exertion immediately after each 900-m running test. A value of 6 on the RPE6-20 scale means "very easy," and a value of 20 corresponds to "total exhaustion."

Accelerometer load and heart rate data were measured using an ActiGraph wGT3X+ monitor (ActiGraph, Pensacola, FL, USA). The ActiGraph is a lightweight (27 g), compact (3.8×3.7×1.8 cm) and rechargeable (lithium polymer battery-powered) accelerometer [93]. The ActiGraph measured acceleration in three axes (mediolateral [X], vertical [Y] and anteroposterior [Z]) and provided activity counts as a composite vector magnitude of these three axes (total). The activity monitors sampled accelerations at a rate of 30 Hz. The output of the accelerometers was given in "counts," with one count equalling 16.6 milliG/s at 0.75Hz. Activity counts, which are the results summing the absolute values of the sampled change in accelerations measured during the time period, represent the quantitative measure of activity over time. The ActiGraph also included the vector summed value $\sqrt{(X^2 + Y^2 + Z^2)}$, known as "vector magnitude" [93].

The accelerometer used to measure heart rate and acceleration loads was mounted at the waist using an elastic belt with a belt clip, along with the manufacturer's accompanying chest strap heart rate monitor. In this study, two accelerometers were used (one on each side of the waist), and the mean values from the two accelerometers were defined as the subject's accelerometer load.

2.4 Test protocols

2.4.1 Data collection from match analyses (Studies I-II, IV-VI)

These studies collected data from match analysis of a Norwegian elite male soccer team. A ZXY Sport Tracking time-motion analysis system mounted at the team's home arena collected data regarding locomotor activity with technology based on an LPM system. Movements of all players were observed, and only data from players completing an entire match were used in the analyses. Some of these players were in different positions across, but not within, the matches included in the data material. Every player movement was captured by small wearable sensors continuously monitoring the players' actions. In addition, the body-worn sensors had tri-axial accelerometers, highly responsive motion sensors that recorded acceleration of body movement in three dimensions: anteroposterior, mediolateral and vertical. Data from these accelerometers were used in Studies II and V.

2.4.2 Evaluation of high-intensity activity in matches

For Study I, we evaluated the total distance and number of high-intensity activities throughout the matches. Due to the relatively low number of observations for each player position, players were further grouped into central position players (central defenders, central midfielders and attackers) and lateral position players (full-backs and wide midfielders). In this study, locomotor variables were also compared between the first and second halves of the matches and in three different phases of the season.

In Study II, the total distance and number of high-intensity actions were evaluated throughout the matches, between halves and between positions. The high-intensity actions were obtained both from time-motion analysis measurements and accelerometer-measured player load.

In Studies IV-VI, we constructed an analysis to capture the immediate, dynamic nature of a match for all players by calculating the mean values for time-motion variables over consecutive (i.e., moving) 5-min periods [26, 30]. For Study IV, these 5-min periods were used to find the players' peak periods of total distance, accelerations, decelerations, sprint distance and HIR distance, and comparisons were then made between these peak periods (Peak), the mean 5-min period of each half, the 5-min period before the peak period (Pre-5-Peak) and the subsequent 5-min periods (Post-5-Peak) up to a maximum of 15 min after the peak (Post-10-Peak and Post-15-Peak). All this was done to evaluate the time course of physical performance variations around the peak periods. For Study V, these 5-min periods were used to investigate patterns of player load and locomotor variables throughout match time. The similarities of patterns were then quantified between positions, and patterns were evaluated across variables.

For Study VI, physical performance variables from home matches and training sessions were collected and analyzed. The training sessions consisted of 6–8 repetitions of 3-min bouts of 4 vs. 4 SSGs (n = 56) and 3–5 repetitions of 6-min bouts of 6 vs. 6 SSGs (n = 28). The active recovery time between SSGs was 3 min for 4 vs. 4 and 2 min for 6 vs. 6. The 4 vs. 4 games were played on 39 x 39 m pitches, and the 6 vs. 6 games were played on 47 x 43 m pitches, resulting in 152 m^2 and 144 m^2 per player (including goalkeepers) for the respective formats. The pitch size for official matches was 105 x 70 m (334 m^2 per player). All matches and training sessions were played on natural grass on the team's home arena and training field, respectively. For each player and for each variable, the peak 5-min intensity was selected using a 5-min moving window similar to Studies IV and V. Physical performance variables were expressed as means per min for total distance, HIR distance, sprint distance, acceleration and player load, for both the average of the official matches and the peak periods.

2.4.3 Test protocol (Study III)

Before each test, the subjects performed a 15-min warm-up. During the first 5 min, the subject ran at an intensity of 70% of maximum heart rate. During the last 10 min, the subject ran at 80% of maximum heart rate, including three maximal 20-m sprints. After the warm-up, the test equipment was fastened, and the test began within 4–5 min after the end of the warm-up. Each of the five test conditions (see Table 2) lasted 5 min and required that the subjects cover a distance of 900 m, making the mean speed for all five tests 3 m/s. The distance of 900 m consisted of 15 shuttle runs, where the subject ran 30 m, turned 180º and ran 30 m back to the start. Each shuttle run lasted for 20 sec and the subjects received a signal every 10 sec to let them know when 10 sec had elapsed. In four of the five tests, maximal actions were performed during each shuttle run. The subject was informed about the number of shuttle runs during the test. For all tests, the subject ran with the same training shoes and was encouraged to perform their best during the maximal actions. The average of all measured variables during each of the five 5-min tests and during a 5-min rest after each test was used for further analyses. During the test, oxygen uptake (mL/kg/min), heart rate and accelerometer load (counts/min) were measured. Immediately after each of the five tests conditions, Borg's RPE was recorded and oxygen uptake was continuously measured for 5 min while the subject sat in an upright position on a chair.

Table 2. Description of the five different test conditions in Study III.

Test condition	Total distance	Time (min)	Maximal action in the condition
Run	900 m (15 shuttle runs, 2 x 30 m)	5	None
Sprint	900 m (15 shuttle runs, 2 x 30 m)	5	15 sprints of 20 m were performed between the 30- and 50-m marks of each 60-m track
Sprint COD	900 m (15 shuttle runs, 2 x 30 m)	5	15 sprints with COD were performed between the 20- and 40-m marks of each 60-m track
Jump	900 m (15 shuttle runs, 2 x 30 m)	5	30 maximal vertical jumps were performed: two jumps during each shuttle run, the first at the 15-m point and the second at the 45-m point
Shot	900 m (15 shuttle runs, 2 x 30 m)	5	15 shots of maximal effort were performed at the 50-m point of each 60-m track

Abbreviation: COD, change of direction.

2.5 Statistical analyses

The descriptive statistics were calculated and reported as mean ± standard deviation (SD) for each group of players on each variable. The level of statistical significance was set at $\alpha = 0.05$. To assess the reliability of position, distance and player load measured by the sport tracking system in use, a two-way mixed intra-class correlation (ICC) reliability test between the measures was performed while running laps around a track (see Studies I and II). All data were then examined using a scatter plot, and a Pearson's correlation coefficient was computed to determine the strength of the relationships between the paired variables from each lap on the track. Further, a linear regression was performed, and the shared variance (r^2) and the equation of the predicted variable were calculated. In addition, data were plotted and investigated using Bland and Altman's 95% limits of agreement.

For Study I, due to the relatively low number of observations for each player position, we further grouped the players into central position players (central defenders, central midfielders and attackers) and lateral position players (full-backs and wide midfielders).

The differences between these two groups of players were examined using independent samples t-tests. For Study II, the differences between player position groups in all measured variables were examined using one-way analysis of variance (ANOVA), with a Tukey post-hoc test. For Studies I and II, the differences between the two halves were analyzed by one-way ANOVA.

In Study III, to investigate the effect of the different soccer-specific maximal actions on physiological response, perceptual response and accelerometer load, a one-way ANOVA (run, sprint, sprint COD, jump, shot) with repeated measures on each response was used. In the case that the sphericity assumption was violated, the Greenhouse-Geisser adjustments to the p-values were reported in the results. Post-hoc tests using Holm–Bonferroni probability adjustments were used to determinate significant differences.

In Study IV, the analysis to investigate whether the number of accelerations is a more precise estimate of match physical performance in soccer compared to HIR distances was conducted in two steps. First, the average number of accelerations and HIR distance were analyzed for each half of the match and across player positions by a multivariate general linear model (GLM) (MANOVA). In all pairwise multiple comparisons, the alpha was Bonferroni-corrected, and the partial eta squared (η^2_p) was applied as a measure of effect size. Second, the minute-by-minute patterns throughout soccer matches in HIR and number of accelerations were analyzed by calculating the goodness-of-fit (r^2) for various functions. These off-line calculations were conducted by applying the *fit* function in Matlab, in which three patterns (linear, logarithmic and cubic) were examined.

In Study V, player load, player load per meter, total distance, accelerations, decelerations, sprint distance and HIR distance were averaged within positions in each match, converted to z-scores and averaged across all matches, yielding one time series for each variable for each position. Pattern similarity between positions was assessed with cross-correlations. Correlation values were interpreted categorically as trivial (0–

0.1), low (0.1–0.3), moderate (0.3–0.5), high (0.5–0.7), very high (0.7–0.9), or nearly perfect (0.9–1) using the scale presented by Hopkins et al. (2009) [94].

For Study VI, a one-way ANOVA with repeated measures was used to test for player differences and format differences (4 vs. 4 SSGs, 6 vs. 6 SSGs, mean match and peak periods of official matches) in physical performance variables (expressed as value per min for total distance, HIR distance, sprint distance, accelerations and player load). Only players with data for all game formats (n = 18) were included in the analyses. Post-hoc comparisons with Bonferroni corrections were used to detect pairwise differences. When sphericity assumptions were violated, Greenhouse-Geisser adjustments of the p-values were reported.

3 Summary of results

3.1 Study I

3.1.1 Acceleration and sprint profiles of a professional elite soccer team in match play

Table 3 shows sprinting distances and number of sprints and accelerations according to player positions and the halves of a full elite soccer match. On average, players across all positions accelerated 90.7 ± 20.9 times per match, with a lower number of accelerations (44.0 ± 12.2 vs. 46.7 ± 11.6, $p < 0.05$) in the second half compared to the first. Further, players in lateral positions accelerated more often compared to players in more central positions during the first half. Although not statistically significant, the same was seen during second halves and overall during full matches. Also, players in lateral positions were found to accelerate more often ($p < 0.05$) during the first half compared to the second. Players sprinted on average 213 ± 111 m distributed over 16.6 ± 7.9 sprints per match, with no differences in distance (106 ± 60 vs. 107 ± 72 m) or number of sprints (8.3 ± 4.2 vs. 8.3 ± 4.8) between the first and second half. Considering sprinting distances, lateral position players were found to sprint longer ($p < 0.01$) during both halves, and therefore also in total. However, the number of sprints was not found to be significantly different between groups, although a tendency towards a higher number of sprints for lateral position players during the second half and in total was observed ($p < 0.10$).

Table 3. Sprinting distances and number of sprints and accelerations across player positions during a full match, first half and second half.

			Central defender	Full-back	Central midfielder	Wide midfielder	Attacker	Players in central positions (n = 59)	Players in lateral positions (n = 42)
Sprint	1st half	Dist.	67±38	147±66	84±54	129±39	90±40	81±46[a]	142±60[a]
		Count	6.2±3.3	10.7±4.4	6.6±3.7	10.4±3.6	6.9±2.5	6.6±3.3	10.6±4.1
	2nd half	Dist.	55±36	137±83	90±65	165±57	91±72	80±55[a]	145±76[a]
		Count	5.0±2.9	10.2±5.2	6.8±3.8	12.8±4.3	7.5±3.4	6.4±3.5[c]	11.0±5.1[c]
	Full match	Dist.	123±48	284±123	174±89	294±76	181±111	160±76[a]	287±211[a]
		Count	11.2±5.0	20.9±8.2	13.4±6.6	23.2±6.8	14.4±4.5	13.0±5.7[c]	21.6±7.8[d]
Acc.	1st half	Count	47.1±11.8	52.0±10.9	41.5±10.8	52.0±12.3	40.8±6.3	43.0±10.4[a]	52.0±11.1[a]
	2nd half	Count	39.8±9.8	43.4±10.7	43.7±14.9	53.5±12.2	42.9±12.2	42.3±12.2	46.3±11.9[b]
	Full match	Count	86.9±18.0	95.4±19.4	85.2±23.6	105.5±22.2	83.7±13.8	85.3±19.5	98.3±20.5

Data are mean ± SD, n = 101 observations. Abbreviations: Dist, distance in meters; Acc., accelerations. Footnotes: [a] significant differences between groups ($p < 0.01$); [b] significantly lower than first half ($p < 0.05$); [c] tendency towards difference between groups ($p < 0.10$).

3.2 Study II

3.2.1 Player load, accelerations and decelerations during elite soccer matches

Over a full match, central defenders, central midfielders, wide midfielders and attackers had a 12%, 18%, 26% and 8% higher player load than full-backs, respectively (Table 4). Also, wide midfielders had 13% and 17% higher player loads compared to central defenders and attackers, respectively, and a trend towards higher player load than central midfielders (7%, $p = 0.09$). Central midfielders had a higher player load than attackers (9%). All positions had a ~5% decrease in player load from the first to the second half.

Full-backs and wide midfielders accelerated more often than central defenders (39% and 43%), central midfielders (15% and 18%) and attackers (15% and 18%) (Table 2). During the first half, full-backs accelerated more often compared to central defenders (30%), central midfielders (19%) and attackers (19%), while wide midfielders accelerated more than central defenders (33%), central midfielders (22%) and attackers (22%). During the second half, central defenders accelerated less compared to full-backs (46%), central midfielders (36%), wide midfielders (50%) and attackers (36%). Player load from accelerations accounted for 8%, 8%, 7%, 10% and 9% of total load for central defenders, full-backs, central midfielders, wide midfielders and attackers, respectively (Table 5).

Full-backs' and wide midfielders' HIR distances were 230%, 48% and 40% longer than central defenders', central midfielders' and attackers', respectively. No differences were detected between full-backs and wide midfielders or between central midfielders and attackers in terms of HIR. The distance covered in HIR by central defenders was shorter than any of the other playing positions ($p < 0.001$).

Table 4. Player load and locomotor variables during match play across the player positions.

	CD (n = 68)	FB (n = 83)	CM (n = 70)	WM (n = 39)	ATT (n = 50)	Total (n = 310)
Player load (au)						
1st half	6868 ± 1213^{b}	6101 ± 873	$7243 \pm 977^{b,e}$	$7782 \pm 1122^{a,b,c,e}$	6625 ± 550^{b}	6823 ± 1114
2nd half	$6555 \pm 351^{b,*}$	$5854 \pm 780^{*}$	$6884 \pm 262^{b,*}$	$7330 \pm 1263^{a,b,e,*}$	$6332 \pm 669^{*}$	$6503 \pm 1191^{*}$
Full match	13423 ± 2501^{b}	11955 ± 1548	$14128 \pm 2030^{b,e}$	$15113 \pm 2304^{a,b,e}$	12957 ± 1078^{b}	13327 ± 2197
High-intensity run (m)	484 ± 134	$1138 \pm 282^{a,c,e}$	770 ± 270^{a}	$1095 \pm 255^{a,c,e}$	776 ± 264^{a}	847 ± 349
Sprint (m)	110 ± 55	$330 \pm 133^{a,c,d,e}$	152 ± 80	$276 \pm 111^{a,c,e}$	198 ± 93^{a}	214 ± 130
Total distance (m)	9951 ± 491	$11426 \pm 648^{a,e}$	$11573 \pm 768^{a,e}$	$11990 \pm 771^{a,b,c,e}$	10429 ± 874^{a}	11046 ± 1015

Data are mean ± SD. Abbreviations: au, arbitrary unit; ATT, attacker; CD, central defender; CM, central midfielder; FB, full-back; m, meters; n, numbers; WM, wide midfielder. Footnotes indicate significant differences by one-way ANOVA with ($p < 0.05$); [a] higher than central defenders; [b] higher than full-backs; [c] higher than central midfielders; [d] higher than wide midfielders; [e] higher than attackers; [*] less than 1st half.

Table 5. Acceleration and deceleration variables during match play across the player positions.

		CD (n = 66)	Fb (n = 80)	CM (n = 67)	WM (n = 37)	ATT (n = 48)	Total (n = 298)
Number	1st half	33 ± 13	43 ± 13[a,c,d]	36 ± 10	44 ± 12[a,c,d]	36 ± 8	38 ± 12
Acc.	2nd half	28 ± 11[*]	41 ± 10[a,¤]	38 ± 12[a]	42 ± 14[a]	38 ± 8[a,#]	37 ± 12[*]
	Full match	61 ± 22	85 ± 21[a,c,d]	74 ± 21[a]	87 ± 25[a,c,d]	74 ± 14[a]	76 ± 22
Distance	1st half	252 ± 133	365 ± 163[a,c,d]	271 ± 91	345 ± 164[a]	290 ± 123	304 ± 147
Acc. (m)	2nd half	215 ± 107[*]	349 ± 151[a]	288 ± 128[¤]	339 ± 178[a]	312 ± 129[a]	298 ± 146[a]
	Full match	468 ± 220	714 ± 298[a,c]	559 ± 232	685 ± 331[a]	602 ± 239	603 ± 278
Player load	1st half	416 ± 148	467 ± 141	404 ± 142	596 ± 212[a,b,c,d]	461 ± 128	457 ± 161
Acc. (au)	2nd half	356 ± 120[*]	435 ± 118[a,*]	420 ± 142	554 ± 215[a,b,c,*]	480 ± 142[a]	436 ± 154[*]
	Full match	773 ± 227[*]	902 ± 231[a]	824 ± 259	1150 ± 401[a,b,c,d]	942 ± 237[a]	893 ± 286
Number	1st half	22 ± 7	32 ± 8[a,c]	25 ± 8	30 ± 6 [a,c,d]	29 ± 10[a]	28 ± 9
Dec.	2nd half	18 ± 6[*]	31 ± 8[a,c]	24 ± 8[a]	30 ± 9[a,c]	31 ± 9[a,c,#]	27 ± 10[*]
	Full match	40 ± 11	62 ± 13[a,c]	49 ± 15[a]	60 ± 13[a,c]	59 ± 18[a,c]	54 ± 16
Distance	1st half	158 ± 56	247 ± 75[a,c]	182 ± 65	227 ± 57[a,c]	212 ± 89[a,c]	204 ± 77
Dec (m)	2nd half	132 ± 53[*]	243 ± 79 [a,c]	179 ± 65[a]	229 ± 69[a,c]	224 ± 79[a,c]	199 ± 81
	Full match	290 ± 91	490 ± 136[a,c]	360 ± 120[a]	456 ± 107[a,c]	436 ± 160[a,c]	403 ± 145
Player load	1st half	330 ± 117	425 ± 148[a,c]	356 ± 151	479 ± 151[a,c]	479 ± 151[a]	395 ± 156
Dec (au.)	2nd half	288 ± 136[*]	412 ± 151[a,c]	328 ± 129[*]	441 ± 165[a,c]	428 ± 156[a,c]	372 ± 157[*]
	Full match	618 ± 220	838 ± 275[a,c]	685 ± 264	920 ± 285[a,c]	854 ± 310[a,c]	768 ± 289

Data are mean ± SD. Abbreviations: au, arbitrary unit; Acc., acceleration; Dec, deceleration; au., Arbitrary unit; ATT, attacker; CD, central defender; CM, central midfielder; FB, full-back; m, meters; n, numbers; WM, wide midfielder. Footnotes indicate significant differences by one-way ANOVA with ($p < 0.05$): [a] higher than central defenders; [b] higher than full-backs; [c] higher than central midfielders; [d] higher than attackers; [*] less than 1st half; [#] more than 1st half; [¤] trend towards less than 1st half ($p = 0.08$).

