Physical fitness and external load in icehockey and football

An exploration of the relationships between physical test performance and external training and match load in highly trained players

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UiA University of Agder

Doctoral Dissertations at the University of Agder 461

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Preface

This doctoral thesis, along with its corresponding research, attests to the author's academic contributions during the period of employment at the University of Agder (UiA), financially supported by the same institution. However, it is paramount to extend heartfelt appreciation to the individuals and associated partners without whom this project would not have been accomplished.

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Per Thomas Byrkjedal
Kristiansand, December 2023

List of papers

Paper I	Byrkjedal, P. T., Luteberget, L. S., Bjørnsen, T., Ivarsson, A., & Spencer, M. (2022). Simulated game-based ice hockey match design (scrimmage) elicits greater intensity in external load parameters compared with official matches. Frontiers in Sports and Active Living, 4, 25. Doi: 10.3389/fspor.2022.822127
Paper II	Byrkjedal, P. T., Bjørnsen, T., Luteberget, L. S., Lindberg, K., Ivarsson, A., Haukali, E., & Spencer, M. (2022). Association Between Physical Performance Tests and External Load During Scrimmages in Highly Trained Youth Ice Hockey Players. International Journal of Sports Physiology and Performance, 18(1), 47-54. Doi: 10.1123/ijspp.2022-0225.
Paper III	Byrkjedal, P. T., Thunshelle, A., Spencer, M., Luteberget, L. S., Ivarsson, A., Vårvik. F., Lindberg, K., & Bjørnsen, T. (2023). In-season autoregulation of one weekly strength training session maintains physical and external load match performance in professional male football players. Journal of Sports Sciences, 41 (6), 536-546. Doi: 10.1080/02640414.2023.2227536.
Paper IV	Byrkjedal, P. T., Bjørnsen, T., Luteberget, L. S., Ivarsson, A., & Spencer, M. (2024). Assessing the individual relationship between physical test improvements and external load match performance in male professional football players – a case study. *Manuscript accepted in Frontiers in Sports and Active Living 2. April 2024.* Doi: 10.3389/fspor.2024.1367894

Sammendrag (summary in Norwegian)

Monitorering av spillere har blitt en uunnværlig komponent i moderne lagidrett. De mest brukte monitoreringsmetodene inkluderer ofte regelmessig testing av fysisk prestasjon og bruk av monitoreringssystemer, et system bestående av brikker som hver enkelt spiller bruker i trening og kamp. Ettersom brikkene blant annet har en global navigation satelite system (GNSS) -chip i seg, blir slike system typisk referert til som GPS-systemer blant praktikere, på tross av at de består av flere komponenter og måleinstrumenter. I motsetning til testing av fysisk prestasjon, har GPS-systemer dukket opp som en metodikk i det siste tiåret og bidratt til objektiv kvantifisering av ekstern trenings- og kampbelastning både av lag og individuelle spillere. Ekstern trenings- og kampbelastning refererer til den objektive arbeidsmengden utført av spilleren, hvor total-, høyintensitets- og sprint distanse, akselerasjoner, deselerasjoner og «total workload» er noen av de typiske variablene som brukes. Monitoreringsdata kan være et verdifullt verktøy for å forbedre treningspraksis og optimalisere forberedelser til kampsituasjoner. Fysisk testing er ofte tidkrevende og gjennomføres derfor sjeldent i sesong, men begrenses til pre-season eller lignende perioder med lavere kamp-aktivitet, f.eks. landslagspauser. Ettersom GPS-systemer brukes daglig i trening og kamp, har tilhørende data blitt foreslått som mulige markører av spillernes fysiske prestasjonsnivå. Til tross for den utbredte anvendelsen av GPS-systemer, er forskning som undersøker disse sammenhengene mangelfull. Selv om GPS-systemer har blitt vanlig i moderne lagidrett, er det fortsatt manglende innsikt fra innendørsidretter, på grunn av nødvendigheten av GPS-signaler. Teknologisk progresjon har imidlertid utviklet innendørs lokale posisjoneringssystemer (LPS) som tilgjengeliggjør samme type data også fra innendørsidretter. Men forsking som undersøker bruken av disse LPS systemene innendørs er også mangelfull.

Med dagens mangel på vitenskapelig litteratur, ble formålet til denne avhandlingen delt opp i tre hovedmål. For det første ønsket vi å undersøke bruken av LPS og tilhørende ekstern trening og kampbelastningsdata fra ishockeyspillere, samt hvordan kampkrav kunne simuleres under trening. For det andre ønsket vi å utforske forholdet mellom ishockey- og fotballspilleres fysiske testprestasjon og eksterne trenings- og kampbelastningsdata. Til slutt ønsket vi å undersøke om ekstern trenings- og kampbelastningsdata kunne gjenspeile endringer i spillernes fysiske testprestasjon.

Avhandlingen omfatter to separate studier (**studie en** og **to**) og fire artikler (**artikkel I-IV**) for å adressere disse målene. I **studie en** kvantifiserte og beskrev vi eksterne trenings- og kampbelastningskrav innen ishockey og gjennomførte fysisk prestasjonstesting. **Artikkel I** sammenlignet kravene til offisielle kamper med et simulert kampdesign (scrimmage), mens **artikkel II** undersøkte sammenhengen mellom spillernes eksterne belastning under scrimmage og resultater fra typiske fysiske tester for ishockeyspillere. **Studie to** involverte en intervensjonsperiode med styrketrening for å forbedre spillernes fysiske testprestasjon og undersøke om eksterne kampbelastningsdata kunne gjenspeile endringer i fysisk testprestasjon etter en slik treningsperiode. **Artikkel III** undersøkte effektene av styrketreningen, mens **artikkel IV** utforsket om ekstern kampbelastning kunne gjenspeile endringer i spillernes fysiske testprestasjon post-inngrep.

Studie en involverte 50 høyt trente mannlige junior-spillere fra ishockey. Ekstern kampbelastning ble monitorert i åtte hjemmekamper, og fire scrimmager ble spilt for å sammenligne kravene mellom de to spilleforholdene. Scrimmage-ene ble standardisert med 3 x 20 minutters perioder, med et kontinuerlig spilldesign, der spillerne utførte 20 x 1-minutters bytter med 2 minutters hvile mellom hvert bytte. I tillegg ble fysisk prestasjonstesting gjennomført i samme periode som scrimmage-ene ble spilt. I **studie to** deltok 30 høyt trente profesjonelle fotballspillere i en 10-ukers styrketreningsintervensjon i løpet av sesongen, der vi vurderte effektene av to forskjellige auto-regulerte treningsregimer (objektiv versus subjektiv regulering av styrketreningsvolum). Målinger av ekstern kampbelastning ble inkludert fra fem kamper i henholdsvis begynnelsen (baseline-periode) og slutten (oppfølgingsperiode) av denne studie-perioden.

Resultatene fra **artikkel I** indikerte at total distanse var lik mellom offisielle kamper og scrimmage-ene. Imidlertid, ettersom scrimmage-ene ble spilt med et kontinuerlig spill-design, ble høyere relativ distanse (meter per minutt) og mer distanse innenfor sonene for høyintensitet og sprint-fart observert under disse, sammenlignet med offisielle kamper. Når man sammenlignet spillernes fysiske testprestasjon med ekstern belastning under scrimmage-ene i **artikkel II**, ble det kun observert et begrenset antall troverdige sammenhenger (8 av 144). Denne knappheten på identifiserte sammenhenger vedvarte når man utforsket forbindelsene mellom fysisk testprestasjon og ekstern kampbelastning i fotball (data er inkludert i avhandlingen, men ikke i respektive artikler). Under styrketreningsintervensjonen i **studie to** gjennomførte begge gruppene tilsvarende styrketreningsvolum, med omtrent én økt per uke med omtrent seks sett i øvelser relatert til underekstremitetene per økt. Ingen signifikante forskjeller ble observert innad eller mellom de to intervensjonsgruppene før og/eller etter intervensjonsperioden i **artikkel III**. **Artikkel IV** identifiserte tre av åtte spillere med meningsfulle forbedringer i fysisk testprestasjon etter intervensjonsperioden. Imidlertid ble disse forbedringene ikke gjenspeilet ved vurdering av endringene i ekstern kampbelastning.

For å konkludere, så understreker denne avhandlingen de komplekse sammenhengene mellom fysisk testprestasjon og ekstern trenings- og kampbelastningsdata hos mannlige ungdomsishockeyspillere og profesjonelle fotballspillere. Selv om det ble funnet noen sammenhenger mellom fysisk testprestasjon og ekstern belastning i variabler fra scrimmage og fotballkamper, var det totale antallet meningsfulle sammenhenger begrenset. Våre data antyder at fysisk testprestasjon kanskje ikke blir nøyaktig gjenspeilet i eksterne trenings- og kampbelastningsdata fra monitoreringssystemer. Med de begrensede sammenhengene mellom fysisk testprestasjon og ekstern belastningsdata, var fraværet av sammenhenger mellom endringer innenfor de samme målingene forventet. Det er avgjørende å merke seg at fraværet av sammenhenger mellom disse målingene ikke skal undergrave betydningen av fysisk prestasjonstesting eller ekstern trenings- og kampbelastningsdata i seg selv. Disse målingene og dataene kan fortsatt gi verdifull innsikt og bidra til å forbedre spillernes prestasjoner og legge til rette for deres utvikling.

Summary

Player monitoring has become an indispensable part of team sports. Modern day player monitoring typically includes regular physical performance testing and utilization of wearable tacking systems. Contrasting to physical performance testing, wearable tracking systems have emerged over the latest two decades, assisting in objectively quantifying the external training and match load at both the team- and individual player level. External training and match load refers to the objective work completed by the player, with total-, high- and sprint intensity running distance/efforts, accelerations, decelerations and "overall workload" being some of the typical variables reported. Monitoring data can assist as valuable tools to enhance training practices and optimize competitive performance preparations. With the inconvenience of performing physical performance testing during the competitive periods, such testing is typically limited to the pre-season or similar periods, such as international breaks, with lower match activity. With external training and match load data being monitored on a daily basis, the associated data has been suggested as a potential marker of players fitness. Despite the wide application of wearable tracking systems, research investigating the relationships between physical fitness and measures of external load remains scarce. While wearable tracking systems have been more commonly used, research has been focused on outdoor field sports, due to the necessity of global navigation satellite system (GNSS) signals. However, recent technological development has made indoor local positioning systems (LPS) available, albeit with a comparable scarcity of research investigating its application in indoor sports.

With the current gaps in the scientific literature, the purpose of this thesis consisted of three main objectives. Firstly, we aimed to investigate the use of external load tracking systems in ice-hockey players and how match demands could be simulated in training. Secondly, we wanted to explore the relationships between team sport players' physical test performance and external training and match load data. Lastly, we wanted to investigate whether external training and match load data could be reflective of changes in players' physical test performance.