3.3 Study III

3.3.1 Influence of different soccer-specific maximal actions on physiological, perceptual and accelerometer measurement loads

Post-hoc comparison showed that accelerometer load in the anterior-posterior direction in the jump condition was significantly higher than all the other actions except the sprint condition, while in the medial-lateral direction, the sprint condition was the lowest compared to all other conditions. In the vertical direction, the total accelerometer load in the jump condition was the highest, followed by the shot and run conditions (with no significant difference between these two conditions, $p = 0.28$), while the sprint and sprint COD conditions produced the lowest vertical and total accelerometer load (Table 6).

Oxygen uptake during and after the run condition was significantly lower than the other conditions, followed by the shot condition. No significant differences in oxygen uptake during and after the sprint, sprint COD and jump conditions were found. However, heart rate was only significantly lower when performing the run condition compared to all other actions. RPE was significantly different between all the soccer-specific actions, except between sprint and the sprint COD ($p = 0.52$), starting from the lower values in run, shot and jump up to the two sprint conditions, which were perceived as the heaviest actions.

Table 6. Acceleration loads in different directions, heart rate, oxygen uptake during and after exercise tests and RPE per soccer-specific condition.

	Run	**Shot**	**Jump**	**Sprint**	**Sprint COD**
Anterior-posterior (count)	429±155	453±140	532±108[#]	476±84	457±86
Medial-lateral (count)	440±123	455±108	464±113	369±86*	414±96
Vertical (count)	1521±256[a]	1465±268[a]	1755±228[§]	1286±210[b]	1265±184[b]
Total acceleration (count)	1657±251[a]	1619±252[a]	1904±213[§]	1441±204[b]	1423±189[b]
Heart rate (frequency/min)	160±15*	170±11	172±9	174±9	174±10
Oxygen uptake (l/min)	2.94±0.35*	3.40±0.40[c]	3.63±0.31	3.69±0.39	3.73±0.33
Oxygen uptake 5 min after exercise (l/min)	1.17±0.12*	1.30±0.18[c]	1.52±0.20	1.69±0.35	1.46±0.17
RPE_{6-20}	10.0±2.6*	12.0±2.4[c]	14.1±2.3*	16.7±1.0	17±1.8

*Mean ± SD of the soccer-specific conditions ordered from left to right according to the RPE results (lowest to highest). Abbreviations: COD, change of direction; RPE, rating of perceived exertion. Footnotes indicate significant differences ($p < 0.05$): * lower than all the other soccer-specific conditions; § higher than all the other soccer-specific conditions; # higher than all the other soccer-specific conditions except sprint condition; a higher than the two sprint conditions; b significantly lower than all the other soccer-specific actions except between the two sprint conditions; c lower than all the other soccer-specific actions except the run condition.*

3.4 Study IV

3.4.1 A new approach to quantify physical performance decline in male elite soccer?

Figure 1 shows the number of accelerations and the distances covered by HIR during match play. Although both variables showed a decline between halves, the number of accelerations throughout the match (Figure 1A) demonstrated a more clear-cut decreasing pattern compared to distance covered by HIR (Figure 1B). In the number of accelerations, a systematic and linear decrease can be observed throughout the match. As for HIR, the most prominent reduction occurs across the first 10 min of the match, followed by a linear reduction throughout the latter part of the first and second halves. Although small bursts of increases in the number of accelerations can be observed in both halves, the pattern closely follows a linear logarithmic function ($r^2 = 0.9$, $p < 0.05$). This pattern of results captures the change in the number of accelerations across all positions, as the minute-by-minute pattern can be fitted with a similar function for all positions (Figures 2A and 2C).

As depicted in Figure 1A, the distance covered by HIR across the entire sample of elite soccer players dropped from a peak of 60 m at the start of the match down to a level of 50 m 10 min into the first half. Thereafter, the players performed HIR at or slightly above/below this level for the rest of the first half. For the last part of the match, a marked reduction in HIR length can be observed (right part of Figure 1A). This pattern of results can be fitted with a piecewise polynomial function ($r^2 = .97$, $p < 0.05$), which reflects the dynamic pattern of decreases and increases in distance covered by HIR throughout the match. When the match pattern of HIR is plotted for each position (Figures 2B and 2D), it is clear that players from all positions demonstrate complex variations, albeit with some positional differences.

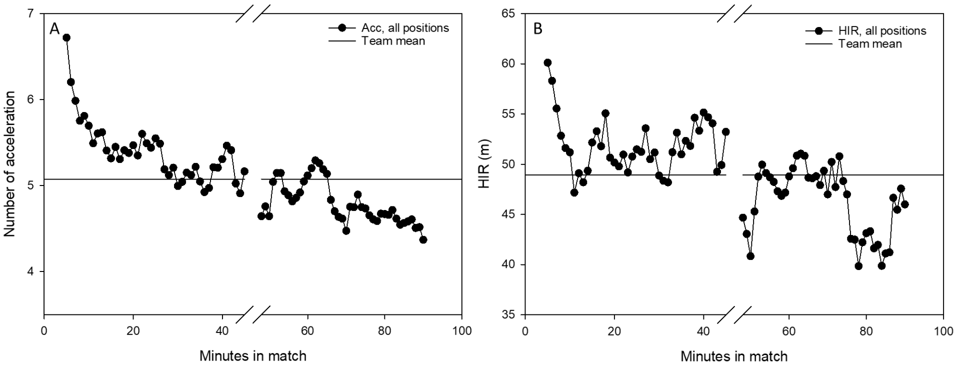

Figure 1. Average number of accelerations and distances covered by high-intensity running in consecutive (moving) 5-min periods across soccer matches. *Data are shown for the entire sample (n = 212) throughout the first and second halves across 34 soccer matches. Abbreviations: HIR, high-intensity running; m, meter; Acc, acceleration.*

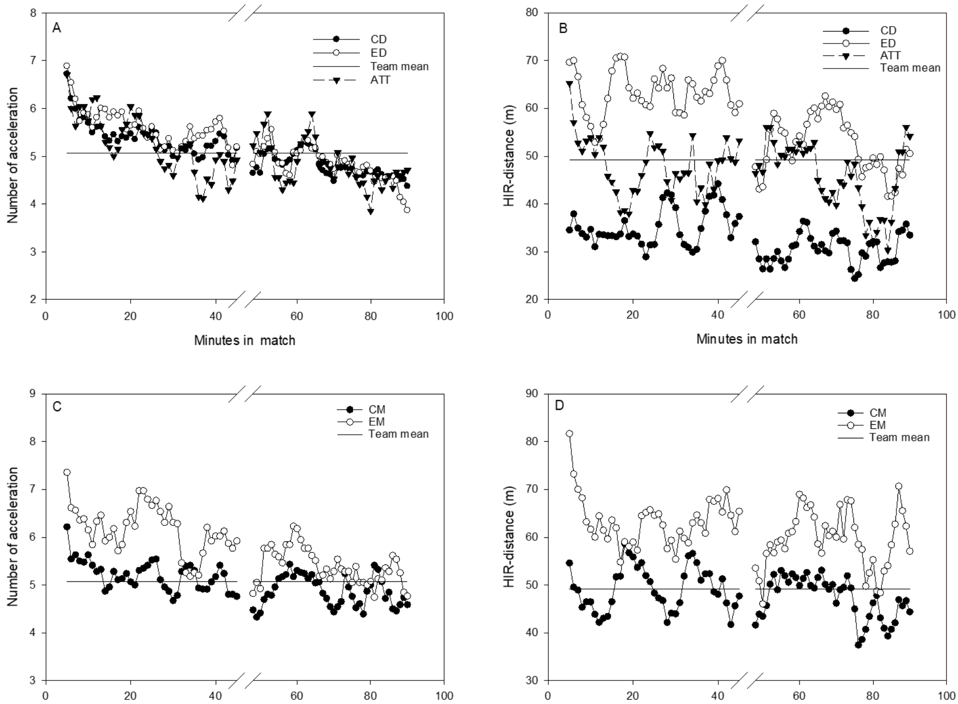

Figure 2. Average number of accelerations in consecutive (moving) 5-min periods according to playing positions during match play. *Accelaration data (panels A and C) and distances covered by high-intensity running in consecutive (moving) 5-min periods (panels B and D) shown for central and external defenders and attackers in A and B, while central and external midfielders are shown in B and D. Abbreviations: ATT, attacker; CD, central defender; CM, central midfielder; ED, external defender; EM, external midfielder; HIR, high-speed running; m, meter.*

There were no positional differences in the reduction of accelerations in the Pre-5-Peak, Post-5-Peak, Post-10-Peak and Post-15-Peak periods ($F = 0.8$, $df = 16$, $p > 0.05$, $\eta 2p = 0.03$). However, there were positional differences in the absolute values of the number of accelerations in the respective peak periods, with the external midfielders having the highest, and the central defenders the lowest, number of accelerations (Table 7). Post-hoc analysis confirmed a significantly lower number of accelerations in the Pre-5-Peak period compared to the Post-10-Peak period ($p < 0.05$). In the Pre-5-Peak period, the number of accelerations in the first and second halves were 19% and 23% lower than the mean, respectively. Corresponding reductions in the Post-5-Peak period compared to the mean were 13% and 16%, respectively. HIR distance around peak periods from the first and second halves are also shown in Table 7. In brief, HIR distance in the Post-5-Peak period was lower than the mean in both the first (35 m vs. 52 m) and second halves (30 m vs. 47 m) ($p < 0.05$). All five playing positions displayed a similar trend in HIR profiles around the peak periods, with no between-position differences ($F = 1.5$, $df = 16$, $p > 0.05$, $\eta 2p = .06$). Post-hoc analysis revealed significantly shorter HIR distances in the Post-5-Peak than in the Post-15-Peak period in the first half ($p < 0.05$).

Table 7. Number of accelerations and high-intensity running distances before and after peak 5-min periods during the first and second halves for the different playing positions.

		Pre-5-peak	Peak	Post-5-peak	Post-10-peak	Post-15-peak
		Number of accelerations (mean ± SD)				
CD	1st half	3.2 ± 1.9	8.9 ± 1.6	4.3 ± 2.1	4.5 ± 1.6	4.4 ± 1.7
	2nd half	3.2 ± 1.9	8.2 ± 1.9	3.6 ± 1.7	3.7 ± 1.9	3.7 ± 1.6
ED	1st half	4.5 ± 1.6	10.6 ± 2.3	4.9 ± 1.9	4.9 ± 1.8	5.4 ± 2.6
	2nd half	3.9 ± 3.2	9.6 ± 2.0	4.5 ± 1.9	4.6 ± 2.0	4.1 ± 1.9
CM	1st half	3.5 ± 1.6	9.5 ± 1.8	3.9 ± 1.8	5.0 ± 1.9	5.2 ± 2.0
	2nd half	3.2 ± 2.1	9.3 ± 2.5	4.5 ± 2.3	4.6 ± 1.6	4.2 ± 2.0
EM	1st half	4.3 ± 2.0	10.9 ± 1.9	4.6 ± 2.2	5.8 ± 2.4	5.7 ± 2.5
	2nd half	4.3 ± 2.5	9.9 ± 2.0	4.4 ± 2.1	5.2 ± 2.0	5.6 ± 2.5
ATT	1st half	4.6 ± 1.7	9.7 ± 1.9	4.1 ± 1.9	4.6 ± 2.0	5.0 ± 2.2
	2nd half	4.4 ± 2.6	8.9 ± 1.9	4.0 ± 2.2	5.1 ± 2.0	4.4 ± 2.1
		High-intensity running distances, meter (mean ± SD)				
CD	1st half	22.4 ± 17.4	82.7 ± 22.7	25.0 ± 18.9	28.9 ± 18.7	35.6 ± 19.5
	2nd half	22.2 ± 15.8	81.5 ± 28.2	19.6 ± 13.7	20.2 ± 15.3	24.0 ± 18.6
ED	1st half	43.1 ± 30.3	136.7 ± 29.7	39.5 ± 28.3	56.5 ± 33.1	59.5 ± 32.0
	2nd half	30.0 ± 42.9	128.6 ± 36.8	30.4 ± 25.2	53.9 ± 26.7	55.5 ± 31.0
CM	1st half	40.4 ± 28.9	107.0 ± 28.2	31.9 ± 25.4	45.9 ± 28.8	44.8 ± 30.8
	2nd half	31.9 ± 22.9	108.4 ± 34.8	34.1 ± 26.7	33.3 ± 25.6	33.5 ± 23.4
EM	1st half	46.5 ± 27.8	129.1 ± 39.2	43.0 ± 24.2	55.9 ± 39.8	54.1 ± 30.6
	2nd half	39.9 ± 27.0	130.9 ± 38.6	44.3 ± 30.7	52.3 ± 29.2	62.4 ± 40.2
ATT	1st half	40.2 ± 28.5	111.4 ± 26.9	34.0 ± 19.3	41.4 ± 21.9	39.6 ± 18.0
	2nd half	35.5 ± 23.5	109.6 ± 28.2	23.4 ± 24.5	38.4 ± 27.5	31.1 ± 25.0

Abbreviations: ATT, attacker; CD, central defender; CM, central midfielder; ED, external defender; EM, external midfielder; high-intensity running (> 19.8 km/h), Peak, peak 5-min periods; Pre-5-Peak, the 5-min period before the peak period; Post-5-Peak, the subsequent 5-min period and the period up to 10 and 15 minutes after the peak (Post-10-Peak and Post-15-Peak). No positional differences in the relative reduction of number of accelerations ($F = 0.8$, $df = 16$, $p > 0.05$, $\eta 2p = .03$) and HIR distance ($F = 1.5$, $df = 16$, $p > 0.05$, $\eta 2p = .06$) were found after the peak periods.

3.5 Study V

3.5.1 Player load in male elite soccer: Comparisons of patterns between matches and positions

Figure 3 shows the mean values of player load and player load indexed to meters per 5-min moving windows throughout match time across all matches (n = 34). Overall, we observed a distinct pattern with peaks at seemingly regular intervals (~15 min), each followed by a period of lower load, typically declining until the next peak. The distinct pattern was clear both for average values of all positions and for the different playing positions (Figure 3A, black line and colored lines, respectively). The same pattern was evident for player load per meter, both overall (Figure 3B, black line) and in all positions (Figure 3B, colored lines), with nearly perfect correlation values (range 0.93–0.97, all p <0.001; Table 1) in all position pairs, all having the highest correlation at zero lag.

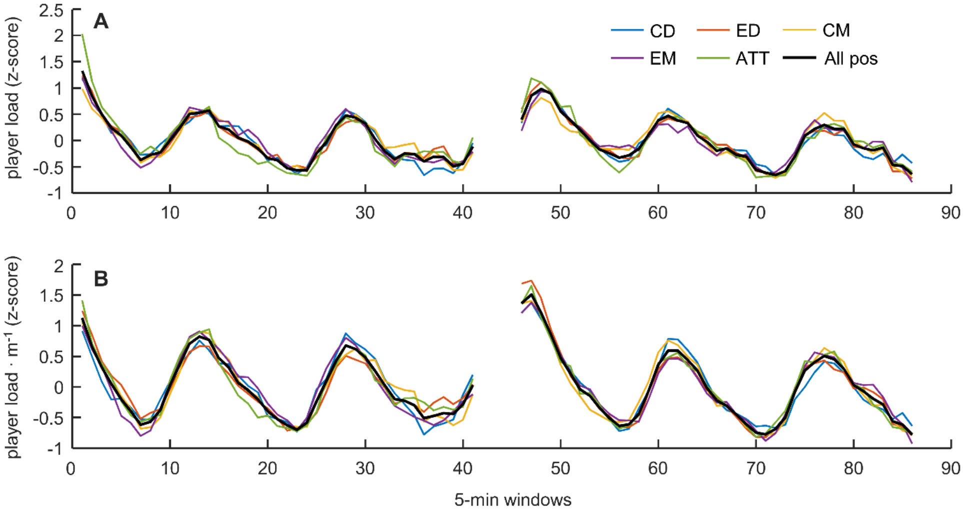

Figure 3. Mean values (z-scores) of player load and player load per meter in 5-min moving windows throughout match time. *Data from all matches (n = 34) shown as mean of all positions (black line) and for each position (colored lines). A: player load; B: player load per meter. Abbreviations: ATT, attacker; CD, central defender; CM, central midfielder; ED, external defender; EM, external midfielder.*

The distinct pattern (as in Figure 3) was also observed in the majority of individual matches (Figure 4). The cross-correlation analysis shown in Table 8 supports the visual evidence, indicating very high to nearly perfect correlations (range 0.88–0.95, all p <0.001) in all position pairs, all having the highest correlation at zero lag.

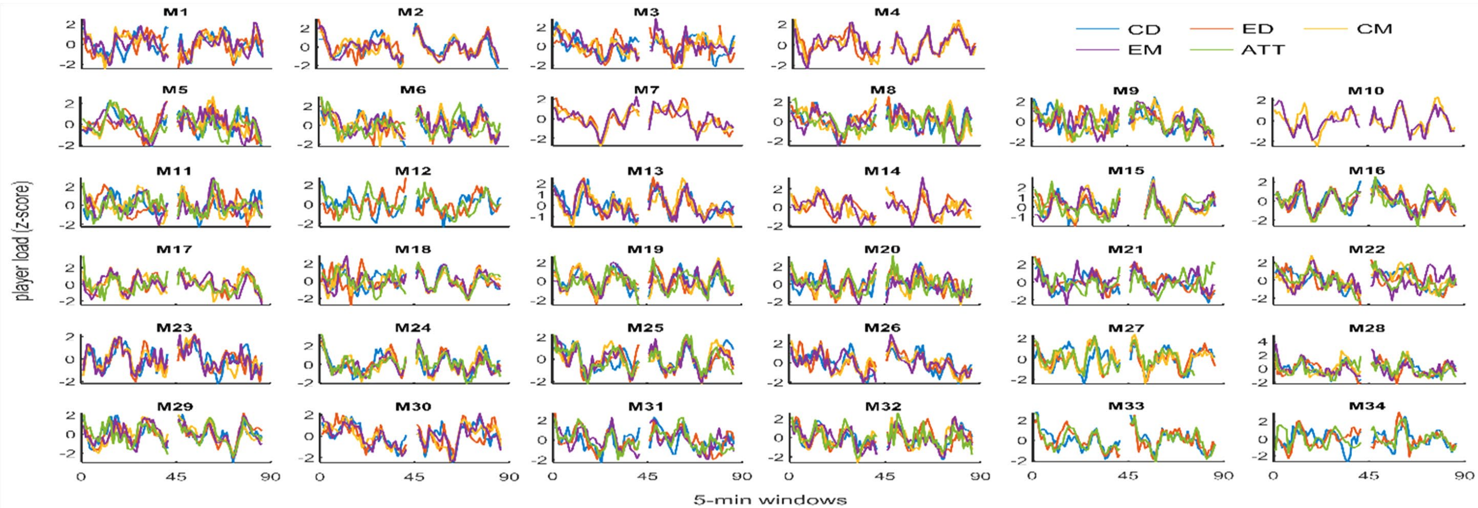

Figure 4. Mean player load (z-scores) in 5-min moving windows throughout match time for all measured positions per match.
Abbreviations: ATT, attacker; CD, central defender; CM, central midfielder; ED, external defender; EM, external midfielder; M, match number.

Table 8. Cross-correlations (95% CI) of mean position values (z-scores) across all matches at zero lag for player load, player load per meter and total distance.

	CD	ED	CM	EM	ATT
Player load					
CD	---				
ED	0.95 [0.92, 0.96]	---			
CM	0.93 [0.89, 0.95]	0.94 [0.91, 0.96]	---		
EM	0.93 [0.89, 0.95]	0.94 [0.91, 0.96]	0.93 [0.90, 0.96]	---	
ATT	0.91 [0.87, 0.94]	0.95 [0.93, 0.97]	0.88 [0.83, 0.92]	0.89 [0.84, 0.93]	---
Player load per meter					
CD	---				
ED	0.93 [0.89, 0.95]	---			
CM	0.95 [0.93, 0.97]	0.95 [0.92, 0.97]	---		
EM	0.95 [0.92, 0.97]	0.94 [0.91, 0.96]	0.95 [0.92, 0.97]	---	
ATT	0.93 [0.90, 0.96]	0.97 [0.96, 0.98]	0.96 [0.94, 0.97]	0.95 [0.92, 0.97]	---
Total distance					
CD	---				
ED	0.88 [0.81, 0.92]	---			
CM	0.80 [0.71, 0.87]	0.84 [0.76, 0.89]	---		
EM	0.89 [0.84, 0.93]	0.87 [0.81, 0.92]	0.86 [0.79, 0.91]	---	
ATT	0.76 [0.65, 0.84]	0.71 [0.59, 0.81]	0.65 [0.51, 0.76]	0.72 [0.59, 0.81]	---

Presented data are from n = 34 matches. Abbreviations: ATT, attacker; CD, central defender; CM, central midfielder; ED, external defender; EM, external midfielder.