The thesis comprises two distinct studies (**study one** and **two**) and four papers (**paper I-IV**) to address these objectives. In **study one**, we quantified and described external training and match load demands in ice-hockey and performed

physical performance testing. **Paper I** compared the demands of official match play to a simulated match design (scrimmage), while **paper II** assessed the association between players' external scrimmage load and physical test performance results in typical ice-hockey tests. **Study two** involved a strength intervention period to improve players' physical test performance and examine if external match load data could reflect changes in physical test performance following such training period. **Paper III** investigated the effects of the strength intervention, while the **paper IV** explored whether external match load could reflect players' changes in physical test performance post-intervention.

Study one involved 50 highly trained male youth ice-hockey players. External match load demands were monitored from eight competitive home matches, and four scrimmages were played to compare demands between the two playing conditions. Scrimmages were standardized with 3 x 20 min periods, employing a non-stop play design where players executed 20 x 1-min shifts with 2 min rest intervals. Additionally, physical performance testing was conducted in proximity to the scrimmages. In **study two**, 30 highly trained professional football players participated in a 10-week in-season strength intervention period where we assessed the effects of two different autoregulated training regimes (objective vs subjective regulation of strength training volume). Measures of external match load were included from five respective matches at the beginning (baseline period) and end (follow-up period) of this period.

Our results from **paper I** indicated that total distance covered was similar between official match play and scrimmages. However, scrimmages, with their continuous play design, exhibited a higher relative distance (distance per minute) and more distance in high- and sprint skating speed thresholds compared to official matches. When comparing players' physical test performance to external scrimmage load in **paper II**, only a limited number (8 of 144) of credible associations were observed. This scarcity of associations persisted when exploring the connections between physical test performance and external match load in football (data included in the thesis but not in respective the papers). During the strength intervention in **study two**, both groups performed similar strength training volumes, with approximately one session per week comprising approximately six sets of leg extensor exercises per session. No significant differences were observed within or between the two intervention groups pre- and post-test in **paper III**. **Paper IV** identified three of eight players with meaningful improvements in physical test performance following the intervention. However, these improvements were not reflected when assessing the changes in external match load data.

In conclusion, this thesis underscores the intricate relationships between physical test performance and external training and match load data in male youth ice-hockey and professional football players. While some associations were found between physical test performance and external scrimmage and match load variables, the overall number of meaningful associations was limited. The data suggests that physical test performance may not be accurately reflected in external training and match load data. With the limited associations between physical test performance and external load data, the lack of associations between changes within the same measures was expected. It is crucial to note that the absence of relationships between these measures should not diminish the importance of physical performance testing or external training and match load data. These measures and data can still offer valuable insights and contribute to enhancing players' performance and facilitating their development.

Abbreviations

Au	Arbitrary units
BF	Bayes factor
Cm	Centimeter
CMJ	Counter movement jump
Covid-19	Coronavirus disease 2019
CV	Coefficient of variation
ES	Effect size
FIFA	Fédération Internationale de Football Association
GNSS	Global navigation satellite system
GPS	Global positioning system
HIEs	High intensity events
HighSS	High speed skating (17.0-23.9 km/h)
HIR	High intensity running (>19.8 km/h)
HSR	High speed running (19.8-25.2 km/h)
Hz	Hertz
IMU	Inertial measurement unit
SlowSS	Slow speed skating (0.0-10.9 km/h)
LPS	Local positioning system
M	Meters
m/s	Meters per second
min	minute
ModSS	Moderate speed skating (11.0-16.9 km/h)
N	Newtons
NAP	Non-overlap of all pairs
NFL	National hockey league
Nr	Number
PL	PlayerLoad™
SD	Standard deviation
SPR	Sprint running (>25.2 km/h)
SprSS	Sprint speed skating (>24.0 km/h)
SWD	Smallest worthwhile difference
TE	Typical error
W	Watt
%TE	Relative typical error

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Thesis at a glance

Table 1: Thesis at a glance

	Aim	Design (timeframe)	N	Finding
Paper I – Study one	Describe competitive ice-hockey demands and how a simulated ice-hockey match design reflects competitive external load match demands	Cross sectional *Q3-4 2020*	25	Male youth ice-hockey players cover the same distance as superior ranked players, however with lower distance in the highest locomotive intensity sones. A simulated match design (scrimmage) provoked a higher relative intensity in external scrimmage load demands, likely explained by the applied non-stop playing design.
Paper II – Study one	Explore the associations between physical performance test and external scrimmage load data in youth male ice-hockey players	Cross sectional *Q3-4 2020*	14	A low number of external load variables from scrimmages were associated to physical performance test-results, indicating that isolated physical performance tests may not be reflected in external scrimmage load data. In addition, external load as a marker of match performance should be further assessed.
Paper III – Study two	Explore the effects of two different autoregulated strength training regimes on physical test performance and external match load data after a 10-week strength intervention period	Experimental *Q2-4 2021*	16	Regulating strength training volume based on HIR distance running performance did not differentiate from letting players self-select their training volume during an in-season intervention period. A similar strength training volume was observed between the groups, and the findings indicate that both groups maintained their physical test performance and external match load data during the intervention period.
Paper IV – Study two	Explore if a meaningful improvement in physical test performance can be reflected in external match load data	Case study *Q2-4 2021*	8	Three players were categorized with meaningful improvement in physical test performance after an intervention period. However, these improvements were not reflected in changes in external load match performance. There's a necessity of more knowledge if improvements in physical test performance can be reflected in external training and match load data and importantly, if such changes translate into improved sport specific performance.