Data for total distance, accelerations, sprint distance and HIR distance across match time are illustrated in Figure 5. For total distance, no distinct pattern was evident throughout match time (Figure 5A, black line). However, data for all positions appeared to be well aligned (Figure 5A, colored lines), also reflected by the high to very high correlation values shown in Table 8 (range 0.65–0.89, all $p < 0.001$, with all position pairs again having the highest correlation at zero lag). For accelerations, no specific pattern was evident throughout match time (Figure 5B, black line), but data from the different positions were roughly aligned (Figure 5B, colored lines). For sprint distance and HIR distance, no specific pattern throughout match time was found (Figures 5C-D, black lines), and the patterns for the different positions were not well aligned (Figures 5C-D, colored lines).

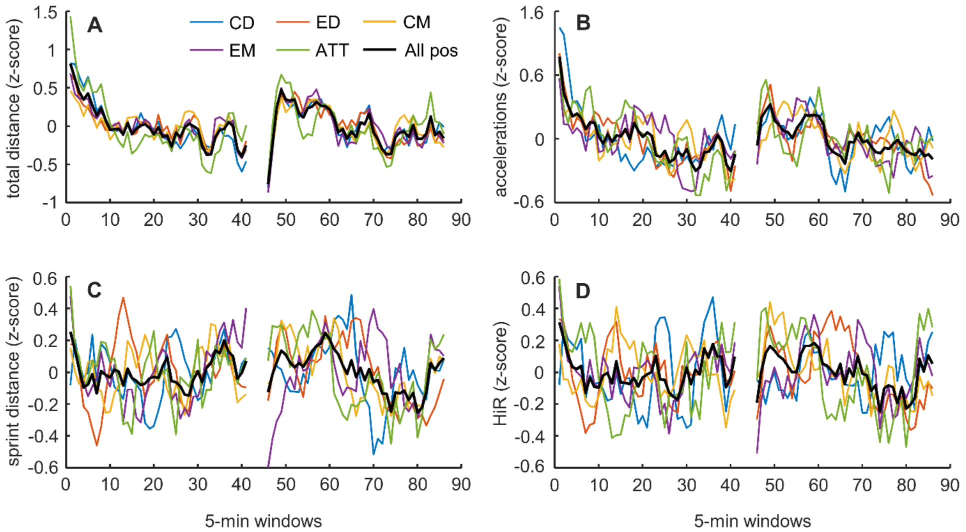

Figure 5. Time-motion variables in 5-min moving windows throughout match time across all matches. *Mean values (z-scores) of time-motion variables in 5-min moving windows across all matches (n = 34) for all positions combined (black lines) and according to positions (colored lines). Panel A shows data for total distance, B for accelerations, C for sprint distance, and D for high-intensity running distance. Abbreviations: ATT, attacker; CD, central defender; CM, central midfielder; ED, external defender; EM, external midfielder; HIR, high-intensity running.*

3.6 Study VI

3.6.1 Differences in acceleration and high-intensity activities between small-sided games and peak periods of official matches in elite soccer players

Physical performance parameters across soccer-related formats such as match peak, match mean, 6 vs. 6 SSGs and 4 vs. 4 SSGs are shown in Figure 6 and Table 9. The total distances covered were lower during SSGs than during the peak match periods (4 vs. 4 and 6 vs. 6 were 16% and 23% lower than peak values, respectively). Correspondingly, HIR distances covered during 4 vs. 4 and 6 vs. 6 SSGs were, respectively, 78% and 86% lower than in the peak match periods and 50% and 67% lower than the match mean. There was very little sprinting during the SSGs (0.2 and 0.1 $m \cdot min^{-1}$ for 4 vs. 4 and 6 vs. 6, respectively), but players performed the same number of accelerations in 4 vs. 4 as in peak match periods, whereas in 6 vs. 6 there were 63% fewer accelerations than in peak match periods. In addition, the mean number of accelerations per min was 113%

higher in 4 vs. 4 and 49% higher in 6 vs. 6 than in matches (Figure 6D and Table 9). Player load during 4 vs. 4 and 6 vs. 6 was, respectively, 13% higher and 15% lower than during peak match periods and 51% and 14% higher than the match mean. No fatigue-related changes in any of the investigated variables were observed over the course of the SSGs during the training sessions.

Table 9. Physical performance variables for peak match periods, match mean and small-sided games.

	TD covered (m/min)	**HIR** (m/min)	**Sprint** (m/min)	**Acceleration** (number/min)	**Player load** (au/min)
Match peak (MP)	137.0 ± 9.9	19.0 ± 3.5	8.8 ± 4.0	1.6 ± 0.3	239.6 ± 36.5
(95% CI)	(133.9 – 143.5)	(17.2 – 20.7)	(6.7 – 11.0)	(1.6 – 1.8)	(221.1 – 258.2)
Match mean (MM)	117.2 ± 8.6	8.3 ± 2.1	1.7 ± 0.7	0.8 ± 0.2	176.8 ± 25.1
(95% CI)	(112.9 – 121.5)	(7.2 – 9.4)	(1.3 – 2.0)	(0.8 – 0.9)	(164.4 – 189.3)
6 vs. 6 SSG	106.4 ± 11.4	2.7 ± 0.9	0.1 ± 0.1	1.2 ± 0.3	197.9 ± 30.6
(95% CI)	(100.8 – 112.1)	(2.3 – 3.2)	(0 – 0.4)	(1.0 – 1.4)	(182.7 – 213.1)
4 vs. 4 SSG	115.9 ± 8.9	3.7 ± 2.1	0.2 ± 0.5	1.7 ± 0.3	247.5 ± 36.5
(95% CI)	(111.4 – 120.4)	(2.6 – 4.7)	(0.1 – 0.2)	(1.6 – 1.8)	(229.3 – 265.7)
Statistical differences	MP > MM = 4 vs.4 > 6 vs. 6 (F = 62.0, p <0.001, η^2 = 0.8)	MP > MM > 4 vs. 4 > 6 vs. 6 (F = 276.5, p <0.001, η^2 = 0.9)	MP > MM > 4 vs. 4 = 6 vs. 6 (F = 67.6, p <0.001 η^2 = 0.8).	MP = 4 vs. 4 > 6 vs. 6 > MM (F = 76.2, p <0.001, η^2 = 0.8)	MP = 4 vs. 4 > 6 vs. 6 > MM (F = 68.8, p <0.001, η^2 = 0.8)

Small-sided games were performed as 4 vs. 4 plus goalkeeper and 6 vs. 6 plus goalkeeper. Data are presented as mean ± SD (95% confidence interval [95% CI]) units of physical performance per minute. Abbreviations: au, arbitrary unit; CI, confidence interval; HIR, high-intensity running (>19.8 km/h); m, meter; min, minute; MM, match mean; MP, match peak; SSG, small-sided game; TD, total distance.

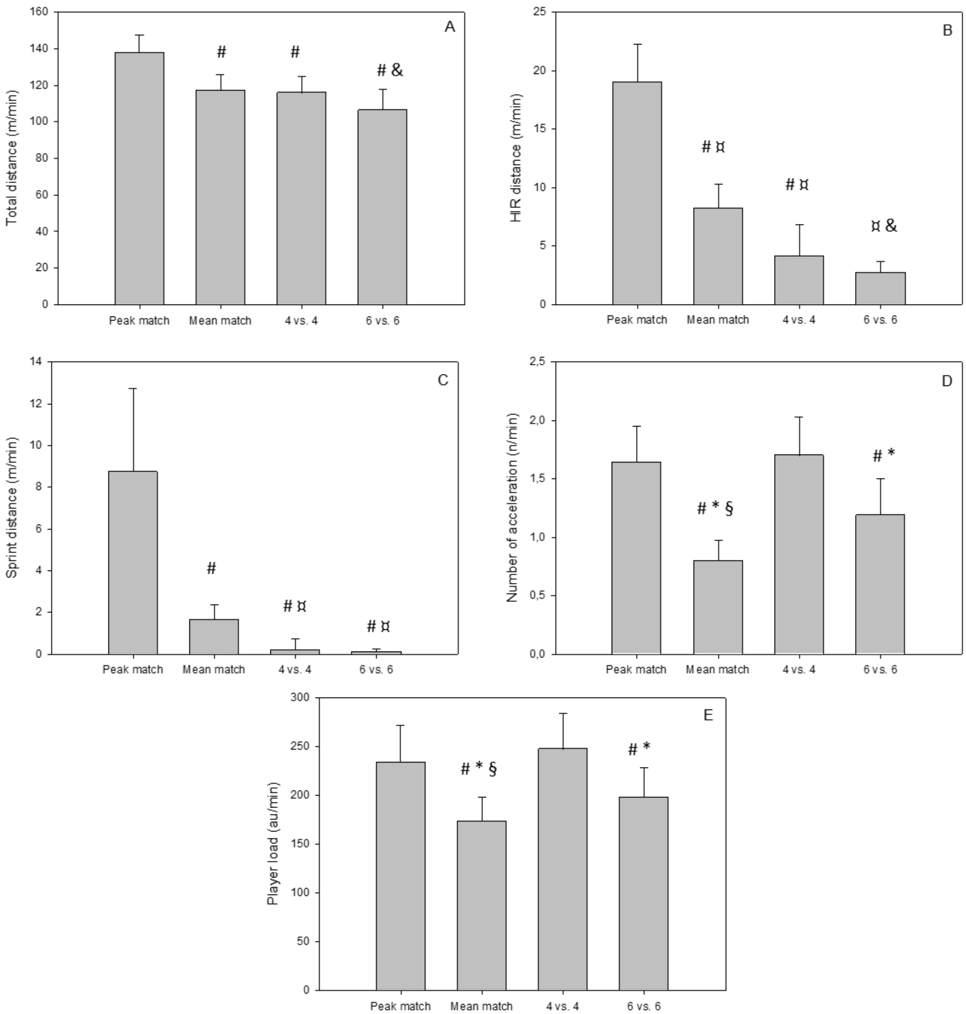

Figure 6. Box-plots of selected physical performance variables for peak match periods, match mean and small-sided games. *Different physical performance measures for peak match periods, match mean, 4 vs. 4 plus goalkeeper SSG and 6 vs. 6 plus goalkeeper SSG showed as total distance in panel A, HIR distance in panel B, sprint distance in panel C, accelerations in panel D, and player load in panel E. Only players with data from all game formats were included. Footnotes: *, lower than 4 vs. 4 (p <0.001); #, lower than peak match period (p <0.001); §, lower than 6 vs. 6 (p <0.001); ¤, lower than the mean match (p <0.001); &, lower than 4 vs. 4 (p <0.05).*

4 Discussion across papers

This thesis found a reduction in accelerations over the time course of a match and after match peak periods, suggesting that accelerations might be a more stable and sensitive measure of physical performance decline compared to HIR distance in soccer match play. While time-motion analysis is a useful tool for examining the physiological demands from high-speed activities, accelerometers can supply information concerning player load from the many discrete actions of a soccer match that may be classified as low-speed activity. Indeed, the present thesis reveals some new factors concerning player load during matches, and that many high-intensity actions without change in location on the pitch may contribute significantly to player load during matches and training. Player load from accelerometer is not a valid measurement for energy costs or RPE, but may function as a complementary tool to investigate player loads during matches and training. Also, the observation of a distinct pattern in player load throughout match time, and the similarity in player load patterns between both matches and positions in elite soccer competition, could indicate a physical "pacing pattern" employed by elite soccer teams. Training with 4 vs. 4 SSGs seems highly valuable in providing the peak demand for accelerations and player load during matches, but neither 4 vs. 4 nor 6 vs. 6 SSGs come close to replicating the demands for HIR or sprints during matches.

Physical demands of Norwegian elite soccer players with special reference to high-intensity movements and actions

The average total distance covered during a full match for Norwegian elite soccer players was well within the previously reported range for top international players [10, 30, 69]. As in other studies [30, 56, 65], the activities in the matches were characterized by prolonged intermittent exercise interspersed with periods of maximal or close to maximal actions [44], although the majority of the game was played within low to moderate intensities [52]. Of the total distance covered, the HIR and sprinting distances accounted for ~8% in the present cohort. This is similar to the ~9% and ~12% observed in previous studies [30, 58, 95]. In this study, the observed sprinting distances were on average shorter than previously reported for elite domestic and international soccer players [8, 26], but comparable to UEFA Cup and Champions League matches [96]. Several different speed thresholds have been used to define when HIR begins. These speed thresholds normally range from 14.4 km/h [58] to 19.8 km/h [59]. Moreover, there are similar differences in speed thresholds in the definitions of sprints [60, 61] as well as time spent in the different speed zones in order to be considered HIR or sprints. These differences in thresholds and cut-offs are important to consider when evaluating the results from different studies and when calculating the physical demands of high-intensity activity in soccer. Studies from soccer have found that match running demands are influenced by a multitude of contextual factors [56]. Elite-level players from the top Italian league and European Champions League perform more HIR and sprinting than (relatively) lower-level players from the top Danish league [7]. However, in the top Spanish League, no differences were found between successful and less successful teams in the two highest velocity zones [62]. HIR and sprinting performance could also be influenced by different playing formation systems. Bradley et al. (2011) found that the general match activity profiles did not differ considerably between soccer players in three different formation systems employed by teams of similar standards in the English Premier League [64]. However, these findings are in contrast to findings from Brazilian soccer, where greater match running performance values were reported for 4-3-3 formations than 4-4-2 formations [63].

Previous research has shown that the physical demands of players are dependent on their position in the team, and that variations in the physical demands are related to the demands specific to playing position [65-67]. Our results concerning central defenders support the general results from other studies that central defenders cover the least HIR and sprinting distance throughout a soccer match [47, 60, 64, 68, 69]. In our study, players in wide positions sprinted longer distances compared to more central players during a full match. It has been speculated that the lower number of sprints among the more central players could be due to a lack of space for reaching sprinting velocity (35). Further, studies have found wide midfielders to cover the greatest HIR and sprinting distance in both Brazilian and English leagues, at different performance levels and independent of playing formation [30, 47, 54, 60, 68]. In addition, Gregson et al. (2010)

found that the largest variation in high-speed activities tended to be among the central players, and suggested that the central players are most susceptible to differences in the overall intensity of the game and the tactics employed by the coach [47]. We found that players in wide positions sprinted longer distances compared to more central players during a full match. Also, playing style, particularly the emphasis on wider players needing to participate in both defensive and offensive phases of the match, has been proposed as a possible reason behind the elevated number of sprints for these players [13]. Even though the present study did not investigate any effect of playing formation, the data were gathered on one of the top-ranked clubs in Norway's top division at their home arena, where the team had the opportunity to "control the match" in most of the matches. The differences between positions in this study are in line with previous research showing that physical demands of players are dependent on their position in the team, and that variations in the physical demands are related to the demands specific to playing position [65-67], as well as previous findings that central defenders cover the least HIR and sprinting distance throughout a soccer match [47, 60, 64, 68, 69].

Although less studied than HIR and sprints, a potentially relevant physical performance-related component of soccer matches is the number of accelerations and decelerations a player performs throughout a match. Maintaining accelerations and decelerations is highly important for soccer performance, as a soccer match may contain as much as eight times more accelerations than sprints [30, 70]. The present study found that players in central positions performed fewer accelerations than players in lateral positions, but that only the players in lateral positions had a decline in accelerations from the first to second half. Acceleration decrements throughout a match have also been found in other studies [59, 71, 72]. A novel finding from this project was that accelerations contribute to 7–10%, and decelerations to 5–7%, of the total player load across all playing positions during match play. Moreover, 12–16% of the total player load accumulates from accelerations and decelerations, indicating that the load from accelerations and decelerations constitutes a considerable part of the total load for a player during match play. Therefore, in order to obtain a "true workload," accelerations and decelerations in numbers, distances and effort, as well as distance covered at various running speeds, must all be included when evaluating a player's total workload during a full soccer game.

Previous studies suggest that inter- and intra-individual variability is smaller for accelerations compared to distance-related measures [47, 51]. Acceleration and deceleration profiles have also been shown to be significantly affected by the time periods between matches, with reduction in both high and maximal acceleration and deceleration during congested periods compared to non-congested periods [74]. These findings suggest that the number of accelerations is a more sensitive measure and a better predictor of players' inability to keep the physical performance constant throughout the match compared to high-speed running and sprint distances [71, 72]. Nonetheless, the lack of a uniform cut-off value for counting acceleration, tracking technology and so on makes it difficult to compare absolute values between studies.

HIR and accelerations as estimates of match physical performance decline

The systematic and consistent decrease in the number of accelerations throughout the match for all positions suggests that accelerations may be a more stable and sensitive measure of performance decline throughout soccer match play compared to distance covered by HIR. A descriptive function of this might be the large coefficient of variation in HIR obtained in other studies, with differences in distance ranging from 16–30% [47] to 25–47.5% [72]. Normally, high-speed activities are subject to large variability between different periods of the match [51, 54]. In our study, the number of accelerations showed a steady decrease throughout the entire match, starting 25% above the mean number of accelerations during the first 5 min of a game and finishing 15% below the mean in the last 5 min. HIR distance, however, seems to be subject to a higher variability between different periods of the match. This study's finding of acceleration and deceleration decrements throughout a match are in line with findings from previous research, although past studies did not investigate using moving windows [71, 72]. These findings suggest that the number of accelerations is a more sensitive measure and a better predictor of players' inability to keep the physical performance constant throughout the match compared to HIR and sprint running distances [71, 72]. Therefore, we propose that a position-specific decline in accelerations throughout the match may be a more precise indication of match physical fatigue compared to the commonly applied HIR profiles.

Similar to the findings of no positional differences of the systematic reductions in accelerations from the start to the end of a game, our study found no positional differences in the reductions of accelerations before and after the peak periods. Furthermore, the number of accelerations in the peak periods were 77–95% higher than the match average. These numbers are higher than the respective peak values in distance covered by accelerations in English Premier Reserve League matches (48% higher than the mean) [72]. The difference between the current results and that of Akenhead et al. (2013) may be influenced by the different computational methods applied to identify peak periods. In this study, peak periods were defined as the highest of any moving 5-min period for each player in each half, whereas Akenhead et al. (2013) identified peak periods based on predefined 5-min periods. This latter approach could potentially lead to lower peak values; it could also influence the pre- and post-peak values compared to identifying peak periods based on moving 5-min periods for each player in each half. Akenhead et al. (2013) found that the number of accelerations was 15% lower in the 5-min period after the peak period compared to the mean value in our study. Akenhead et al. (2013) further demonstrated that accelerations were compromised following a peak period of activity, but they did not analyze this pattern across positions. In our study, we observed positional differences in the number of accelerations around the peak period, but similar relative reductions between positions in the 5-min period after the peak period. Therefore, the performance reduction in number of accelerations in the 5-min period after the peak period was independent of position.

The current study found that the number of accelerations was more than 20% lower than average in the 5-min period before the peak period; Akenhead et al. (2013), meanwhile, found no differences from the mean number of accelerations in the Pre-5-Peak period, but a significant 11% reduction in decelerations in the same period. These differences between studies may also relate to the above-mentioned methodological differences. Additionally, different measurement criteria for accelerations, investigations of number of accelerations vs. acceleration distances and/or different sport tracking systems might have introduced differences between studies [59, 72]. In line with previous studies [7, 66, 77], we observed that the HIR distance was twice as high during the peak periods and lower than the mean in the Pre-5-Peak period. However, the reductions observed in the Post-5-Peak period in the present study (27–40% for the first and second halves) were somewhat lower than the 60% reduction observed in English Premier League matches by Di Mascio et al. (2013) [65]. The latter study used the same speed threshold for HIR as in our work (<19.8 km/h). We observed positional differences in absolute HIR distance and in HIR distance from the start to the end of the matches, but no significant positional differences in relative reductions of HIR distance in the Post-5-Peak period. Results from this and other studies confirm differences in the demand for absolute values of HIR distance between positions [65, 97], challenging the application of HIR as an overall measure of physical performance decline in elite soccer.

The influence of high-intensity, soccer-specific actions on physiological, perceptual and accelerometer loads

The finding from this study that the sprint and sprint COD conditions showed the lowest accelerometer load, and that the acceleration load was the highest in the jump condition, indicate that an extra change in direction (vertical jump) causes considerable extra acceleration loads. This suggests that the vertical component from the accelerometer load seems to be exaggerated compared to the mediolateral and anteroposterior axes. The squared values from the mediolateral and anteroposterior axes were found to be about 10% of the squared value from the vertical axis in this study. Therefore, the difference in accelerometer load is mainly due to a difference in vertical accelerations. These results are in line with the results of Sasaki et al. (2011), who achieved vector magnitude counts/min (here called acceleration load) close to the counts/min from vertical acceleration [98]. Therefore, less acceleration load in sprinting can be explained by the fact that less vertical oscillation occurs than in running [99]. Results from our conditions show that the run condition has a higher accelerometer load than both the sprint and sprint COD conditions, although these conditions have higher measures of oxygen uptake, heart rate and RPE. Although accelerometer load is an established measure of physical activity [100], it is clear from this study that it does not correspond with oxygen uptake, heart rate or RPE in these types of activities. Therefore, one might question whether accelerometer load is a valid measurement for energy costs or ratings of perceived exhaustion in types of activity that include high-speed running and sprinting [100, 101]. While soccer and other team sports usually have other time-motion analysis systems to investigate running at different intensities, these systems have a problem detecting high-intensity actions performed during low-velocity speed [102]. Therefore, accelerometer load data may function as a complementary tool to investigate player loads during matches and training—an area of study that has previously been misrepresented by time-motion analysis, which has classified high-intensity bouts as low-speed activities [102, 103].

Player load during elite soccer matches

The combined data from tri-axial accelerometer and time-motion analysis used in this work revealed that player load accumulates in a variety of ways across the different playing positions. Our data indicate that the use of speed and distance variables alone to assess physical demands may underestimate high-intensity bouts in soccer such as jumping, tackling, collisions, accelerations, decelerations, passing, shooting and unorthodox movements (sideways and backward running). Although these actions may all be classified as low-speed locomotor movements, they exert a high physical strain on the player. In light of this, a training load based on time-motion analysis or heart rate-based measures may not be a stimulating load for the players, since there are positional differences in the way different positions accumulate load [104]. Similarly, only using time-motion analysis may under- or overestimate how players are exposed to physical strain. The use of tri-axial accelerometer technology in combination with time-motion analysis may therefore be useful in assessing the players' load in soccer match play [103]. While time-motion analysis is a useful tool for examining the physiological demands from high-speed activities, accelerometers supply information concerning player load from the many discrete actions of a soccer match that may be classified as low-speed activities due to the arbitrary thresholds [40, 78, 103]. Based on the present study's findings, the within-match player loads show distinct patterns in most of the matches, with three "high-load periods" in each half, separated by "lower-load periods." Although the new methodology for analyzing player load patterns used in the present project provides novel information about high- and lower-load periods of soccer matches, these distinct patterns found in almost all matches were rather surprising, since differences in the opponents' level and tactics in theory should have influenced player load patterns between matches. In addition, one would suppose that player load is largely determined by the players' decision-making about opportunities to become engaged in play. In the present results, the patterns of the different HIR and sprint distances throughout match time show heterogeneity; patterns of sprint and HIR distance show that high-intensity periods occur at different times both between matches and between positions. These differences could be caused by different tactical elements, opponents' playing style, pacing strategies, score line and team formation, all of which would affect the players' ability to regulate their physical effort and maintain work rates at appropriate levels [105, 106]. There are numerous companies that develop devices to measure accelerometer loads, and different companies call these values by different names (e.g., dynamic stress load, body load, total load, force load, player load and so on) [103]. Like our study, these indexes are based on accelerometry data in three axes of movements, but each one applies different algorithms and scaled values to quantify workload during training and matches. This makes comparability of data from different devices very difficult [107].

Differences in high-intensity activities between SSGs and official matches

This study found that the number of accelerations per min in 4 vs. 4 SSGs (152 m^2 per player) was similar to the peak periods observed during match play on a full-size pitch (334 m^2 per player). Castellano and Casamichana (2013) observed that semi-professional players performed almost twice as many accelerations above 2 m/s^2 and more than twice as many accelerations above 1 m/s^2 per min during SSGs than during friendly match play [108]. Our finding of equal player load in 4 vs. 4 SSGs as in peak periods of matches, as well as a corresponding load in peak and mean match values for 6 vs. 6 SSGs, suggests that the higher player load during SSGs may be due to the smaller pitch size, resulting in increased frequency of turns, jumps and tackles [109]. The similarity of acceleration frequency and player load during 4 vs. 4 SSGs and the peak 5-min period of matches implies that training SSGs are sufficiently physically demanding to improve peak physical performance of match play in these specific variables [1, 45]. Further, it is reasonable to assume that during match play, players experience greater demands with respect to a more diverse range of physical parameters, such as HIR, sprinting and running, that play a less important role in SSGs [108]. Our results indicate that the SSG formats used in this study do not impose the same sprinting or HIR demands as match play. Thus, SSGs are not appropriate for training of the HIR demands of soccer matches. Even though the discrepancy with respect to HIR and sprinting between SSGs and the 5-min match peak may be due to several factors, it is reasonable to suggest that the smaller pitch size used during training SSGs may limit the possibility of matching the amount of HIR undertaken during the 5-min peak of matches. It is also possible that the size of the pitch during SSGs in the presented work was insufficient to perform adequate distances of HIR or sprints, suggesting that players need a certain distance before reaching a speed high enough to be categorized as HIR.

Methodological considerations

Since this project investigated one of the top-ranked clubs at their home arena, it is unclear to what extent the results will be generalizable to other teams or matches outside the home arena. This project has limitations related to its lack of attention to differences between various tactical elements, opponents' playing styles, ball in versus out of play, score line or team formations, all of which could affect the players' ability to regulate their physical effort and maintain work rate profiles.

Differences in measurement technology make it difficult to compare parameters between different tracking systems (or even different versions of the same system). Although previous research indicated that various technological measurement systems for soccer match locomotion show relatively similar relative distributions of the various activities (e.g., running and sprinting) [31], it should be noted that different measurement technologies could cause a discrepancy in absolute measurements between the present study and other studies. Hence, caution should be taken when comparing different studies of soccer match play activities. Also, it cannot be ruled out that different styles of play, match score or the quality of the opponent could be the reason behind the discrepancy in values of the different activities compared to other previously published research [35].

The measurement used for player load in this work is based on acceleration data only, thereby making it biased towards forceful speed changes rather than high-speed runs. Thus, this method likely underestimates load at high but constant velocity runs, which may partly explain the findings in Study III in particular. Future studies should address this problem by either combining this method with time-motion analysis or by developing algorithms that accurately combine acceleration and velocity.

These projects did not control for environmental conditions. Some previous studies have ascribed performance reductions in soccer to dehydration and hyperthermia [110]. However, this may be less problematic in Central Norway due to the cold climate, a notion supported by studies showing that cold climate has little impact on physical activity profiles and match running performance of soccer players [111].

5 Conclusions

1) In elite soccer players across all positions, we observed fewer accelerations during the second half compared to the first half of the matches. Players in lateral positions accelerated more often than those in more central positions, although this was only statistically significant for the first half. Further, average sprint distances and number of sprints during the match showed no significant differences between the halves, while players in lateral positions covered longer sprint distances.

2) In the elite soccer players investigated, accelerations were found to contribute to 7–10%, and decelerations to 5–7%, of the total player load from accelerometers across all playing positions during match play. Therefore, in order to obtain a "true workload," accelerations, decelerations (i.e., number, distance, effort) and distance covered at various running speeds must all be included when evaluating a player's total workload during a full soccer game. Also, this study found that only using time-motion analysis may under- or overestimate how players are exposed to physical strain. This finding highlights the potential application of accelerometers to measure player load at low velocities, which may be underestimated for certain positions.

3) In evaluating different soccer-specific maximal actions (such as continuous running, sprinting, sprinting with COD, jumping and shooting), the total accelerometer load was lowest in the sprint and sprint COD conditions, although the physiological (oxygen uptake and heart rate) and perceptual (RPE) responses were highest in those same conditions. The order of physiological and perceptual responses of the specific soccer actions from low to high differed from those of the acceleration load, indicating that accelerometer loads are not similar to physiological and perceptual responses.

4) This study found a continuous reduction in accelerations over the course of the match and after peak working periods of the match in elite soccer players. Although there are positional differences in the number of accelerations in a match, the positional similarities seem applicable to performance decline both from the start to the end of matches and after the peak periods of each half. The HIR distance, however, seems to be subject to a higher variability between different periods of the match. Thus, findings

from this study suggest that accelerations may be a more stable and sensitive measure of physical performance decline compared to HIR distance in soccer match play.

5) By using 5-min moving windows throughout the match, this study demonstrated similarity in player load patterns between positions in elite soccer matches. The novelty is the clear pattern, consisting of three high-load periods in both halves followed by periods with reduced load. The present study did not find similar unambiguous patterns for any of the locomotor variables. The evident pattern in player load indicates a physical "pacing pattern" employed by the team. These "pacing patterns" were relatively similar between positions and occurred at the same time points during the matches over three successive seasons.

6) Physical performance parameters of male elite soccer players differed between the soccer-related activities in the two formats of SSGs and match play. The total, HIR and sprint distances were lowest during SSGs, and HIR and sprint distances were significantly lower than mean match values in both 4 vs. 4 and 6 vs. 6 games. The number of accelerations was similar in 4 vs. 4 and peak match periods but less than half in 6 vs. 6. Compared to average match data per min, players had twice the number of accelerations during 4 vs. 4 SSGs and almost 50% more during 6 vs. 6. Player load during SSGs was somewhat lower than peak match periods, but higher than the match mean (being highest for 4 vs. 4).

6 References

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ORIGINAL ARTICLE

Acceleration and sprint profiles of a professional elite football team in match play

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Abstract
The aim of this study was to characterise the acceleration and sprint profiles of elite football match play in one Norwegian elite football team (Rosenborg FC). Fifteen professional players in five playing positions took part in the study (n = 101 observations). Player movement was recorded during every domestic home game of one full season (n = 15) by an automatic tracking system based on microwave technology. Each player performed 91 ± 21 accelerations per match, with a lower number in the second compared with the first half (47 ± 12 vs. 44 ± 12). Players in lateral positions accelerated more often compared to players in central positions (98.3 ± 20.5 vs. 85.3 ± 19.5, $p < 0.05$). Average sprint distance was 213 ± 111 m distributed between 16.6 ± 7.9 sprints, with no differences between first (106 ± 60 m, 8.2 ± 4.2 sprints) and second halves (107 ± 72 m, 8.3 ± 4.8 sprints). Players in lateral positions sprinted longer distances (287 ± 211 m vs. 160 ± 76 m, $p < 0.05$) and tended to sprint more often (21.6 ± 7.8 vs. 13.0 ± 5.7, $p = 0.064$) compared to players in central positions. We found more walking and less of the more intense activities during the last third of the season compared to the first. The main finding in this study was that Norwegian elite players had substantially less number of accelerations and fewer but longer sprints than previous studies reported for higher-ranked leagues. Also, less high-intensity activity was found towards the end of the season. Ultimately, these data provide useful information for the fitness coach (1) in planning of position-specific football training and (2) to avoid the decline in high-intensity activities the last third of the competitive season.

Keywords: *Soccer, positional differences, activity profile, automatic tracking system*

Introduction

Various video- and GPS-based time–motion analysis systems have been widely used in the attempt to comprehend the sport-specific and physical demands of football match play (Carling, Bloomfield, Nelsen, & Reilly, 2008; Randers et al., 2010). Today there exists consensus that a football player covers 9–14 km during a 90-minute match (Bradley, Di Mascio, Peart, Olsen, & Sheldon, 2010). The activity is characterised by prolonged intermittent exercise interspersed by periods of maximal or close to maximal effort exercise (Randers et al., 2010), although the majority of the game is played within low to moderate intensity (Ingebrigtsen, Dillern, & Shalfawi, 2011).

Although some conflicting findings exists (Di Salvo, Gregson, Atkinson, Tordoff, & Drust, 2009; Rampinini, Impellizzeri, Castagna, Coutts, & Wisloff, 2009), previous studies have demonstrated the importance of high-intensity running (Bradley et al., 2010; Di Salvo et al., 2009; Ingebrigtsen et al., 2012) and that male and female players at higher performance levels are able to perform more high-intensity running than players of lower (Ingebrigtsen et al., 2012; Krustrup, Mohr, Ellingsgaard, & Bangsbo, 2005; Mohr, Krustrup, & Bangsbo, 2003).

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Di Salvo and colleagues (2010) found that players in UEFA Cup matches and European Champions League throughout the seasons 2002–2006 on average sprinted ~200 m distributed over ~27 sprints, whereas Bradley and colleagues (2010) reported that the sprint distance in English Premier League and international games was ~260 m distributed over ~35 sprints during a full match. Although sprinting constitutes only ~1 to ~12% of the distance covered during match play (Di Salvo et al., 2010), and on average lasts from 2 to 4 seconds (Wisløff, Castagna, Helgerud, Jones, & Hoff, 2004), the sprint ability may define outcomes of decisive situations of football matches.

Furthermore, even though previous research has shown differences in both activity profiles and physical characteristics across playing positions in both male and female players (Dillern, Ingebrigtsen, & Shalfawi, 2012; Di Mascio & Bradley, 2012; Ingebrigtsen et al., 2011; Krustrup et al., 2005; Mohr, Krustrup, Andersson, Kirkendal, & Bangsbo, 2008; Mohr et al., 2003), very few studies have investigated the sprint and acceleration activities separated from the other high-intensity activities during football match play. The knowledge and understanding of these activities may be important for a successful tailoring of position specific physical training programmes (Serpiello, McKenna, Stepto, Bishop, & Aughey, 2011; Shalfawi et al., 2012). Also, this information may be valuable in planning of the total physical load of training and match play as the number of sprints and accelerations in football have been suggested as important underlying factors for mechanical muscular fatigue (Greig & Siegler, 2009; Greig, McNaughton, & Lovell, 2006). This assumption is strengthened by the findings of muscular stress being the main reason for injuries in football (Hawkins, Hulse, Wilkinson, Hodson, & Gibson, 2001). However, as stated by Varley and colleagues (Varley & Aughey, 2012), a high sampling rate of the hardware used to collect acceleration data is of importance. The ZXY Sport Tracking system can project a position by advanced processing of 40 Hz radio signals from belts worn by each of the soccer players on the pitch (http://www.zxy.no/zxy_sensor.html). Hence, this system could be useful for the mapping of acceleration and sprint data in football matches.

Therefore, the aims of this study were to characterise the sprint and acceleration profiles of elite football match play, assessed by the ZXY Sport across five different player positions in one professional elite football team over 15 home games. We hypothesised that the present elite players would sprint and accelerate more during the first compared to the second half, and we expected to see that players in wide player positions on the team sprinted longer distances and accelerate more often compared to players in the central team positions.

Methods

Study design

It has been suggested that high-frequency radio technology would be beneficial for a detailed analysis of acceleration profiles in football (Varley & Aughey, 2012). Hence, in this study a fully automatic sport tracking system based on novel RadioEye^{TM} technology was applied to evaluate match performances over one full season of professional elite football players. Every player movement was captured during all 15 games by small body worn sensors continuously monitoring the players' actions (ZXY Sport Chip, 2013). These data were transferred by microwave radio channel to 10 RadioEye^{TM} sensors (ZXY SportTracking AS, Radionor Communications AS, Norway) mounted on the team home arena. According to the manufacturer technical documents, the sensors are individually capable of tracking (40 Hz) the body-located transponders with centimetre accuracy. The data are stored in a SQL server database, and the technology is claimed by the manufacturer to conform to global proven ISO/ETSI/IEEE unlicensed ISM band standard (ZXY Positioning Sensor, 2013).

Reliability of tracking system

Information about the reliability of the ZXY tracking system is previously published in Bendiksen et al. (2013). Additionally, preliminary and unpublished data collected by our research group in a controlled on-field track indicates a test–retest reliability, assessed by the intraclass correlation (ICC) coefficient, of $r = 1.0$, $r = 0.999$ and $r = 0.999$ ($p = 0.000$) for the x- and y-positions (from which, together with time, speed and acceleration are derivatives) and the total distance covered respectively. Further, a Students' paired t-test indicated no significant differences between the test and retest data for the same variables. Also, Bland–Altman plots, as introduced by Altman and Bland (Altman & Bland, 1983), indicated good agreement between the test and the retest x- and y-position data as well as the total distance data. We interpret these findings to indicate good reliability of the current tracking system (Figures 1 and 2).

Subjects and match analyses

Fifteen different players across five different playing positions were included in the study (n = 101 observations). The sample included three central

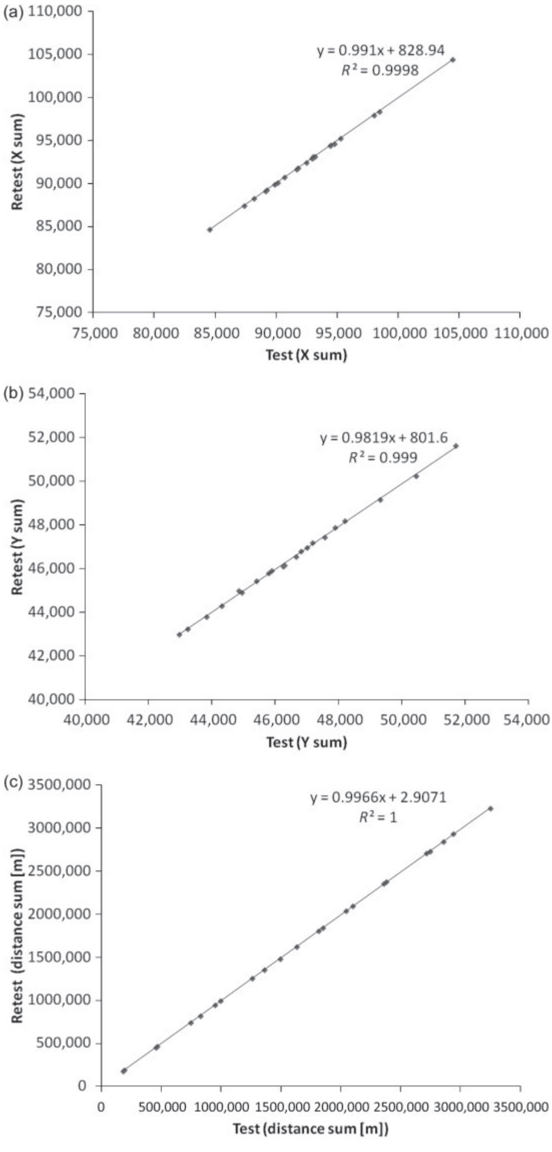

Figure 1. Line of identity, the linear regression equation and the R^2 between the test and retest data for the X position (a), Y position (b) and distance covered (c).

defenders, four full-backs, two central midfielders, four wide midfielders and two attackers. Some of these players were used in different positions across, but not within, matches that is included in the data material. The present team won the Norwegian top league and participated in the qualification for the UEFA Europa League the same year as the data were collected. Following explanation of all procedures, all participants gave verbal and written informed consent to participate in the studies and ethics approval was granted by the Ethics in Human Research Committee of the University.