1 Introduction

Player monitoring has evolved into an indispensable component in modern team sports (Bourdon et al., 2017; Miguel et al., 2021). Monitoring players' training and match load is a critical aspect of developing an effective training program (Dolci et al., 2020), which can enhance player development (Dolci et al., 2020; Impellizzeri et al., 2023) and performance (Jaspers et al., 2017) while minimizing the risk of injuries (Boullosa et al., 2020; Impellizzeri et al., 2023; Jaspers et al., 2017; Kalkhoven et al., 2021; Torres-Ronda et al., 2022). Typically, team sports player monitoring of load is categorized into two domains: internal and external load (Impellizzeri et al., 2023). While external load pertains to the work completed by players, measured independently of their internal characteristics, internal load entails the physiological stress imposed on players in response to the training stimulus (Impellizzeri et al., 2023; Rice et al., 2022; Scott et al., 2013; Wallace et al., 2009). While external load may be seen as a measure for all external training (e.g., strength training/kg lifted), external load within the context of field-based team sports, typically evolve around their on-field activities. External load player monitoring has the potential to provide coaches and practitioners with a comprehensive understanding of the training and match loads imposed on the players (Barker-Ruchti et al., 2021; Douglas & Kennedy, 2019; Ravé et al., 2020). Consequently, this aids in developing individualized training programs that are optimal in terms of intensity, volume, and duration for each individual player (Cardinale & Varley, 2017; Theodoropoulos et al., 2020). By monitoring external load, coaches can quantitatively assess the total work completed by the player, which may include distance covered, speed, number of sprints, efforts, and other relevant variables (Douglas & Kennedy, 2019; Theodoropoulos et al., 2020; Torres-Ronda et al., 2022).

The increased availability of wearable tracking systems has brought significant advancements in the domain of team sport player monitoring, benefitting researchers and practitioners alike, due to its potential for low effort quantification of external load (Barker-Ruchti et al., 2021; Theodoropoulos et al., 2020). In recent times, the monitoring of external training and match load has gained immense popularity, primarily due to the emergence of such systems (Luteberget & Gilgien, 2020). Specifically, wearable tracking systems include a number of devices which are worn by the players. These devices are typically equipped with a global navigation satellite system (GNSS) sensor, and an inertial measurement unit (IMU) that facilitates the detection and categorization of players movements and actions with minimal effort by practitioners (Theodoropoulos et al., 2020). Until recently, the application of such systems has been constrained to outdoor field sports owing to the reliance of GNSS signals. The current application and research on data derived from wearable tracking systems has therefore been focused on field sports such as football. The advent of local positioning systems (LPS) and IMUs has circumvented this limitation and has enabled a more specific quantification of external training an match load in indoor sports such as handball (Luteberget & Spencer, 2017), basketball (García et al., 2020), and ice-hockey (Douglas & Kennedy, 2019). However, the research pertaining to external training and match load in indoor conditions remains relatively scarce. An interesting distinction for ice-hockey is the obvious difference in physiological attributes in skating vs running (Neeld, 2018; Vigh-Larsen & Mohr, 2022). This underscores the necessity for increased understanding of the application of external load data from on-ice training and match situations (Huard Pelletier et al., 2021; Perez, Brocherie, et al., 2022).

Accurately quantifying match demands within a team and individual position-specific level, can facilitate the development of individualized training programs to prepare for match performance (Sarmento et al., 2018; Torres-Ronda et al., 2022). For example, it has been shown that football players cover 10-20% of their total distance in high-intensity zones (Bradley & Ade, 2018). Notably, in ice-hockey, ~50% of total distance is observed coved within similar zones (Douglas & Kennedy, 2019; Lignell et al., 2018; Vigh-Larsen, Ermidis, et al., 2020). Unlike football, is there's no limit to the number of interchanges in ice-hockey, and changes are typically performed every ~1 minute, with players' average playing time varying from 15-25 minutes, depending on their position and skill level (Vigh-Larsen & Mohr, 2022). On average, ice-hockey players register 5-7 high-intensity actions during typical 1-minute shifts (Wagner et al., 2021). In contrast, high-intensity actions occur less frequently in football, with approximately 2-2.5 actions per minute (Wiig et al., 2019). Notable, such high-intensity actions have been observed in relation to goal-scoring opportunities within both sports and may therefore be seen as influential for the match outcome (Huard Pelletier et al., 2021; Schulze et al., 2022). Wearable tracking data can therefore be seen as a useful tool to quantify these demands, rather than postulating the players efforts, and prepare towards competitive demands accordingly.

Physical performance and well developed physical fitness is in general highlighted as a central component within both ice-hockey and football (Burr et al., 2008; Dolci et al., 2020; Modric et al., 2021; Vigh-Larsen & Mohr, 2022). However, research investigating the relationships between players physical fitness and sport specific demands seems limited. Football-specific training and match activity has been suggested to impact measures of physical performance (Jaspers et al., 2017), and the literature features a plethora of descriptive research focused on physical performance markers and the relationships with various performance markers across different competitive levels (Clemente et al., 2019; Fox et al., 2018; Huard Pelletier et al., 2021; Rice et al., 2022). With the daily monitoring of players physical efforts during training and matches, research has discussed external training and match load data as potential indicators of players fluctuations in physical fitness (Fox et al., 2018; Jaspers et al., 2017). However, the relationships between external load variables and measures of physical performance seems unexplored.