The selected games were every domestic league home game (n = 15) of one full season. The matches

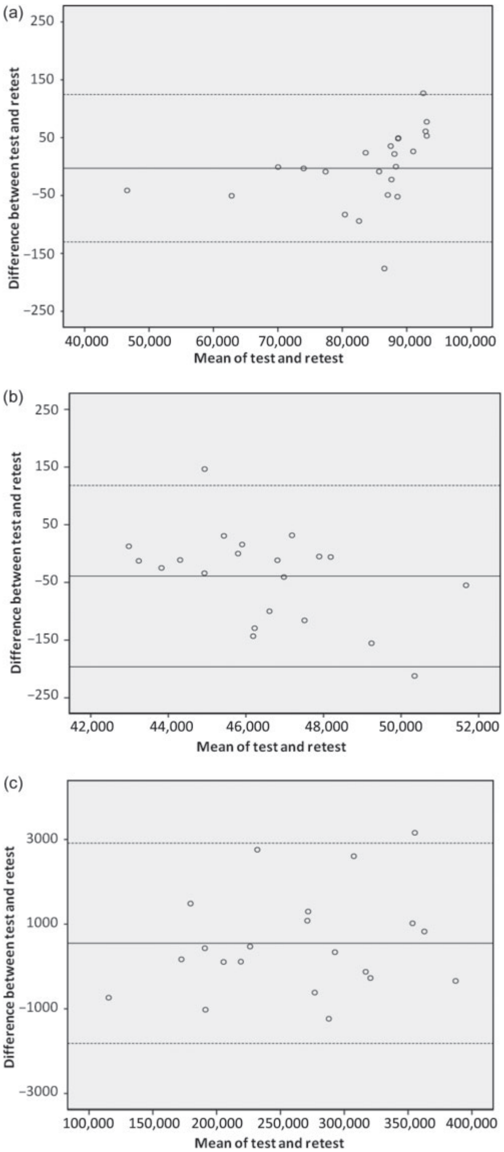

Figure 2. Bland–Altman plots displaying the mean of the test and retest data for *x*-position (a) summated, *y*-position summated (b), distance covered summated (c) on the *x*-axis and the difference between the test and the retest on the *y*-axis. Bias (mean difference) is presented as the middle horizontal line and limits of agreement (±1.96 SD) as dashed lines.

were all played on grass surface. Movements of all players were observed, but to avoid indirect comparisons with playing time, only data from players completing an entire match were used (goalkeepers were excluded).

The following locomotors categories were selected: walking (from 0 to 7.1 km·h^{-1}), jogging (from 7.2 to 14.3 km·h^{-1}), running (from 14.4 to 19.7 km·h^{-1}), high-speed running (from 19.8 to 25.2 km·h^{-1}) and sprinting (≥25.2 km·h^{-1}). The speed thresholds applied for each locomotors category are similar to those reported in some previous studies (Bradley et al., 2009, Di Mascio & Bradley, 2012; Di Salvo et al., 2009; Rampinini, Coutts, Castagna, Sassi, & Impellizzeri, 2007). The above activities were later divided into three locomotors categories: total distance covered (sum of the distances covered during each type of activity), low and moderate intensity activities (locomotion <19.8 km·h^{-1}) and high-intensity activities (locomotion ≥19.8 km·h^{-1}).

Accelerations

Accelerations are defined by four event markers by the ZXY Sport Tracking system. First, the start of the acceleration event is marked by the acceleration reaching the minimum limit (1 m·s^{-2}). Second, to be counted the acceleration has to reach 2 m·s^{-2}. Third, the acceleration must remain above the 2 m·s^{-2} for at least half a second. Finally, the duration of the acceleration lasts until it passes the minimum acceleration limit (1 m·s^{-2}).

Statistical analyses

The descriptive statistics was calculated and reported as mean ± standard deviations of the mean (SD) for each group of players on each variable. Due to the relatively low number of observations for each player position we further grouped the players in to central playing players (central defenders, central midfielders and attackers) and lateral playing players (full-backs and wide midfielders). The differences between these two groups of players were examined using independent samples *t*-tests. Further, differences between the matches and groups of five matches in all measured variables were examined using one-way ANOVA, followed by a subsequent Tukey's post-hoc test when differences were detected. Statistical significance was set at $p \leq 0.05$.

To further assess the reliability of position and distance measures of the tracking system in use, a two-way mixed ICC reliability test between the measures done while running rounds around a track were obtained, following the guidelines provided by Hopkins (2000) for all measures. All data were then examined by a scatterplot, and a Pearson's r correlation coefficient was computed to determine the strength of the relationships between the paired variables from each round on the track. Also, a linear regression was drawn to the scatterplot and the shared variance (r^2) and the equation of the predicted variable calculated. Furthermore, data were also plotted and investigated, using Bland and Altman's 95% limits of agreement as described by Atkinson and Nevill (1998).

All statistical analyses were carried out with SPSS 19.0 (SPSS Inc., Chicago, IL, USA).

Results

Total distance covered

The players covered on average 11,230 ± 992 m during a full match with no differences between first and second halves (5635 ± 491 vs. 5595 ± 567 m). Players in lateral playing positions covered longer distances during both halves and in total compared to players in central positions. No differences were found between first and second halves within the groups of lateral or central playing players. Low- and high-intensity activities on average constituted 10,385 ± 767 and 845 ± 332 m of the total distance, respectively. Within both running and high-speed running distances we found differences between lateral and central playing players, with lateral players covering longer distances running both during the first and second halves and in total. Further, both groups covered shorter running distances during the second half compared to the first (Table I).

Acceleration profiles

On average players across all positions accelerated 90.7 ± 20.9 times per match, with a lower number of accelerations (44.0 ± 12.2 vs. 46.7 ± 11.6, $p \leq 0.05$) during the second compared to the first half of the matches. Further, players in lateral positions on the team accelerated more often compared to players in more central positions during first halves. Although not significant, the same was seen during second halves and overall during full matches. Also, players in lateral playing positions were found to accelerate significantly more often during first compared to second half.

Sprint profiles

On average players sprinted 213 ± 111 m distributed over 16.6 ± 7.9 sprints, with no differences in distance (106 ± 60 vs. 107 ± 72 m) or number of sprints (8.3 ± 4.2 vs. 8.3 ± 4.8) between the first and second halves (Table II). Considering sprinting distances we found lateral playing players to sprint longer during both halves and therefore also in total. However, the number of sprints were not found to be significant different between groups, although we observed a higher number for lateral playing players [a tendency during second half ($p = 0.083$) and in total ($p = 0.064$) was observed].

Table I. Distances covered walking, jogging, running and high-speed running across all player positions during full match, first and second halves (n = 101 observations). Statistical differences were only investigated between players in central vs. lateral positions.

		Walking (0–7.1 km h^{-1})	Jogging (from 7.2 to 14.3 km h^{-1})	Running (from 14.4 to 19.7 km h^{-1})	High-speed running (from 19.8 to 25.2 km h^{-1})	Total distance covered
Central defenders	First half	1950 ± 73	2159 ± 148	715 ± 98	301 ± 88	5131 ± 216
	Second half	2091 ± 69	2152 ± 175	614 ± 87	241 ± 91	5088 ± 239
	Full match	4041 ± 117	4311 ± 231	1329 ± 152	542 ± 131	10,219 ± 381
Full-backs	First half	1914 ± 121	2295 ± 234	1017 ± 171	559 ± 155	5785 ± 326
	Second half	2033 ± 79	2236 ± 234	905 ± 174	491 ± 177	5666 ± 425
	Full match	3946 ± 165	4531 ± 360	1923 ± 304	1051 ± 299	11,451 ± 673
Central midfielders	First half	1866 ± 151	2644 ± 304	949 ± 235	386 ± 180	5831 ± 440
	Second half	1934 ± 222	2501 ± 499	901 ± 280	386 ± 157	5715 ± 686
	Full match	3800 ± 337	5145 ± 708	1850 ± 492	772 ± 304	11,546 ± 1024
Wide midfielders	First half	1801 ± 182	2651 ± 355	1096 ± 2814	532 ± 131	6081 ± 560
	Second half	1870 ± 123	2585 ± 202	1147 ± 265	636 ± 153	6239 ± 465
	Full match	3671 ± 271	5236 ± 512	2244 ± 520	1168 ± 249	12,320 ± 979
Attackers	First half	2026 ± 128	2195 ± 253	691 ± 99	331 ± 83	5245 ± 274
	Second half	2088 ± 117	2165 ± 225	711 ± 92	377 ± 108	5340 ± 234
	Full match	4114 ± 223	4360 ± 415	1402 ± 155	708 ± 166	10,584 ± 461
Players in central positions (n = 59)	First half	1932 ± 141[c]	2382 ± 342	812 ± 210[a]	346 ± 139[a]	5468 ± 472[a]
	Second half	2021 ± 179	2309 ± 397	765 ± 233[ab]	339 ± 142[a]	5428 ± 554[a]
	Full match	3953 ± 291	4691 ± 662	1577 ± 421[a]	686 ± 248[a]	10,896 ± 950[a]
Players in lateral positions (n = 42)	First half	1882 ± 148[c]	2397 ± 315	1040 ± 208[a]	551 ± 147[a]	5870 ± 421[a]
	Second half	1986 ± 118	2336 ± 268	975 ± 229[ab]	533 ± 181[a]	5829 ± 505[a]
	Full match	3868 ± 234	4732 ± 515	2014 ± 399[a]	1084 ± 288[a]	11,699 ± 858[a]

[a]Significant ($p \leq 0.01$) differences between groups. [b]Significantly ($p \leq 0.05$) lower compared to first half. [c]Tendency ($p = 0.082$) towards difference between groups.
Data are mean ± SD.

Variation in locomotor activities

The one-way ANOVA, and post-hoc analyses, showed that the players tended to walk longer during match 10–15 (459 ± 134 m; $p = 0.061$ and 450 ± 134 m; $p = 0.063$) compared to the first match of the season. Players also jogged a longer distance during the first compared to the last match (1051 ± 294 m; $p = 0.039$). We observed that all players had a significant higher (range 31 ± 6–62 ± 6, $p < 0.05$) number of accelerations during the first compared to all the 14 other matches.

For players in central playing positions the number of accelerations varied significantly from match to match ($p = 0.000$), with post-hoc analysis showing that match 1 differed ($p < 0.05$) from all other matches (range 38 ± 10 to 66 ± 9). We also found a variation in number of accelerations from match to match during a full season for players in lateral positions ($p < 0.01$). The post-hoc analyses revealed that players in match 1 accelerated more often compared to players in match 11 (53 ± 12; $p = 0.012$) and 14 (58 ± 12; $p = 0.004$), respectively.

Table II. Sprinting distances, and number of sprint and accelerations across player positions during full match, first and second halves (n = 101 observations).

			Central defenders	Full-backs	Central midfielders	Wide midfielders	Attackers	Players in central positions (n = 59)	Players in lateral positions (n = 42)
Sprint	First half	Distance (m)	67 ± 38	147 ± 66	84 ± 54	129 ± 39	90 ± 40	81 ± 46[a]	142 ± 60[a]
		Count	6.2 ± 3.3	10.7 ± 4.4	6.6 ± 3.7	10.4 ± 3.6	6.9 ± 2.5	6.6 ± 3.3	10.6 ± 4.1
	Second half	Distance (m)	55 ± 36	137 ± 83	90 ± 65	165 ± 57	91 ± 72	80 ± 55[a]	145 ± 76[a]
		Count	5.0 ± 2.9	10.2 ± 5.2	6.8 ± 3.8	12.8 ± 4.3	7.5 ± 3.4	6.4 ± 3.5[c]	11.0 ± 5.1[c]
	Full match	Distance (m)	123 ± 48	284 ± 123	174 ± 89	294 ± 76	181 ± 111	160 ± 76[a]	287 ± 211[a]
		Count	11.2 ± 5.0	20.9 ± 8.2	13.4 ± 6.6	23.2 ± 6.8	14.4 ± 4.5	13.0 ± 5.7[d]	21.6 ± 7.8[d]
Accelerations	First half	Count	47.1 ± 11.8	52.0 ± 10.9	41.5 ± 10.8	52.0 ± 12.3	40.8 ± 6.3	43.0 ± 10.4[a]	52.0 ± 11.1[a]
	Second half	Count	39.8 ± 9.8	43.4 ± 10.7	43.7 ± 14.9	53.5 ± 12.2	42.9 ± 12.2	42.3 ± 12.2	46.3 ± 11.9[b]
	Full match	Count	86.9 ± 18.0	95.4 ± 19.4	85.2 ± 23.6	105.5 ± 22.2	83.7 ± 13.8	85.3 ± 19.5	98.3 ± 20.5

[a]Significant ($p \leq 0.01$) differences between groups. [b]Significantly ($p \leq 0.05$) lower compared to first half. [c]Tendency (p = 0.083) towards difference between groups. [d]Tendency (p = 0.064) towards difference between groups.
Data are mean ± SD.

Concerning the variation between the averages of the first (S1), second (S2) and third (S3) phase of the season we found significant differences in number of accelerations and sprints, walking, jogging, running and total distance covered throughout the match. Post-hoc analysis showed that during S1 players walked shorter (177 ± 64 m; p = 0.019), jogged (465 ± 141 m; p = 0.004) and ran (343 ± 109 m; p = 0.006) longer distances, and covered a higher total distance (786 ± 231 m, p = 0.003), compared to the average of S3. Also, overall players accelerated more during S2 compared to S2 and S3 (14 ± 4; p = 0.005 and 26 ± 4; p = 0.000), and during S2 compared S3 (12 ± 4; p = 0.025). For players in central positions on the team we only found the number of accelerations to differ between the three phases of the season, with a higher number of accelerations performed during S1 compared to S3 (21 ± 6, p = 0.002). For players in lateral positions we found all variables to differ between the three phases of the season, except from sprinting distance. Post-hoc analysis revealed that walking (264 ± 78 m; p = 0.005), jogging (−579 ± 173 m; p = 0.005), running (−480 ± 130 m; p = 0.002) and high-speed running (−298 ± 98 m; p = 0.012) distances was different within S3 compared to S1. Also, running distances (−336 ± 135 m; p = 0.044) were lower within S2 compared to S1. Analysis also revealed a higher number of accelerations during S1 compared to S2 and S3 (18 ± 6; p = 0.013 and 32 ± 6; p = 0.000), and for S1 compared to S3 for sprints (7 ± 3; p = 0.031), respectively.

Discussion

The main finding in this study was that Norwegian elite players had substantially less number of accelerations than previously reported in higher-ranked leagues. Furthermore, we found a substantially lower number of sprints (~16.6) compared to previously published data (27–35 sprints; Bradley et al., 2010; Di Salvo et al., 2010) from higher-ranked leagues, although players sprinted comparable distances during a full match (~212 m) to what has been reported for the European cups before (Di Salvo et al., 2010). Players in lateral playing positions sprint the longest distances (~290 m) and more often (not significant) compared to more central playing players. Also, in general a shift towards more walking and less high-intensity locomotor activities during match play was found towards the end compared to the start of the season.

Present data on average indicate a higher number of accelerations during first compared to second half (~47 vs. ~44) and a total number of ~91 accelerations during a full match. To the best of our knowledge only two previous studies quantified acceleration profiles in elite football (Bradley et al., 2010; Varley & Aughey, 2012). Bradley and colleagues (2010) found that international and elite domestic players had about 30% more accelerations (average of 119 during matches) than in the present study, even though they used a higher threshold for defining accelerations than we did (2.5 $m \cdot s^{-2}$ vs. 2 $m \cdot s^{-2}$).

Across player positions we found the lateral playing players to accelerate significantly more than central players during the first half, while no difference were found during the second half or during a full match. Only one study has previously reported acceleration data for specific playing positions in a football team. Varley and colleagues (Varley & Aughey, 2012) found similar, but not identical, patterns within Australian football as the present study as full-backs in their cohort accelerated more often compared to players in other playing positions and central defenders and central midfielders had the lowest number of accelerations during a match.

The observed sprinting distances was on average shorter than previously reported for elite domestic and international football players (Bradley et al., 2010; Mohr et al., 2003), but comparable to UEFA Cup and Champions League matches (Di Salvo et al., 2010). Also, the present players performed substantially lower number of sprints (~16.6) compared to what has previously been published for elite players in higher-ranked tournaments than the Norwegian top league (27–35 sprints; Bradley et al., 2010; Di Salvo et al., 2010). Unlike previous research (Bradley et al., 2010; Mohr et al., 2003), we found no differences in sprinting distances between the first and second halves of the matches. Nor the number of sprints differed between the two halves of the match. In line with our hypothesis, players in lateral positions sprinted longer distances compared to more central playing players during a full match. This is in line with previous findings within elite football cohorts (Bradley et al., 2009; Di Salvo et al., 2009; Mohr et al., 2003). The present data indicate that the superior sprinting distances for the lateral players comes from the higher number of sprints performed during the match compared to the more central playing players, as the average sprinting distances is very similar across player positions. It has previously (Varley & Aughey, 2012) been speculated that a lower number of sprints among the more central players could be due to a lack of space for the sprinting velocity to be reached. Also, the playing style, with emphasis on the need for the wider players to participate in both defensive and offensive phases of the match has been proposed as a possible reason behind the elevated number of sprints for these players (Di Salvo et al., 2010).

The average total distance covered during a full match (~11,230 m) was well within the range for top players previously reviewed by Stølen, Chamari, Castagna, & Wisløff (2005). On average the total distances only decreased by 40 m (not significant) from the first to the second half. This finding is not in line with what has previously been found in top-level football (Bradley et al., 2010; Mohr et al., 2003; Varley & Aughey, 2012). However, as indicated by the larger SD in total distances covered during the second compared to the first half, a larger variation across players' distances covered during the second half was found. Of the total distance covered the amount of high-intensity activity accounted for ~7.5% in the present cohort. Also, this is not in line with previous findings that found high-intensity activities to account for between ~9% and ~12% (Bradley et al., 2010; Mohr et al., 2003).

Concerning the variations in locomotor activities for all players across the season, our findings showed a shift towards more walking and less of the more intense activities during S3 compared to S1. This was particularly evident for players in the lateral positions. And as previous investigations have indicated a reduced physical capacity during the season (Stølen et al., 2005) and a relationship between higher physical capacity and more intense match locomotor activities (Ingebrigtsen et al., 2012; Krustrup et al., 2005; Mohr et al., 2003; Rebelo, Brito, Seabra, Oliveira, & Krustrup, 2012), this (i.e. player fitness) could be an explanation behind lowered amounts of intense activities towards the end of the season. However, as we do not have any fitness data on the present players, or information about tactical, technical or score line variables during the season, it is difficult to fully understand and interpret these present findings.

Limitations

Although previous research indicated that various technological measurement systems for football match locomotion show relatively similar relative distributions of the various activities (e.g. running and sprinting; Randers et al., 2010), it should be noted that different measurement technologies could cause the discrepancy in absolute measurements between the present and other studies (Randers et al., 2010; Varley & Aughey, 2012). Hence, caution should be taken when comparing different studies of football match activities. Also, it cannot be ruled out that a different style of play, match score, the quality of opposition or the fact that the present study relies on one team's home games, could be the reason behind the discrepancy in values of the different activities compared to other previously published studies (Varley & Aughey, 2012).

Conclusion

In summary, the present results provide a useful and novel insight to Norwegian elite football players sprint and acceleration profiles during match play and show a distinct variation in both variables between the different player positions. Hence, these data could provide valuable information to the fitness coaches about the sprint and acceleration profiles of elite football players of different positions. An important aspect when considering the impact of the number of accelerations is that accelerations have previously been shown to start, and undergo, within the lower velocities. Hence, an underestimation of player load could be found if one only analyses the number high-velocity actions during match play. The data could serve as normative values that could be used for comparisons for other elite football players, and furthermore, provide useful information for the designing of (1) position-specific football training and (2) a programme avoiding the decline in physical performance in the last third of the season.

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ORIGINAL RESEARCH

Influence of different soccer-specific maximal actions on physiological, perceptual and accelerometer measurement loads

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Background: The aim of this study was to compare the effect of different soccer-specific maximal actions (Continuous run, Sprint, Sprint with change of direction [Sprint COD], Jump and Shot) upon physiological (oxygen uptake and heart rate) and perceptual (rating of perceived exertion [RPE]) responses and accelerometer load.

Materials and methods: Ten moderately to well-trained male soccer players volunteered to serve as subjects in this study. A repeated within-subject design was used in which each subject was tested on five occasions on different days, one test each day, during a period of 2 weeks. Each of the five tests had a distance of 900 m and lasted 5 minutes, thus the mean speed for all five tests was 3 m/s. During the test, oxygen uptake, heart rate and accelerometer load were measured. Immediately after each test, RPE was recorded, and after the test, oxygen uptake was measured for 5 minutes while the subject sat in an upright position on a chair.

Results: In the comparison of different soccer-specific maximal actions upon physiological and perceptual responses and accelerometer load, this study found that the total accelerometer load was lowest in Sprint and Sprint COD conditions, although the physiological (oxygen uptake and heart rate) and perceptual (RPE) responses were highest in the respective conditions. The Jump condition experienced lower RPE than Sprint and Sprint COD but achieved the highest accelerometer load.

Conclusion: Accelerometer load is not a valid measurement for energy costs or RPE but may function as a complementary tool to investigate the player loads during matches and training.

Keywords: soccer, oxygen uptake, rate of perceived exhaustion, repeated sprint, jump, shot

Introduction

It is well established that soccer is characterized by low-intensity (eg, standing and walking) and high-intensity (eg, running and sprinting) activities. Several studies have investigated the physical and physiological demands of elite soccer players based on distance covered by running at different intensities during a match.[1–3] However, these analyses of differences in work rate measured as running speed and distance do not take into account fast discrete movements in soccer (jumping, tackling, collisions, accelerations and decelerations, passing, shooting and change of directions [CODs]),[1,4,5] also called maximal actions, which together take place several 100 times in each match. Quite a few of these soccer-specific movements can cause high physical stress on the players, even though the distance and speed are low. These maximal actions may be classified in the low-speed locomotor category, although there will be high physical strain on the player.[6–8] Although the energy expended in traveling a fixed distance during continuous

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exercise is independent of the velocity of the movement, this relationship does not hold under conditions of locomotion that apply during soccer matches. Energy costs throughout a match would be grossly underestimated if they were calculated from only distance covered and did not account for the frequent changes in velocity and direction of motion.[6]

Triaxial accelerometers are highly responsive motion sensors that record acceleration of body movement in three dimensions. These systems have been found useful not only for quantifying physical activity in a variety of populations but also for quantifying physical and physiological demands in Australian football[7,8] and basketball.[9] Movements with accelerations are more energetically demanding than constant velocity running.[10,11] Even at a low running speed, a high metabolic load is imposed on a soccer player when acceleration is elevated.[10,11] Decelerations are just as common as accelerations in soccer[11] and will also contribute significantly to the players' load. Therefore, accelerometers may be a complementary tool for measuring the load from activities misrepresented by other measuring systems, such as time–motion analysis (ie, high-intensity bouts classified as low-speed activities), oxygen consumption and heart rate measurements.[5,6,12] A recent study[12] combined data from a time–motion analysis and triaxial accelerometery and demonstrated that player load is accumulated in a variety of ways across different playing positions. Dalen et al[12] found that only using time–motion analysis might underestimate the players' physical strain, and the potential application of accelerometers for measuring player load at low velocities may be underestimated in a time–motion analysis system. However, other studies have also emphasized the limitations of accelerometers to measure differences in activity with movements at high speed.[13] It is clear that the most realistic way of investigating the physical demand of soccer-specific intermittent activity is to monitor physiological responses (ie, oxygen uptake) during match play. However, this approach faces difficulties with the experimental control of the environment because it is impossible to make use of all the measuring instruments during matches. Therefore, different treadmill protocols have previously been used in an attempt to simulate the work rate of a soccer match.[14,15] In addition, different intermittent shuttle running tests have been used to simulate the activity patterns of soccer.[16] Without doubt, these protocols have allowed a more detailed determination of the physiological responses during soccer-specific intermittent exercises and have provided a better understanding of the demand of these activities. However, these protocols only involved running movements of different intensity with and without a ball and it can be argued that a laboratory-based replication of purely the activity profile would not elicit the same physiological response as match play.[17] The effects, on physical and perceptual responses, of including fast discrete maximal actions—such as shooting, tackling and jumping—in an already ongoing movement were not taken into account in these studies. In later years, triaxial accelerometers were used to specify the accelerometer load of these discrete actions. Several studies in team sports have investigated the accelerometer load and used triaxial accelerometers as an additional part of their global positioning system (GPS) or radio-based systems for performance analyses (ie, GPSport, Catapult, ZXY Sport Tracking).[12,18–21] However, to the best of our knowledge, studies on accelerometer loads in combination with physiological and perceptual measurements in order to specify the demand of these fast, discrete, maximal actions in soccer are rather sparse.

Therefore, the aim of this study was to compare the effect of different soccer-specific maximal actions (Continuous run, Sprint, Sprint with change of direction [Sprint COD], Jump and Shot) on physiological (oxygen uptake and heart rate) and perceptual (rating of perceived exhaustion) responses and accelerometer load. It was hypothesized that accelerometer load, physiological and perceptual responses increase with the discrete maximal actions, but that accelerometer load would be underestimated in conditions with high-speed activities (Sprint and Sprint COD). In addition, it was hypothesized that Sprint and Sprint COD would have the highest values in physiological and perceptual responses because of the highest percentage of time spent' in maximal activity during the conditions.

Materials and methods

Subjects

Ten moderately to well-trained male soccer players volunteered to serve as subjects in this study. The average age of the subjects was 25±2.7 years, body height 179.0±5.4 cm and body mass 78.3±7.4 kg. The subjects had three to five training sessions each week before the start of the competition season, and none reported taking any medication or being under medical care. The subjects were informed orally and in writing about the purpose of the experiment, the experimental procedure and possible risks and discomfort. All subjects gave their written informed consent to take part in the study and were assured that they as volunteers could leave the study at any stage without giving a reason. The subjects were also told not to change their training routines during the study, to avoid hard training and to avoid alcohol the day before each test. The study was conducted according to the Declaration of Helsinki and approved by the Norwegian Centre for Research Data.

Design

A repeated within-subject design was used in which each subject was tested on five occasions during different days, one test each day, during a period of 2 weeks. The tests were performed in a randomized order. The test venue was in a sports hall, and all tests were performed on a tartan floor. Four of the tests consisted of different series of maximal actions (detailed below) carried out sequentially, with running breaks in between. Continuous submaximal running was chosen as a baseline condition test with which the four maximal action tests could be compared.

Procedures

Before each test, the subject performed a 15-minute warm-up. During the first 5 minutes, the subject ran at an intensity of 70% of maximum heart rate. During the last 10 minutes, the subject ran at 80% of maximum heart rate, where three maximal 20 m sprints were included. After the warm-up, the test equipment was fastened and the test began within 4–5 minutes after the end of the warm-up. During the test, oxygen uptake, heart rate and accelerometer load were measured. Immediately after each test, the rating of perceived exertion (RPE) was recorded. After the test, oxygen uptake was measured for 5 minutes while the subject sat in an upright position on a chair. To measure oxygen uptake, a portable oxygen analyzer was mounted in a small backpack on the subject`s back and tightened with a belt at the breast and above the hip level. The complete instrument including batteries weighed 1.3 kg. To measure heart rate and acceleration loads, an accelerometer was mounted at the waist using an elastic belt with a belt clip, along with the manufacturer's accompanying a chest strap heart rate monitor.[22]

Test conditions

Each of the five tests involved a distance of 900 m and lasted 5 minutes, thus the mean speed for all five tests was 3 m/s. This pace is the mean value of the "jogging category" used in investigations of physical demands in soccer games.[12] The distance of 900 m consisted of 15 shuttle runs where the subject ran 30 m, turned 180° and ran 30 m back to the start, 15 times (15 shuttle runs). Each shuttle run lasted for 20 seconds with the use of a digital signal for the pace every 10 seconds. During each shuttle run, in four of the five tests maximal actions were performed (Table 1). The subject was informed about the number of shuttle runs during the test. For all tests, the subject ran with the same training shoes and was encouraged to perform their best during the maximal actions.

Instruments

Oxygen uptake was measured using the Metamax II metabolic cart (Cortex Biophysics, GmbH, Leipzig, Germany) portable metabolic analyzer, with the instrument's breathing valve (Triple V) mounted on the face mask. A standard two-point gas calibration procedure against ambient air and a commercial gas of known concentrations of O_2 (16.00%) and CO_2 (4.00%) was performed in the morning after a 30-minute warm-up period for the instrument. Ambient air measurement was also carried out before each test. The flow transducer was calibrated using a 3 L high-precision calibration syringe (Calibration syringe D, SensorMedics, Yorba Linda, CA, USA) before each test. The Metamax II has been validated and the oxygen uptake reported by this analyzer was precisely measured within subjects.[23]

Accelerometer load and heart rate data were measured using an ActiGraph wGT3X+ monitor (ActiGraph, Pensacola, FL, USA). The ActiGraph is a lightweight (27 g), compact (dimensions of 3.8 cm×3.7 cm×1.8 cm) and rechargeable accelerometer (ie, lithium polymer battery powered).[24] The ActiGraph measured acceleration in three axes (vertical [Y], mediolateral [X] and anteroposterior [Z]) and provided activity counts as a composite vector magnitude of these three axes (total). The activity monitor samples acceleration at a rate of 30 Hz. The output of the accelerometers is given in "counts", with one count equaling 16.6 miliG/s at 0.75 Hz.[24] Activity counts, which are the results summing the absolute values of the sampled change in acceleration measured during the

Table 1 Description of the five different test conditions

Test condition	Total distance	Time (minutes)	Maximal action in the condition
Run	900 m (15 shuttle runs, 2×30 m)	5	None
Sprint	900 m (15 shuttle runs, 2×30 m)	5	15 sprints of 20 m were included between 30 and 50 m of each 60 m track
Sprint COD	900 m (15 shuttle runs, 2×30 m)	5	15 sprints with COD were included between 20 and 40 m of each 60 m track
Jump	900 m (15 shuttle runs, 2×30 m)	5	30 maximal vertical jumps were included, two jumps during each shuttle run, the first at the 15 m point and the second at the 45 m point
Shot	900 m (15 shuttle runs, 2×30 m)	5	15 shots of maximal effort were included at the 50 m point of each 60 m track

Abbreviation: Sprint COD, Sprint with change of direction.

time period, represent the quantitative measure of activity over time. The ActiGraph also included the vector summed value $\sqrt{(Y^2+X^2+Z^2)}$, known as "vector magnitude".[24] In this study, two accelerometers were used, one on each side of the waist, and the mean values from the two accelerometers were defined as the subject's accelerometer load.

To register subjective perceived exertion, Borg's rating scale was used ($RPE_{6–20}$),[25,26] with the subject instructed to report an overall feeling of exertion immediately after each 900 m running test. A 6 on the RPE_{6-20} scale means "very easy" and 20 corresponds to "total exhaustion".

The average of all measured variables during each of the five 5-minute tests and during a 5-minute rest after each test was used for further analyses.

Statistical analysis

To investigate the effect of different soccer-specific maximal actions on the physiological and perceptual responses, a one-way analysis of variance (Run, Sprint, Sprint COD, Jump and Shot) with repeated measures on the accelerometer load and each response was used.

In the case that the sphericity assumption was violated, the Greenhouse–Geisser adjustments to the *p*-values are reported in the results. A post hoc test using Holm–Bonferroni probability adjustments was used to locate significant differences. The criterion level for significance was set at $p<0.05$. The effect size was evaluated with η^2 (partial eta squared), where $0.01<\eta^2<0.06$ constitutes a small effect, $0.06<\eta^2<0.14$ constitutes a medium effect, and $\eta^2>0.14$ constitutes a large effect.[27] Statistical analysis was performed using SPSS 23.0 for Windows (SPSS Inc., Chicago, IL, USA).

Results

A significant effect was found for each of the variables measured during different soccer-specific maximal actions ($F\geq2.86$; $p=0.037$; $\eta^2\geq0.24$, Figure 1 and Table 2). Post hoc comparison showed that accelerometer load in the anterior–posterior direction in the Jump condition was significantly higher than all the other actions except the Sprint condition (Figure 1 and Table 2); whereas in the medial–lateral direction, the Sprint condition was the lowest compared with all other conditions. In the vertical direction, the total accelerometer load in the Jump condition was the highest followed by the Shot and Run conditions (no significant difference between these two conditions, $p=0.28$), whereas Sprint and Sprint COD conditions had produced the lowest vertical and total accelerometer load (Figure 1 and Table 2).

Oxygen uptake during and after the Run condition was significantly lower than the other conditions, followed by

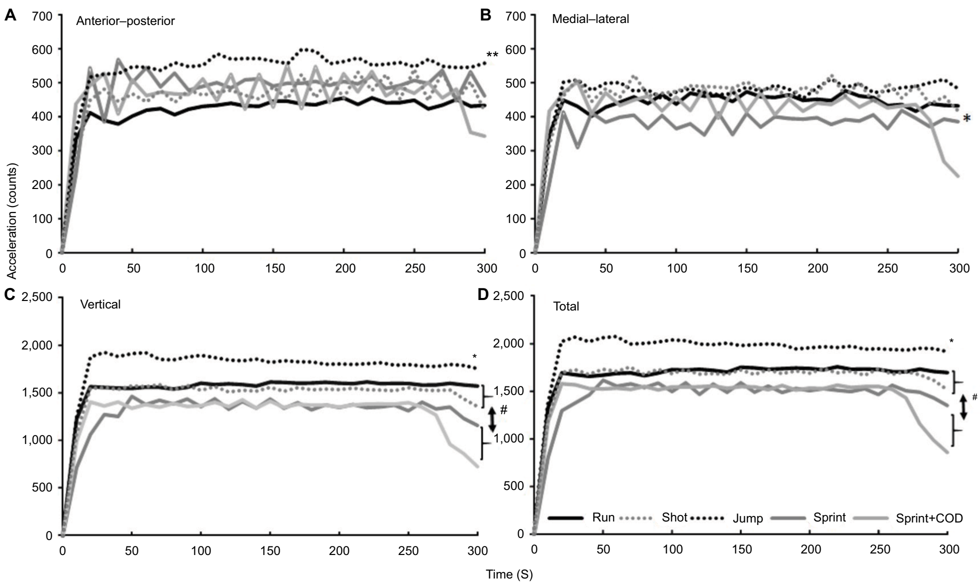

Figure 1 Mean acceleration development over time in anterior–posterior (**A**), medial–lateral (**B**), and vertical (**C**) directions and total amount of acceleration (**D**) per soccer-specific action.

Notes: *Significant difference with all the other soccer-specific actions on a $p<0.05$ level. **Significant difference with all the other soccer-specific actions except sprint on a $p<0.05$ level. #Significant difference between run and shot actions with the two sprint actions on a $p<0.05$ level.

the Shot condition. No significant differences in oxygen uptake during and after the Sprint, Sprint COD and Jump conditions were found (Table 2 and Figure 2). However, the heart rate was only significantly lower when performing the Run condition compared with all other actions (Figure 3).

RPE was significantly different between all the soccer-specific actions, except between Sprint and the Sprint COD (p=0.52) starting from Run–Shot–Jump to Sprint and Sprint COD, which were perceived as the heaviest actions (Table 2).

Discussion

The main objection of this study was to compare the effect of different soccer-specific maximal actions upon physiological and perceptual responses and accelerometer load. The main findings were that the total accelerometer load was lowest in Sprint and Sprint COD conditions, although the physiological (oxygen uptake and heart rate) and perceptual (RPE) responses were highest in the respective conditions. Moreover, we found no differences in physiological response between Sprint, Sprint COD and Jump conditions. The Jump condition experienced lower RPE than Sprint and Sprint COD but achieved the highest accelerometer load.

The ranking order from high to low in RPE between the conditions indicates that Sprint and Sprint COD conditions led to the highest perception of exhaustion, followed by Jump, Shot and Run, in that order. With the exception of the Jump condition, the RPE values correspond to oxygen uptake (throughout and after exercise) and heart rate values. In this investigation, all the five conditions involved moving the same distance (900 m) in the same time (5 minutes). Therefore, approximately the total amount of work completed should be the same for all conditions, except for the jumps in the Jump condition. Not surprisingly, this shows that it is not the work done that explains the rate of perceived exhaustion, but that interval-based activities require higher demands of oxygen uptake and oxygen deficit.[17,28] Soccer involves a number of acyclical changes in activity, each increases the energy demands placed on the athlete even when running speed is low. The oxygen uptake was 23% higher in the Jump condition compared with the Run condition and 30% higher in the

Table 2 Mean ± SD of acceleration load in different directions, heart rate, oxygen uptake, oxygen uptake after exercise and RPE per soccer-specific action ordered (left to right) after RPE results (lowest to highest)

Variables	Run	Shot	Jump	Sprint	Sprint COD
Anterior–posterior (count)	429±155	453±140	532±108**	476±84	457±86
Medial–lateral (count)	440±123	455±108	464±113	369±86*	414±96
Vertical (count)	1521±256[a]	1465±268[a]	1755±228*	1286±210[b]	1265±184[b]
Total acceleration (count)	1657±251[a]	1619±252[a]	1904±213*	1441±204[b]	1423±189[b]
Heart rate (beats/min)	160±15*	170±11	172±9	174±9	174±10
Oxygen uptake (L/min)	2.94±0.35*	3.40±0.40*	3.63±0.31	3.69±0.39	3.73±0.33
Oxygen uptake 5 minutes after exercise (L/min)	1.17±0.12*	1.30±0.18*	1.52±0.20	1.69±0.35	1.46±0.17
$RPE_{6–20}$	10.0±2.6*	12.0±2.4*	14.1±2.3*	16.7±1.0	17±1.8

Notes: *Significant difference with all the other soccer-specific actions on a $p<0.05$ level. **Significant difference with all the other soccer-specific actions except sprint on a $p<0.05$ level. [a]Significant difference with all the other soccer-specific actions except between shot and run action on a $p<0.05$ level. [b]Significant difference with all the other soccer-specific actions except between the two sprint actions on a $p<0.05$ level.
Abbreviations: Sprint COD, Sprint with change of direction; RPE, rating of perceived exhaustion.

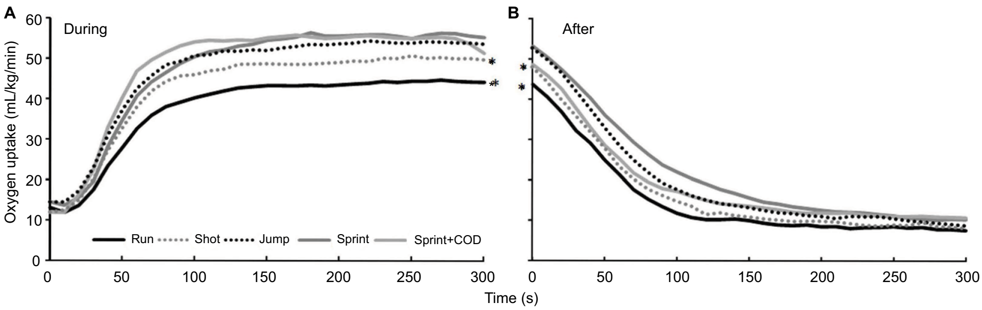

Figure 2 Mean oxygen uptake development over time during (**A**) and after (**B**) each soccer-specific action.
Note: *Significant difference with all the other soccer-specific actions on a $p<0.05$ level.

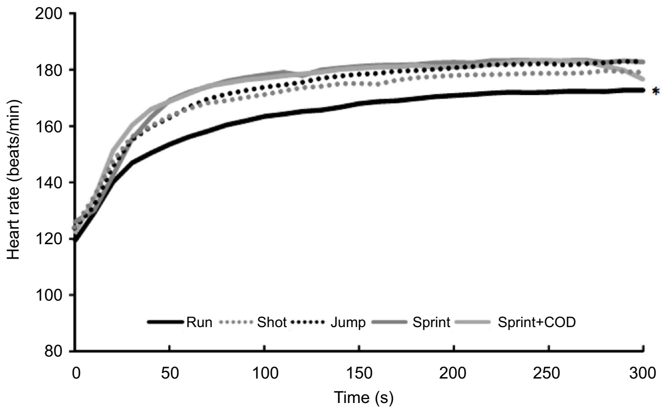

Figure 3 Mean heart rate development over time per soccer-specific action.
Note: *Significant difference with all the other soccer-specific actions on a $p<0.05$ level.