Assessments of physical fitness are typically conducted several times during the season, particularly in relation to periods emphasizing strength and conditioning, such as pre-season training or training interventions (Haugen et al., 2021; Rice et al., 2022; Rønnestad et al., 2011). These periods have been shown to result in improvements in sprint performance, jumping abilities, and one-repetition maximum (1RM) strength (Rønnestad et al., 2011). Theoretically, players who are faster and more explosive are subject to greater external force (Suchomel et al., 2016). Thus, if a player increases his max acceleration or sprint abilities following such training periods, its reasonably to hypothesize that this will be expressed in relatable external training and match load variables. Moreover, although enhancements in physical performance capabilities are assumed to correspond with improvements in sport-specific skills (Suchomel et al., 2016), the methods for evaluating performance improvements remain confined to conventional measures of physical performance (Gabbett et al., 2017; Rice et al., 2022). Comparable to cross-sectional assessments, research examining the longitudinal changes in physical performance and changes in external match load is lacking (Huard Pelletier et al., 2021; Rice et al., 2022)

1.1 Aim of thesis

The overall aim of the thesis was to explore if physical test performance is related to measures of external training and match load derived from tracking systems. To explore this aim, the project was divided into two separate studies. With limited knowledge of external training and match load demands, and application LPS in indoor conditions, **study one** aimed to provide novel insight into external load demands of junior/academy players from a Norwegian ice-hockey club. Thereafter, the external training and match load was compared and assessed in relation to players physical test performance.

In contrast to ice-hockey, a large body of research literature exist on external load monitoring within a football-context. However, very little is known regarding the relationships between longitudinal changes in external load variables obtained during training and matches, and changes in physical test performance. Thus, the aim of **study two** was to explore the relationship between physical test performance and external match load data, and if a change in physical test performance could be related to football players external match load data.

The overall research questions that have guided the present work and research project are:

- What is the external match load demands in ice-hockey, and can these demands be replicated in a simulated match design (scrimmage)?
- What is the association between physical test performance and measures of external training and match load in ice-hockey and football?
- If players improve their physical test performance, will these changes be reflected in external match load data for professional football players?

2 Background

2.1 External load player monitoring

Monitoring of players external match load has been performed since the 1970s, initially performed as a manual time-consuming process (Carling et al., 2008). In the early 2000's semiautomatic video systems became common, however limited to wealthy and elite organizations. With recent technological advancements, monitoring technology has now become widely applied across several competitive levels in various sports and applied in both match and training situations (Luteberget & Gilgien, 2020; Otero-Saborido et al., 2021; Whitehead et al., 2018). While video-based time motion analysis still exists, especially applied in competitive matches at the top-levels, the application of wearable tracking systems is becoming more common. Contrasting to video-based systems, wearable tracking systems typically includes an IMU, consisting of an accelerometer, magnetometer, and gyroscope (Luteberget & Spencer, 2017), allowing them to quantify short explosive actions such as jumps/vertical force, tackles, and other impacts not quantifiable by video or GNSS-signals (Dolci et al., 2020).

Video-based systems require a fixed installation, making them challenging to transfer between training and match grounds, home or away. In contrast, wearable tracking systems are portable and can be used everywhere. In football, the use of wearable tracking systems was not permitted in competitive matches prior to 2015 (FIFA, 2015; Pettersen et al., 2018). Since then, the application and number of studies involving wearable tracking systems have significantly increased (Luteberget & Gilgien, 2020). Technological advancements in recent years have led to the development of LPS. Thus, the need for GNSS signals has been overcome by LPS being applied in indoor conditions or locations with weak GNSS signals, such as large stadiums. However, like video-based systems, LPS also necessitates the installation of equipment around the playing surface by installing a set of nodes above the playing surface to create a local satellite network, allowing for access to the same type of data as traditional GNSS tracking systems.

In football, a large body of research has been published on the use of time-motion analysis, with an explosive increase seen in recent years due to the application of wearable tracking systems. Conversely, limited research has been conducted under similar conditions in ice-hockey. However, publications involving IMU or LPS devices are increasing (Huard Pelletier et al., 2021). While time-motion analysis has allowed for the individualized quantification of various aspects of match demands, wearable tracking systems have provided the ability to individually monitor each player in both training and matches, facilitating individual training prescriptions and follow-up (Theodoropoulos et al., 2020). Traditionally, team sport players have completed the same type and amount of training, with some modifications for position-specific groups. However, with wearable tracking systems, baseline data and reference points during training and matches can be established for a player's typical values, making it possible to observe the typical variations for a particular player, detect any abnormal values, and make individual adjustments if necessary. Additionally, if a player is injured, the individual profile of that player can be used when programming a return-to-play training program, rather than relying on general recommendations or previous experiences, potentially not relevant for the specific player (Torres-Ronda et al., 2022).