Jump condition than 5 minutes after. In the Jump condition, there was one maximal jump every tenth second, and in total maximal 30 jumps over a 5-minute period. The Jump condition also increases the subjects' mean RPE ($RPE_{6–20}$) from "fairly light" to "hard" compared with the Run condition. In the traditional measurements in team sports of speed and distance (time–motion analysis), jumps would not have been registered because they do not include movement from one location to another. In our study, there are no differences between the Jump, Sprint and Sprint COD conditions in oxygen uptake or heart rate. This indicates that performing 30 jumps costs approximately the same amount of energy as 15 sprints or sprints with COD, while it feels easier to perform than the sprints, as indicated by the lower RPE (Table 1).

Conversely, the Shot condition as a specific maximal action did not result in similar physiological and perceptual responses compared with the other soccer-specific actions. The Shot condition cost more effort than the Run condition, but although the heart rate was similar, oxygen uptake (Figure 2 and Table 1) and RPE were lower than in the Jump and Sprint conditions (Figure 3 and Table 1). This indicates that this type of action did cost less for soccer players even when they had to shoot with maximal effort. A possible reason for this could be that they only shot a total of 15 times, while in the Jump condition, 30 jumps were made. Perhaps by doubling the total number of shots, physiological and perceptual responses could be similar to jumping and sprinting. Moreover, a vertical jump is a countermovement activity with a large eccentric phase during the landing, which is different from a shot movement.

In this study, the total horizontal workload (900 m) and exercise time (5 minutes) was the same for each condition to avoid an effect of this on the responses. In the Jump and Shot conditions, the subjects had approximately the same horizontal velocity as in the Run condition, whereas in the Sprint conditions, the ratio of sprinting compared with jogging was ~1:4. This shows that with these 15 sprints and lower jogging velocity between the sprints, physiological and perceptual responses increased by 26%–28%. This was in accordance with Greig et al who found the RPE and physiological load to be consistently greater during an interval than a steady-state protocol with an equivalent total distance covered.[17]

The order of physiological and perceptual responses of the specific soccer actions from low to high (Run–Shot–Jump–Sprint–Sprint COD) were not similar to those of the acceleration load (Table 1 and Figure 1), indicating that accelerometer loads are not similar to physiological and perceptual responses. Acceleration load (anterior–posterior) was the highest in the Jump condition, indicating that an extra change in direction (vertical) causes extra acceleration loads. This also resulted in a total acceleration load compared to the other conditions. This demonstrates that the vertical component from the accelerometer load seems to be exaggerated compared to the mediolateral and anteroposterior axes. The squared value from medio–lateral and anteroposterior axes is about 10% of the squared value from the vertical axes. Therefore, the difference in accelerometer load is mainly due to a difference in vertical accelerations. This is in line with the results of Sasaki et al who achieved vector magnitude counts/minute (here acceleration load) close to the counts/minute from vertical acceleration.[29]

Another novel finding from this study was that the Sprint and Sprint COD conditions experienced the lowest values from accelerometer load, especially in vertical and mediolateral directions. This can be explained by the fact that, in sprinting, less vertical oscillation occurs than in running.[30] Probably, the same occurs in a mediolateral direction. This causes a lower acceleration load in the Sprint conditions compared with the other conditions. Our results suggest the difficulty in measuring high-velocity activity from accelerometer load. Results from our conditions show that the Run condition has a higher accelerometer load than both the Sprint and Sprint COD conditions, although these conditions have higher measures of oxygen uptake, heart rate and $RPE_{6–20}$. Although accelerometer load is an established measure of physical activity,[31] it is clear from this study that it does not correspond with oxygen uptake in these types of activities. Therefore, one might question if accelerometer load is a valid measurement for energy costs or ratings of perceived exhaustion in types of activity that include high-speed running.[13] However, soccer and other team sports usually have other time–motion analysis systems to investigate running at different intensities, but these systems have a problem with detecting high-intensity actions performed during low-velocity speed.[8] Therefore, accelerometer load data may function as a complementary tool to investigate the player loads during matches and training.[12]

A limitation of our study was that we used a triaxial accelerometer from ActiGraph that has the company's own settings to calculate acceleration load. This calculation was different from other well-known manufacturers in team sport analysis that use triaxial accelerometers (ie, GPSport, Catapult and ZXY Sport Tracking). This makes it difficult to compare the acceleration loads measured in our study with those from these other systems. Furthermore, the accelerometers of ActiGraph have an operating range of 6 g, which underestimate the kinematics during running compared with those that measure with 32 g or higher.[32] With sprinting, this underestimation will be enhanced.[13]

However, examples from soccer show similar to our results that accelerometers underestimate load of high-velocity movements but might be a complementary tool for the measurement of load in low-velocity movements.[12] Dalen et al[12] found that full backs covered 230% and 300% longer high-intensity running and sprint distance (<19.8 and 25.2 km^{-h}) than central defenders and accelerated (>2 m/s^2) and decelerated (< –2 m/s^2) 39% and 55%, respectively, more often than central defenders. In spite of these differences in time–motion analysis data, central full backs had less (accelerometer) player load than central defenders. This finding highlights the potential application of accelerometers to measure player load at low velocities that may be underestimated by other measurement systems.[8,33] Therefore, accelerometers may be a complementary tool for measuring the load from activities misrepresented by time–motion analysis (ie, high-intensity bouts classified as low-speed activities), which, as we know from previous studies, occur several 100 times in a match. In future studies, these systems should be included together with the physiological and perceptual measurements to gain more knowledge about demands caused by fast, discrete and maximal actions in combination with running.

Conclusion

The order of physiological and perceptual responses of the specific soccer actions from low to high (Run–Shot–Jump–Sprint–Sprint COD) were not similar to that of the acceleration load indicating that accelerometer loads are not similar to physiological and perceptual responses. This demonstrates that the vertical component from the accelerometer load seems to be exaggerated compared to the mediolateral and anteroposterior axes. It also questions whether accelerometer load is a valid measurement for energy costs or ratings of perceived exhaustion in types of activity that include high-speed running. However, soccer and other team sports usually have other time–motion analysis systems to investigate running at different intensities, but these systems have a problem with detecting high-intensity actions performed during low-velocity speed. Therefore, accelerometer load data may function as a complementary tool to investigate player loads during matches and training that have previously been misrepresented by time–motion analysis (ie, high-intensity bouts classified as low-speed activities).

Disclosure

The authors report no conflicts of interest in this work.

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RESEARCH ARTICLE

Player load in male elite soccer: Comparisons of patterns between matches and positions

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Abstract

Our primary aim was to explore the development of player load throughout match time (i.e., the pattern) using moving 5-min windows in an elite soccer team and our secondary aim was to compare player load patterns between different positions within the same team. The dataset included domestic home matches (*n* = 34) over three seasons for a Norwegian Elite League team. Player movements (mean ± SD age 25.5 ± 4.2 years, height 183.6 ± 6.6 cm, body mass 78.9 ± 7.4 kg) were recorded at 20 Hz using body-worn sensors. Data for each variable (player load, player load per meter, total distance, accelerations, decelerations, sprint distance, high-intensity running distance) were averaged within positions in each match, converted to z-scores and averaged across all matches, yielding one time series for each variable for each position. Pattern similarity between positions was assessed with cross-correlations. Overall, we observed a distinct pattern in player load throughout match time, which also occurred in the majority of individual matches. The pattern shows peaks at regular intervals (~15 min), each followed by a period of lower load, declining until the next peak. The same pattern was evident in player load per meter. The cross-correlation analyses support the visual evidence, with correlations ranging 0.88–0.97 ($p < .001$) in all position pairs. In contrast, no specific patterns were discernible in total distance, accelerations, decelerations, sprint distance and high-intensity running distance, with cross-correlations ranging 0.65–0.89 ($p < .001$), 0.32–0.64 ($p < .005$), 0.18–0.65 ($p < .005$ in nine position pairs), 0.02–0.38 ($p < .05$ in three pairs) and 0.01–0.52 ($p < .05$ in three pairs), respectively. This study demonstrated similarity in player load patterns between both matches and positions in elite soccer competition, which could indicate a physical "pacing pattern" employed by the team.

Introduction

For optimal performance in team sports like soccer (association football), players are required to maximize their technical, tactical, and physical abilities. The physical demands of soccer matches are characterized by a constant variation between low- (e.g., standing and walking),

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high- (e.g., running), and very high-intensity (e.g., accelerations, decelerations and sprinting) activities [1–3]. Along with additional sport-specific activities (e.g., tackles, turns, headers, dribbles), these locomotor activities constitute the total physical load of a player during training and matches [4]. However, the total physical load of the players is determined by a combination of direct involvement in play, responding to movements of attacking players, tactical restrictions, and willingness to support team-mates [5]. These variations are likely to result in a relatively large match to match variability in physical performance [6, 7].

Time-motion analyses have provided accurate and objective quantification of the players' activities, and therefore improved our understanding of the physical demands in soccer [8–11]. However, measurements of different locomotor classifications or speed zones may be insensitive to the totality of mechanical stresses common to team sports. Tri-axial accelerometers provide complementary information to time-motion analysis for understanding player load during matches and training [12, 13] as they record the acceleration of body movement in three dimensions, which better estimates the players' physical exertion. Therefore, manufacturers of global positioning systems (GPS) and local positioning measurements (LPM) have incorporated high-resolution triaxial accelerometers as a measure of player load. Such analyses are shown useful for validly quantifying the physical demands in soccer [12, 14–16], in which various estimations of player load are regarded as acceptable measures of external load and largely correlated to players' physiological and perceptual responses to training [17, 18]

To date, monitoring external training and match load measures in soccer has tended to rely on results based on locomotor activities. In previous analyses of soccer matches, considerable heterogeneity has been observed in the within-match development of locomotor activities (total distance, HiR, sprint, accelerations and decelerations) throughout match time (i.e., the pattern) across studies [6, 9, 19–25]. Some studies report a reduction in total and high-intensity running (HiR) distances toward the end of each half [9, 26], whereas others do not find such changes [20, 21]. These contradictory results are likely caused by different measurement systems, different tactical elements, opponents' playing style, pacing strategies, score line, and team formation, which would all affect the players' ability to regulate and maintain their physical effort [22]. However, previous studies show high variability in high-speed activities within matches and that individual players show inconsistency in high-speed activity (i.e., HiR and sprinting) across matches [6, 23]. A component of soccer matches that has received relatively less attention is the players' number of accelerations and decelerations [19], although some previous studies suggest that inter- and intra-individual variability is smaller for accelerations compared to distance-related measures [6, 24]. Additionally, a recent study found a continuous reductional pattern in accelerations over the course of a match and after peak working periods of a match, which was consistent across positions [25].

In the existing literature, the within-match player load based on three-dimensional movement analyses has been investigated using a standardised soccer simulation with 15-min standardised activity blocks [27]. Here, the authors found that player load increased over time in each half, likely due to a change in movement strategy and/or a reduced locomotor efficiency [27]. In contrast to this, reductions in player load were identified in the latter stages of each half in the analyses of 86 matches in U-21 English Championship teams [14]. However, in the same 15-min time periods, the player load per total distance covered increased, suggesting an increased loading for every given meter covered on the pitch [14]. These investigations have allowed a general determination of player load patterns during soccer matches and soccer-specific intermittent exercises. However, to understand more in detail how teams and individual players distribute their player load and related locomotor activities throughout soccer matches, the same factors need to be analyzed over shorter time-periods than 15-min blocks. More instantaneous analyses of player load and the corresponding activities during soccer matches would logically show a variable "pacing" influenced by e.g., tactical elements, player position, and the level of the opponents. In order to quantify this across e.g., positions, the similarity of patterns throughout the duration of matches must be analyzed. Long term analyses of such data and the relationships to changes in tactics, different opponents, and match outcome have the potential to provide imperative understanding of how the team and the players in different positions distribute the load (i.e., "pacing strategies") during different types of matches.

Since analyses based on predefined periods cannot provide information about the "real" peaks and valleys in the analysis of patterns throughout a match, moving windows is a potential solution, providing more accurate information about player load and locomotor variables (total distance, acceleration, deceleration, HiR and sprint). Our primary aim was to explore the patterns of player load, as well as locomotor variables for comparison, with analyses from moving 5-min windows in an elite soccer team. Our secondary aim was to compare these patterns between different positions within the same team.

Methods

Participants

The dataset includes domestic home matches (*n* = 34) over three full seasons for a team in the Norwegian Elite League. In one of the seasons, the team participated in the Europe League group stages. All matches were played on a grass surface. Movements of all players (mean ± SD age 25.5 ± 4.2 years, height 183.6 ± 6.6 cm, body mass 78.9 ± 7.4 kg) were observed, and only data from the 39 players completing an entire match were used (*n* = 212: complete match data of players, goalkeepers excluded). The sample included eight central defenders (CD, *n* = 47), six external defenders (ED, *n* = 52), six central midfielders (CM, *n* = 46), 11 external midfielders (EM, *n* = 40), and eight attackers (ATT, *n* = 27). Some players participated in different positions across, but not within, the matches included in the data material. Following an explanation of the procedures, all participants gave verbal and written informed consent to participate in the study. The study was conducted according to the Declaration of Helsinki and has been approved by the Norwegian Social Science Data Services (reference number 468065).

Study design and methodology

This study used a fully automatic sport tracking system to evaluate match performances of professional soccer players at the elite level over three full seasons. Player movement was captured by small, body-worn sensors located at the lumbar region, continuously recording the players' actions. Data were transferred by microwave radio channel to 10 RadioEye™ sensors (ZXY SportTracking, ChyronHego, Trondheim, Norway) mounted in the team's home arena. Player movement was registered at 20 Hz. Accelerations and decelerations were recorded when they reached limits of $2\ m{\cdot}s^{-2}$ and $-2\ m{\cdot}s^{-2}$, respectively, and a HiR category of $>19.8\ km{\cdot}h^{-1}$ and sprint category of $>25.2\ km{\cdot}h^{-1}$ were selected for this study. The thresholds for accelerations, HiR, and sprint were similar to those reported in previous studies [12, 28]. In this study, the player load is calculated as a downscaled (by a factor of 800) value of the sum of the squared, high pass-filtered accelerometer values for the respective axes (X, Y, and Z): $(X^2 + Y^2 + Z^2) / 800$ [12]. Test-retest reliability of the sport tracking system is reported earlier, indicating good reliability [12, 28].

Evaluation of 5-minute periods throughout match time. To construct an analysis capturing the immediate, dynamic nature of a match for all players, mean values were calculated over consecutive (i.e., moving) 5-min periods for player load and player load per meter, as well as time-motion variables (total distance, accelerations, decelerations, sprint distance, HiR distance) for comparison, beginning with the first five minutes of the match [25, 29]. The second 5-min period lasts from the second to the sixth minute, and so on. This method is argued to provide a more accurate representation of the distances covered by players [29]. These 5-min periods were used to investigate patterns of player load and locomotor variables throughout match time. The similarities of patterns were then quantified between positions and patterns were evaluated across variables.

Statistical analysis

All data processing and statistical analysis was performed in Matlab R2019b version 9.7.0.1190202 (Mathworks, Natick, MA, USA). For each match, data for each variable (player load, player load per meter, total distance, accelerations, decelerations, sprint distance, HiR distance) were averaged within positions if there was data from multiple players at the same position, yielding a single time series per variable for each position measured in that match. These data were then converted to z-scores, to facilitate the direct comparison of patterns, disregarding absolute magnitudes. Finally, the z-scores were averaged across all matches for each position, resulting in one time series for each position for each variable. The degree of similarity of patterns between positions was assessed with cross-correlations. For statistical purposes, the break in the time series caused by halftime was disregarded (i.e., the data were treated as continuous for the duration of playing time). Linearity was assessed visually using scatter plots. Cross-correlations were calculated for every position pair for n-1 lags at either side of zero, where $n = 82$, the number of moving 5-min windows in a 90-min match (41 5-min windows in each 45-min half). To best represent the development of player load and time-motion variables across positions throughout match time, the correlation at zero lag (with 95% confidence interval and p-value) is presented. For comparison, maximum correlations and corresponding lags are also reported. A negative lag means that the first time series (player position in table columns) shifts to the left relative to the second time series (player position in table rows). The level of statistical significance was set at $\alpha = .05$. Correlation values were interpreted categorically as trivial (0–0.1), low (0.1–0.3), moderate (0.3–0.5), high (0.5–0.7), very high (0.7–0.9), or nearly perfect (0.9–1) using the scale presented by Hopkins et al. [30].

Results

Overall, we observed a distinct pattern in player load throughout match time (Fig 1, black line). The pattern shows peaks at seemingly regular intervals (~15 min), each followed by a period of lower load, typically declining until the next peak. This pattern was clear in all positions (Fig 1A, colored lines), and could also generally be observed in the majority of individual matches (Fig 2). The cross-correlation analysis (Table 1) supports the visual evidence, indicating very high to nearly perfect correlations (range 0.88–0.95, all $p < .001$) in all position pairs, all having the highest correlation at zero lag. The same pattern was evident for player load per meter, both overall (Fig 1B, black line) and in all positions (Fig 1B, colored lines), with nearly perfect correlation values (range 0.93–0.97, all $p < .001$; Table 1) in all position pairs, all having the highest correlation at zero lag.

For total distance, no distinct pattern throughout match time was evident (Fig 3A, black line). However, the patterns for all positions appear to follow each other reasonably well (Fig 3A, colored lines), which is reflected in high to very high correlation values (range 0.65–0.89, all $p < .001$; Table 1), with all position pairs again having the highest correlation at zero lag.

For accelerations, no specific pattern was evident throughout match time (Fig 3B, black line), but the different positions appear to follow roughly similar patterns (Fig 3B, colored lines). Further, correlation values were moderate to high (range 0.32–0.64, all $p \leq .005$; S1

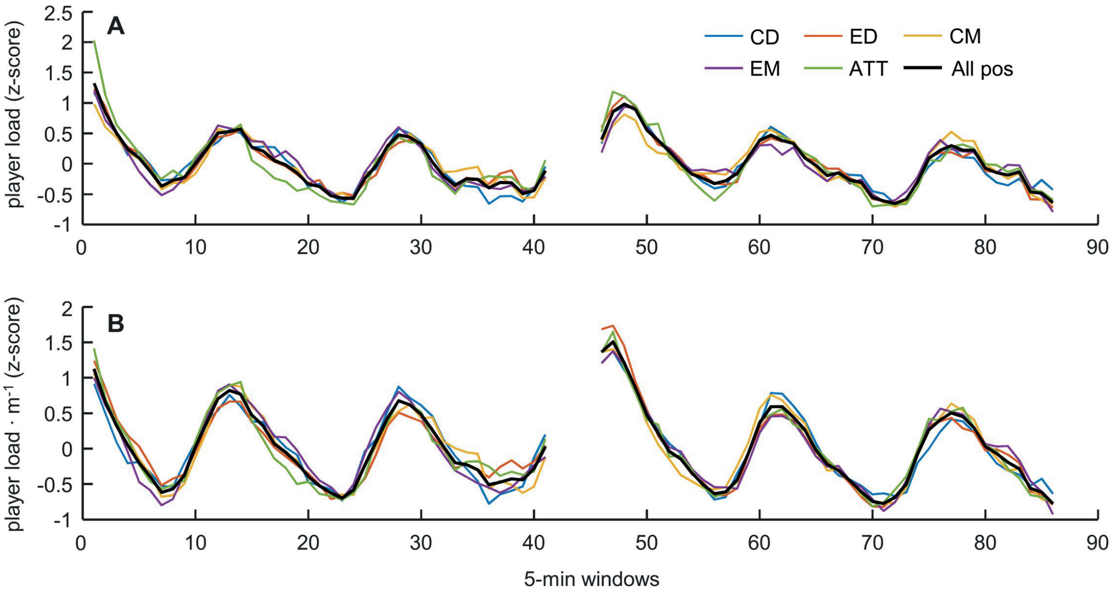

Fig 1. Mean values (z-scores) of player load and player load per meter in 5-min moving windows throughout match time across all matches (*n* = 34) for each position (colored lines) and for all positions combined (black line). A: player load; B: player load per meter.

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Table), with all but one position pair having the highest correlation at zero lag (EM vs. CD highest absolute correlation 0.56, lag -27; S2 Table). For decelerations, again no specific pattern was evident throughout match time (Fig 3C, black line), but the different positions sporadically follow roughly similar patterns (Fig 3C, colored lines). Correlation values were low to high (range 0.18–0.65, all but one $p \leq .005$; S1 Table), with more than half of all position pairs having the highest correlation at zero lag (highest correlation absolute range 0.32–0.65, lag -4–44; S2 Table).

For sprint distance and HiR distance, no specific pattern throughout match time could be discerned in either variable (Fig 3D and 3E, black lines). Further, the patterns for the different positions do not follow each other well (Fig 3 and 3E, colored lines). In line with this, trivial to moderate correlation values were found for sprint distance (absolute range 0.02–0.38, $p < .05$ in three position pairs, two having the highest correlation at zero lag; highest correlation absolute range 0.29–0.53, lag -29–54 [S1 and S2 Tables]), whereas trivial to moderate (one high) correlation values were found for HiR distance (absolute range 0.01–0.52, $p < .05$ in three position pairs, two having the highest correlation at zero lag; highest correlation absolute range 0.32–0.52, lag -28–32 [S1 and S2 Tables]).

Discussion

The primary aim of this study was to explore the patterns of player load with analyses from moving 5-min windows in an elite soccer team. Further, the secondary aim was to compare the player load patterns between different positions within the same team. The main finding was the distinct player load pattern with three "high-load periods" in each half, separated by "lower-load periods". The player load patterns were relatively similar between positions and

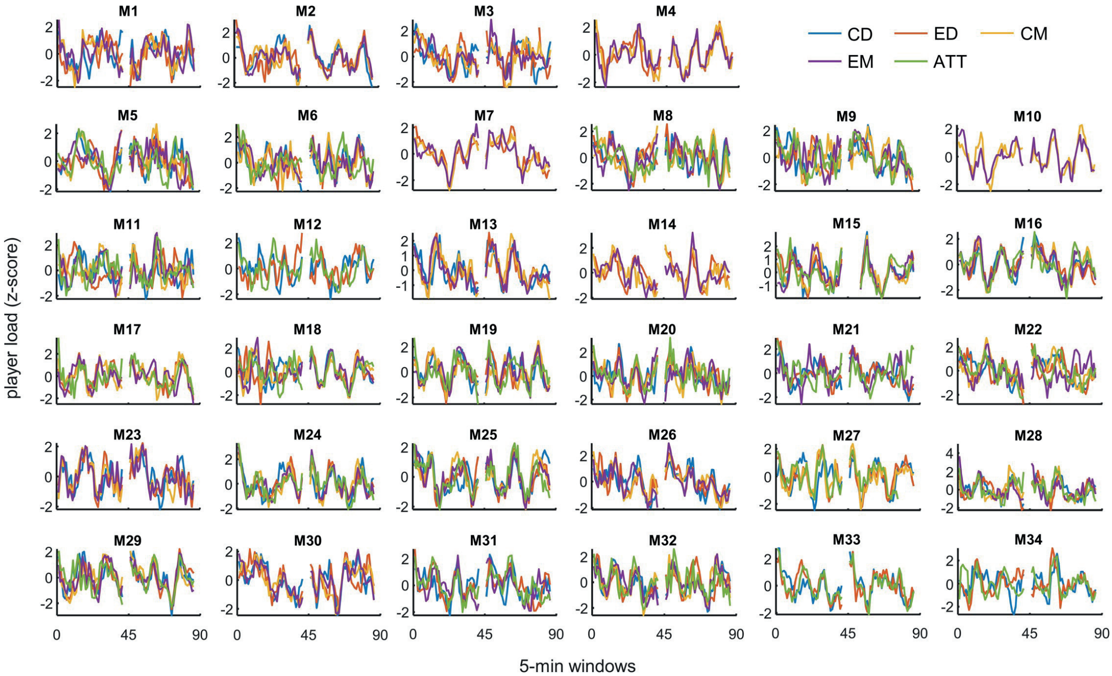

Fig 2. Mean player load (z-scores) in 5-min moving windows throughout match time for all measured positions per match. M: match number.

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occurred at approximately the same time points during the majority of matches. These novel findings will be discussed with two points of departure: the team's pacing strategy from a physical viewpoint and from a perspective based on interpersonal coordination between player positions.

Player load patterns and pacing

The use of 5-min moving averages to analyze within-match player load patterns in this study allowed us to study the players' "pacing strategies" (i.e., distribution of player load and related locomotor activities) in more detail than in previous studies evaluating simulated soccer matches [27] and English championship matches [16] by dissection into 15-min periods. The present results show distinct player load patterns with three "high-load periods" in each half of the match (Fig 1), separated by "lower-load periods", in most of the matches (Fig 2), which differs from patterns found in research on English championship players [16]. Although the new methodology for analyzing player load used in the present study provides novel information about high- and lower-load periods of the soccer matches, these distinct patterns found in almost all matches were rather surprising since differences between the opponents' level and tactics should rationally have influenced player load patterns between matches. In addition, the player load would also largely be determined by the players' decision-making about opportunities to become engaged in play. One likely explanation of this apparent player load pattern is that this study investigated one of the top-ranked clubs in the Norwegian top division at

Table 1. Cross-correlations [95% CI] of mean position values (z-scores) across all matches (*n* = 34) at zero lag for player load, player load per meter, and total distance.

	CD	ED	CM	EM	ATT
Player load					
CD	---				
ED	0.95 [0.92, 0.96]	---			
CM	0.93 [0.89, 0.95]	0.94 [0.91, 0.96]	---		
EM	0.93 [0.89, 0.95]	0.94 [0.91, 0.96]	0.93 [0.90, 0.96]	---	
ATT	0.91 [0.87, 0.94]	0.95 [0.93, 0.97]	0.88 [0.83, 0.92]	0.89 [0.84, 0.93]	---
Player load per meter					
CD	---				
ED	0.93 [0.89, 0.95]	---			
CM	0.95 [0.93, 0.97]	0.95 [0.92, 0.97]	---		
EM	0.95 [0.92, 0.97]	0.94 [0.91, 0.96]	0.95 [0.92, 0.97]	---	
ATT	0.93 [0.90, 0.96]	0.97 [0.96, 0.98]	0.96 [0.94, 0.97]	0.95 [0.92, 0.97]	---
Total distance					
CD	---				
ED	0.88 [0.81, 0.92]	---			
CM	0.80 [0.71, 0.87]	0.84 [0.76, 0.89]	---		
EM	0.89 [0.84, 0.93]	0.87 [0.81, 0.92]	0.86 [0.79, 0.91]	---	
ATT	0.76 [0.65, 0.84]	0.71 [0.59, 0.81]	0.65 [0.51, 0.76]	0.72 [0.59, 0.81]	---

CD = central defender; ED = external defender; CM = central midfielder; EM = external midfielder; ATT = attacker. All correlations $p < .001$. For all correlations, the maximum value occurred at zero lag.

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their home arena, where they had the opportunity to "control the match" in most of the matches. Thus, it seems reasonable to ask whether these similar positional fluctuations in player load are typical for this team at their home arena matches where they normally were the dominant team. Therefore, an interesting approach for future studies would be to investigate these patterns with the same moving average-method in teams at different performance levels (i.e., if the investigated team or the opposition controls the match or in teams with different overall tactical dispositions).

Since locomotor actions in soccer are not performed in isolation, consideration of player load as a proxy for "overall external load" might be useful. A previous investigation of player load found high to very high associations between player load and measures of internal training load (TRIMP and sRPE) [18], with internal load being especially related to the volume of accelerations. Barrett et al. [18] found nearly perfect within-subject correlation between player load and heart rate/VO_2, but trivial to moderate association for the between-subject correlation on the same variable [19]. Overall, this suggests that the fluctuations in player load found in the present study are also associated with fluctuations in internal load, thereby indicating a physical "pacing pattern" (pattern in distribution of load) employed by the investigated team (Fig 1). These "pacing patterns" were relatively similar between positions and occurred at the same time point during the matches (Fig 2), even though the different positions have different roles during attacks and defense; one single attack gives higher intensities on attacking players, but not for the defending players, and vice versa. However, the time scale with 5-min moving averages is too long to differentiate between high-intensity periods based on one single attack or one defensive stand and normally contain several attacking and defensive actions. Moreover, player load patterns based on moving 5-min windows will give more information about

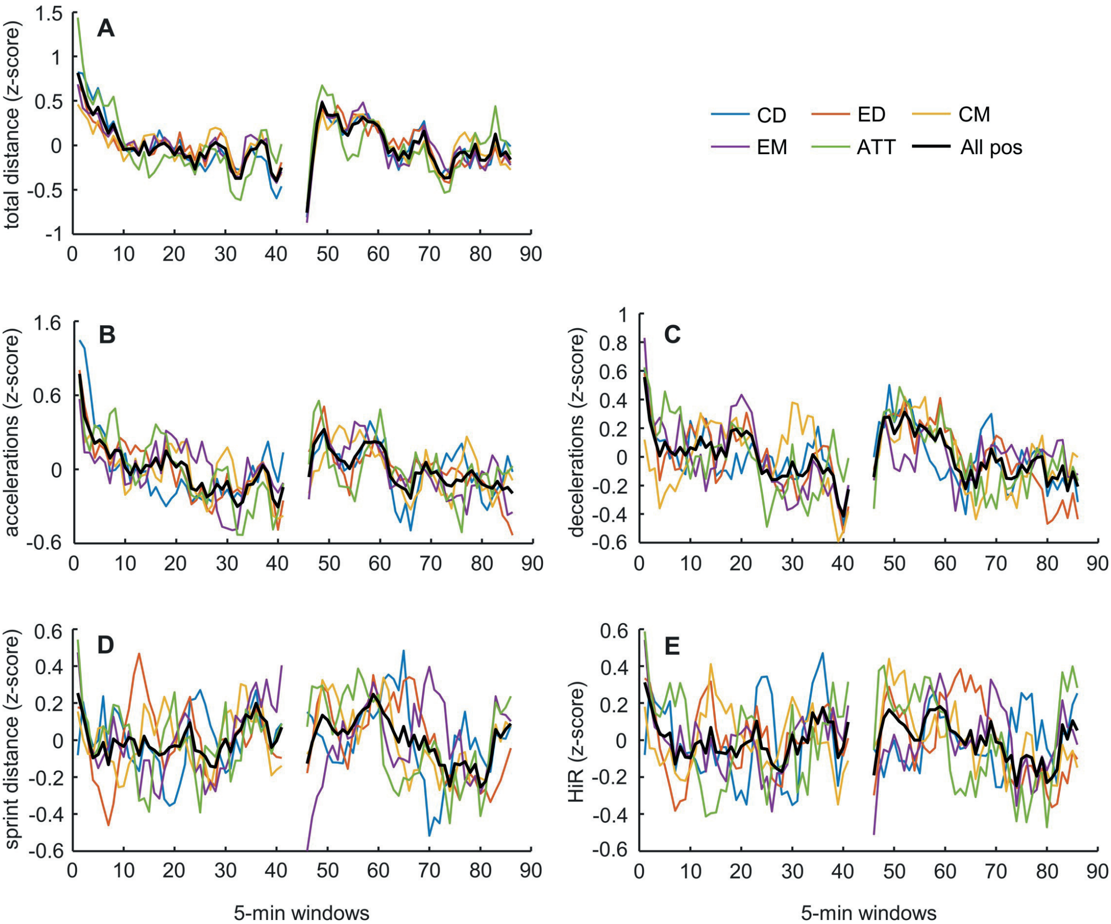

Fig 3. Mean values (z-scores) of time-motion variables in 5-min moving windows throughout match time across all matches (*n* = 34) for each position (colored lines) and for all positions combined (black lines). A: total distance; B: accelerations; C: decelerations; D: sprint distance; E: high-intensity running distance (HiR).

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the overall load of the match, instead of detailed information about when the team is attacking (more load on offensive players) or defending (more load on defensive players).

The present study shows very high to nearly perfect associations between positional patterns of player load and player load per meter (Table 1). Hence, the periods of high player load are associated with movements on the field that increases the player load per meter, which is shown to be associated with unorthodox movements such as jumping, tackling, collisions, passing, accelerations, decelerations etc., movement which are common for soccer and detected when triaxial accelerometers are employed [12, 13]. Although this study found differences in the absolute values of the highest and lowest player load periods in the presented results, there were no positional differences in the pattern of increase and decrease of player load throughout the matches (Fig 1). Thus, the present study is the first to report similarity across playing positions in the player load patterns throughout matches in male elite soccer players. The use of this approach and the findings from this study may contribute to new hypotheses concerning the patterns of player load and intensity throughout a soccer match. Therefore, before one can conceptualize more in-field applications, different aspects of player load patterns should be investigated further.

Whereas other investigations show a considerable heterogeneity in the within-match pattern of total distance, HiR and sprint across studies [9, 20, 21], in this study, total distance was the variable besides player load and player load per meter which displayed the highest correlation between positions, with no lag between positional patterns (Table 1). Regardless of this, the patterns of total distance for the different positions do not follow the same distinct pattern as the player load variables. For accelerations and deceleration, no specific pattern was evident throughout match time (Fig 3B and 3C), but the different positions appear to follow roughly similar patterns with correlations ranging from low to high (S1 Table). For sprint and HiR distance, the present study shows no meaningful similarities between positions, with negligible to moderate cross-correlations (S1 Table). These findings are similar to those from other studies investigating high-intensity patterns [6, 7]. In the present results, the patterns of the different HiR and sprint distance throughout match time show heterogeneity; patterns of sprint and HiR distance show that high-intensity periods occur at different times both between matches and between positions. These differences could be caused by different tactical elements, opponents playing style, pacing strategies, score line, and team formation, which would all affect the players' ability to regulate their physical effort and maintain work rates at appropriate levels [22].

Player load and interpersonal coordination patterns

The observed in-phase pattern for player load in this study is also interesting from perspectives of interpersonal coordination patterns, and it demonstrates that the interaction in player load between the team's subunits probably is more complex than the behavior of each individual player considered separately [31, 32]. Specifically related to soccer, the actions of one player or a player subunit (e.g., attackers, midfielders, defenders) cause re-actions and adjustments from other players or player subunits to stabilize performance, and these adjustments interact and influence player load collectively. The emergence of the synchronized player load patterns between subunits is likely self-organized to improve team performance and is a result of the interactions of a player's constraints and information exchange within their own team and those imposed by the opponent. What type of constraints and information that evolves in spontaneous self-organization and synchronization of player load is not easy to identify, but might be easily understood intuitively. Examples of such constraints in soccer could be other players' positions and movements, position and speed of the ball, tactical decisions, fatigue, etc. According to the rationale by Haken and Portugali [33], if the meaning of a player's action is understood (information exchange), it triggers action and changes the structure or behavior (player load) in the whole team. E.g., the reaction of players on the action of another depends on the success or failure (information) of that action. The interesting finding of the present study is that, even though each action's success or failure may occur randomly, the player load pattern that evolves seems very stable. Thus, the interpersonal patterns of coordination of player load in a soccer team might be modelled as an open complex dynamical system at a behavioral level of analysis, as suggested in evolutionary game theory [34]. Given the stable player load pattern over various matches, even though a soccer match is the complex combination of actions by individuals, no individual player (or subunit) seems to initiate or control the behavior of the match. In other words, each player is enslaved in a self-organized system that at the same time consists of all these same players. This self-organized system could be affected by the fact that this study investigated one of the top-ranked clubs at their home arena, which could have produced a more consistent player load pattern due to typically being the dominant team.

Limitations

Since this study investigated one of the top-ranked clubs at their home arena, it is possible a more consistent player load pattern was produced due to typically being the dominant team. It is unclear to what extent the results will replicate across teams or if they are particular to either the investigated team or e.g., teams sharing certain characteristics. This study did not investigate differences between various tactical elements, opponents' playing styles, ball in versus out of play, score line, or team formations, which could all affect the players' ability to regulate their physical effort and maintain work rate profiles. Differences in measurement technology makes it difficult to compare player load variable between different tracking systems (or even different versions of the same system), since differences in measurement technology could partly account for eventual discrepancies between the values registered in this study and other studies. Hence caution is required when comparing analyses of football match activities across studies.

Conclusion

This study demonstrated similarity in player load patterns between positions in elite soccer matches. The novelty is the clear pattern which consists of three high-load periods in both halves, where these "high load" periods are followed by periods with reduced load. The present study did not find similar unambiguous patterns on any of the locomotor variables. The evident pattern in player load indicates a physical "pacing pattern" employed by the team. These "pacing patterns" were relatively similar between positions and occurred at the same time points during the matches over three successive seasons. From the perspective of interpersonal coordination patterns, these synchronized player load patterns between positions are likely self-organized to improve team performance and are a result of the interactions of the players' constraints and information exchange within their own team and those imposed by the opponents. It should be noted that a more consistent player load pattern might have been produced due to the investigated team being a top-ranked club playing home matches.

Practical applications

Since this study is the first to report this distinct pattern of player load it is important that more studies of player load patterns are conducted, in teams at different performance levels before in-field applications can be firmly conceptualized. Considering the previously reported high association between player load and internal training load, it could be argued that coaches might want to regulate player load in training for an overreaching effect. This could eventually allow for a more aggressive pacing strategy, shortening the lower-load periods and hence putting more pressure on the opposition. However, an approach like this must be cautious against overloading. During matches, coaches can also use the method proposed here in real-time to monitor if certain players or position groups appear to be "out of sync" with the rest of the team.

Supporting information

S1 Table. Cross-correlations [95% CI] of mean position values (z-scores) across all matches (*n* = 34) at zero lag for accelerations, decelerations, sprint distance, and high-intensity

running distance. CD: central defender; ED: external defender; CM: central midfielder; EM: external midfielder; ATT: attacker. For p-values, bold text indicates significance at α = .05.
(DOCX)

S2 Table. Maximum cross-correlations (corresponding lag) of mean position values (z-scores) across all matches (*n* = 34) for accelerations, decelerations, sprint distance, and high-intensity running distance. CD: central defender; ED: external defender; CM: central midfielder; EM: external midfielder; ATT: attacker. A negative lag means that the first time series (player position in table columns) shifts to the left relative to the second time series (player position in table rows).
(DOCX)

S1 Dataset.
(XLSX)

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The overall objective of this thesis was to investigate the physical demands of elite soccer players, with special focus on high-intensity movements and actions. In order to investigate the overall objective, this project wanted to characterize the sprint and acceleration profiles of elite soccer players and investigate whether the number of accelerations constitutes a more precise estimate of match physical performance and performance decline in elite soccer players compared to high-intensity running (HIR) distances, as well as whether small-sided games (SSGs) in training could give a high enough training load for high-intensity movements and actions. Finally, the aim was to obtain knowledge concerning player load using accelerometers and the patterns of player load during matches, and how different soccer-specific high-intensity actions influence physiological, perceptual and accelerometer loads.

This thesis suggest that accelerations may be a more stable and sensitive measure of physical performance decline compared to HIR distance in soccer match play. Time-motion analysis is a useful tool for examining the physiological demands from high-speed activities, but accelerometers may supply information concerning player load from the many discrete actions of a soccer match that may be classified as low-speed activity. Indeed, the present thesis reveals some new factors concerning player load during matches. This thesis also suggests that many high-intensity actions without change in location at the pitch may contribute significantly to player load during matches and training. Player load from accelerometer may function as a complementary tool to investigate player loads during matches and training in addition to other tracking systems. Furthermore, the similarity in player load patterns between both matches and positions in elite soccer competition could indicate a physical "pacing pattern" employed by elite soccer teams. Training with 4 vs. 4 SSGs seems highly valuable to provide the peak demand for accelerations and player load during matches, but neither 4 vs. 4 nor 6 vs. 6 SSGs are close to the HIR or sprint demands during matches.

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