2.1.1 Player monitoring data variables

Wearable tracking systems can provide valuable insights into players physical activity levels and performance. However, they also generate vast amounts of data that can be overwhelming and difficult to manage (Barker-Ruchti et al., 2021). One of the main challenges from these systems is the selection of which variables to apply, as there are hundreds of potential variables derived from numerous metrics, sub-metrics and algorithms (Barker-Ruchti et al., 2021; Miguel et al., 2021). With so much information available, it can be challenging to identify patterns and trends that are relevant to the coaches' goals or objectives. This can result in a situation where one becomes overwhelmed by the data and is unable to take any meaningful action based on the insights provided (Barker-Ruchti et al., 2021). As such, managing data overload from wearable tracking devices requires careful consideration to which variables to apply (Barker-Ruchti et al., 2021), the context of which these are meaningful (Impellizzeri et al., 2023), as well as the need for effective data analysis techniques to extract actionable insights (Barker-Ruchti et al., 2021; Buchheit & Simpson, 2017; Miguel et al., 2021; Ravé et al., 2020).

For example, practitioners from 41 top-level football-clubs reported the application of 56 different variables (including internal load variables) utilized in player monitoring (Akenhead & Nassis, 2016). However, the high number of individual measures may stem from a variation in variable specific thresholds. For instance, among the top 10 applied variables to assess physical match performance, are five of these are related to distances within different running speed categories (>5.5, >5.8, >6.7, >7.0 and >7.5 m/s). Accordingly, the most applied measures seem to be total distance, followed by distance in zones (e.g., sprint and high running distance) and measures of accelerations and decelerations (Akenhead & Nassis, 2016; Miguel et al., 2021). On average, 7 ± 2 variables were used to evaluate training sessions, while 3 ± 2 were used when evaluating match performance (Akenhead & Nassis, 2016). In general, there's a plethora of variables applied in the current literature (Miguel et al., 2021). Practitioners are therefore recommended to restrain their number of variables when analyzing external training and match load data, an thoroughly assess their specific relevance (Barker-Ruchti et al., 2021). The findings reported by Akenhead and Nassis suggest that practitioners indeed comply with these recommendations (Akenhead & Nassis, 2016).

In ice-hockey, wearable tracking systems are becoming increasingly prevalent. However, the amount of research including external load measures is scarce (Huard Pelletier et al., 2021). Nevertheless, similarities to football are seen in the current publications and total distance, distance covered within different speed zones, acceleration variables and a measure of "load" seem to be reported across studies (Douglas & Kennedy, 2019; Miguel et al., 2021; Perez, Brocherie, et al., 2022; Vigh-Larsen & Mohr, 2022).

The lack of uniformity in player monitoring variables is a major challenge and makes it difficult to compare and interpret data generated from different manufactures and systems (Barker-Ruchti et al., 2021; Buchheit & Simpson, 2017). This inconsistency can stem from several factors, including differences in the selection of specific variable-metrics (Barker-Ruchti et al., 2021), the algorithms and software used to filter the data (Malone et al., 2017), and the thresholds used to define different zones, such as speed or acceleration (Bastida Castillo et al., 2018; Bastida-Castillo et al., 2019; Malone et al., 2017; Rico-González et al., 2019). Total distance is an absolute and uniform metric and is typically the most reported player monitoring variable (Akenhead & Nassis, 2016; Malone et al., 2017). While it may reflect upon an overall workload, the importance of this variable is vague (Torres-Ronda et al., 2022; Whitehead et al., 2018). Therefore, increased focus is placed on variables related to distance covered across different speed zones, such as high- or sprint running distances (Dello Iacono et al., 2023). While several different thresholds have been applied previously, a vast majority of today's research apply 19.8 km/h (5.5 m/s) and 25.2 (7.0 m/s) as thresholds for high speed and sprint running distance, respectively (Akenhead & Nassis, 2016; Beato, Drust, et al., 2021; Dello Iacono et al., 2023; Miguel et al., 2021).

With regards to IMU-derived data, the most applied variables are acceleration, deceleration, change of direction, and a measure of instant or accumulated workload (Cardinale & Varley, 2017; Malone et al., 2017). These workload variables are typically manufactural-specific, which limits the comparativeness between systems (Malone et al., 2017). One of the more commonly applied workload variables is PlayerLoad™ from Catapult sports (Fox et al., 2018; Gómez-Carmona et al., 2020). PlayerLoad™ uses the square root of the sum of the squared instantaneous rate of change in acceleration in the x, y, and z axes divided by 100 and is presented in arbitrary units (Boyd et al., 2011). While GNSS-based variables are reliant on the quality of the satellite signal, these load variables are calculated purely from accelerometer data and can therefore be collected indoors or in areas with poor signal quality. Research that has used PlayerLoad™ to quantify external load during training has found it to have a strong relationship with total distance covered (Boyd et al., 2013). It was earlier suggested that practitioners could use PlayerLoad™ as a surrogate variable for of total distance when GNSS signals is not available (i.e., indoors) (Polglaze et al., 2015). However, with the current developments, LPS is a more feasible and valid method for quantifying distance based variables (Douglas & Kennedy, 2019).

Studies have explored the reliability of different data-variables, such as accumulated distance in different speed-zones (Buchheit et al., 2014; Linke et al., 2018), accelerations (Buchheit et al., 2014; Linke et al., 2018; Luteberget et al., 2017), and workload variables such as PlayerLoad™ (Barrett, 2017; Luteberget et al., 2017). However, with numerous manufactures, models, software's and variable thresholds, a generalization is challenging. Likewise, the plethora of available variables, metrics, and sub-categorizations (such as thresholds and zones) does not make it easier. Furthermore, differences in data filtering and smoothening methods makes the comparison of potential equal variables challenging. There's also gap in the literature on the many available variables within each tracking system which makes their application challenging. Additionally, when dividing variables into new categories or zones based on thresholds, an observed tendency suggest that sub-categories tend to be less reliable than more general categories (Luteberget et al., 2017). Lastly, the use of more general categorizes cannot withstand the fact that higher intensity and more complex movements (such as match play) induces poorer reliability (Ali, 2011; Luteberget et al., 2017).

2.1.2 Match demands

The overarching objective of player monitoring, training, and testing is to prepare and optimize athletic performance for competitive match play (Bradley & Ade, 2018; Llana et al., 2022). Competitive demands serve as the primary determinant for designing training programs and preparing players for competition (Miguel et al., 2021). Studies have demonstrated that football players typically cover a greater distance than their ice-hockey counterparts, ranging from 9-14 km compared to 4-7 km, respectively (Dolci et al., 2020; Douglas & Kennedy, 2019; Lignell et al., 2018; Vigh-Larsen & Mohr, 2022). Total distance covered during match play appears to remain constant across various competitive levels in both sports (Sæterbakken et al., 2019), however, higher-ranked players tend to excel in high-intensity variables such as distance covered within high intensity and sprint effort thresholds and other variables related to intense activities (Bradley et al., 2016; Carling, 2013; Lignell et al., 2018; Sæterbakken et al., 2019).

Analysis of a National hockey league (NHL) match revealed that half of the total distance was covered above the high intensity skating threshold (>17.0 km/h), corresponding to ~4-10 efforts per minute, with an average distance of ~15 m (Lignell et al., 2018). In contrast, football players cover most of their total distance with moderate intensity and only ~10% of total distance above the high intensity threshold (>19.8 km/h), corresponding to ~0.5 efforts per minute and an average distance of ~20 m per effort (Ade et al., 2016; Dolci et al., 2020; Oliva-Lozano et al., 2023). Despite this difference, it is well established that high intensity actions play a vital role for match performance in both ice-hockey and football as actions such as vertical acceleration, sprints, and breaking free from the opposition often are observed in relation to goal-scoring opportunities (Dolci et al., 2020; Huard Pelletier et al., 2021; Schulze et al., 2022).

With emphasis on positional differences, forwards are shown to perform more high-intensity skating per minute compared to defensemen, whereas total on-ice time and total distance covered were highest in the defensemen (Douglas & Kennedy, 2019; Lignell et al., 2018). Coherent observations are seen for peak sprint speed, as well as peak acceleration and deceleration intensities, in varsity level forwards compared to defensemen (Gamble et al., 2022). Thus, these studies clearly suggest an accentuated emphasis on intensity of play in forwards compared to defensemen, which is reflected by often shorter and less frequent on-ice shifts for forwards, but with limited differences in fitness characteristics between positional roles. Anecdotally, distance-based categorization of ice-hockey match demands are dissociated from the actual physiological stress imposed on a player, as major parts of a game include gliding across the ice, which is in contrast to other team sports (Vigh-Larsen & Mohr, 2022).

In football, attacking players, including wide midfielders and fullbacks, are typically regarded as the most demanding positions (Bush et al., 2015; Modric et al., 2020b). However, this is highly dependent on tactical formations (Bush et al., 2015) and individual characteristics of the players (Boullosa et al., 2020), and may vary depending on contextual factors (Boullosa et al., 2020; Bush et al., 2015; Dolci et al., 2020; Novak et al., 2021). Depending on the competitive level of the players, distances of 500-1000 m and 100-300 m covered in high speed and sprint running distance zones are typically observed (Beato, Drust, et al., 2021; Bush et al., 2015; Dolci et al., 2020; Taylor et al., 2022).

In addition to distance-based variables, the inclusion of IMU-data has allowed for quantification of more explosive actions. For example, short explosive efforts, covering small distances (~5 m), occurs 25-60 times during a football match (Loturco et al., 2019) and players have shown >90 high intensity accelerations during match play (Akenhead et al., 2013). Furthermore, an increasing number of studies have included measures of decelerations and change of directions (Miguel et al., 2021). In addition to individually presenting these efforts, some studies utilized a summary variable, high intensity events (HIEs), adding together the number of acceleration-, deceleration- and change of direction efforts (Luteberget & Spencer, 2017; Wiig et al., 2020). Nevertheless, the lack of uniformity in thresholds determination is, comparably to distance-based variables, also observed for IMU-variables (Malone et al., 2017).

Lastly, whenever assessing match related performance, it's important to account for several contextual factors, such as match location (Aquino et al., 2017), opposition standard (Aquino et al., 2017; Barrett et al., 2018), match importance (Modric et al., 2023), tactical factors (Modric et al., 2020b) and match score (Aquino et al., 2017; Barrett et al., 2018; Brocherie et al., 2018), potentially influencing the outcome variables (Aquino et al., 2017; Barrett et al., 2018; Brocherie et al., 2018; Novak et al., 2021; Oliva-Lozano et al., 2020). For instance, variations in high-speed running (Modric et al., 2020b) and sprinting (Vilamitjana et al., 2021) characteristics have been noted across various playing formations. Additionally, there is an observed increase in high-speed running distance (>19 km/h) during home matches in comparison to away matches. This trend is prominent when facing weaker opposition as opposed to stronger opponents, and is further accentuated in matches where the team won (Aquino, Carling, Palucci Vieira, et al., 2020). When assessing the context, a notable difference between football and ice-hockey is observed in the match schedules. While football typically consists of one to two matches per week, it is not uncommon for ice-hockey teams to play three matches per week. However, during congested periods this may increase to four matches per week (Dellal et al., 2015; Julian et al., 2021; Torres-Ronda et al., 2022; Vigh-Larsen & Mohr, 2022). Therefore, it's imperative to incorporate these factors whenever monitoring and evaluating players external match load data.

2.1.3 Application of external load tracking systems

Tracking systems are currently utilized in two main settings: training and competitive match play. Data from competitive match play have typically been applied as a marker to design training (Theodoropoulos et al., 2020). For example, by knowing the specific match demands for a position specific group of players, training sessions can be manipulated to stimulate a specific performance measure and prepare players for match demands (Beato, Drust, et al., 2021; Ravé et al., 2020). Likewise, knowing how a change in formation or tactics affects specific positions, can help optimize and tailor the physical match preparations to different conditions.

A common training modality in team sports, is the application of small-sided games (Sarmento et al., 2018). These drills are widely applied as a specific training prescription tool, as the manipulation of pitch size and number of players can stimulate an intended aspect of match performance, such as running distance, intensity, ball touches, oppositional challenges, change of directions, accelerations, and/or other sport specific variables (Sarmento et al., 2018). After the introduction of wearable tracking systems, coaches and practitioners may now quantify how manipulations of different training conditions (e.g., pitch size, number of players, goal size, etc.) affects players external training load data during these drills. Standardizing and repeating such drills over time can allow for individual and longitudinal follow-up and potentially facilitate the detection of abnormalities in a player's data (Derbidge et al., 2020; Rago et al., 2018).

In the field of small-sided games research, predominant focus has been directed towards outdoor field sports, leaving a noticeable gap regarding the applicability of these training methods in ice-hockey contexts. Despite the scarcity of published research data, such drills are applied by practitioners (Lachaume et al., 2017). However, the extent to which these strategies are employed in ice-hockey, remains underexplored in the current literature. There have, however, been other attempts to replicate match demands in ice-hockey. For example, a study applied standardized repeated efforts skating bouts to simulate match demands (Steeves & Campagna, 2019). Comparable, but more realistic to actual match play, a previous study simulated match play in compliance with official regulations. Playing time was, however, standardized to 1-min shifts with a 1:2 work/rest ratio (Vigh-Larsen, Ermidis, et al., 2020). The replication of match-play in this manner can be referred to as scrimmage (Vazquez-Guerrero et al., 2021), and does, as small-sided games, intend to simulate specific match demands and address the experienced match complexity during training (Aguiar et al., 2012; Luteberget et al., 2018; Vazquez-Guerrero et al., 2021). Contrastingly to previous attempts, the utilization of external load data does allow for a quantification that facilitates a more direct comparison to other drills, teams, and/or leagues.

2.2 Physical performance assessments

Physical performance testing is highlighted as an essential component within player monitoring, development and follow-up (Svensson & Drust, 2005; Williams et al., 2020). It is a powerful tool used to assess and monitor a player's fitness levels (Haugen et al., 2021; Rice et al., 2022), physical capabilities (Boland et al., 2019; Turner et al., 2011), and is intended to reflect upon the players overall physical performance related to a specific sport (Boullosa et al., 2020; Haugen et al., 2021; Rice et al., 2022; Taylor et al., 2022). For example, physical test performance results can be utilized to monitor improvement and develop strategies to improve performance and follow a player's physical development over time (Delisle-Houde et al., 2018; Haugen et al., 2021), or setting a minimum of fitness requirements on a positional (Vigh-Larsen et al., 2019), team (Peterson et al., 2015; Vigh-Larsen et al., 2019), and national specific level (Haugen et al., 2021; Vigh-Larsen, Haverinen, et al., 2020). Furthermore, well-developed physical skills contribute to reduced physical and mental exhaustion, affecting players' decision making, technical/tactical skills and injury risk (Boullosa et al., 2020; Haugen et al., 2021; Suchomel et al., 2016).

Physical performance testing has been applied as a tool in talent identification and selection, especially in American sport disciplines, such as American football, basketball, and ice-hockey (Nightingale et al., 2013; Rishis et al., 2023; Robbins, 2010). Within ice-hockey, physical off-ice testing has been completed for decades, with the NHL being a large-scale pioneer by their implementation of the National Hockey League Entry Draft Combine test battery, annually inviting all potential future NHL players to complete off-ice physical performance tests (Nightingale et al., 2013). Together with visual scouting observations, these physical test scores can assist coaching staff in their player prospect selection processes. However, the usefulness of such tests is questioned, due to the lack of relation to markers of match performance (Boland et al., 2019; Delisle-Houde et al., 2018; Fereday et al., 2020; Green et al., 2006; Haugen et al., 2021; Peyer et al., 2011; Stanula et al., 2018, may; Williams & Grau, 2020). Nevertheless, the focus and attention given to events such as the draft combine and similar situations where physical testing is used as "competition", can have indirect effects by inspiring and motivating players to train more and harder towards known benchmarks (Connaughton et al., 2008; Haugen et al., 2021). On the other hand, an excessive emphasis on enhancing specific physiological aspects may, in extreme cases, hinder sport-specific abilities. This is considering the time required to improve beyond a certain level and the transferability of those improvements to sport specific actions (Young, 2006). The high test-focus seen in ice-hockey and other American sports, is however, less observed within football. This does however not imply that physical testing is neglected within a football context. Indeed, physical performance testing is similarly performed during off-season training periods, and to some extent, as a part of talent selection processes (Ali, 2011; Murr et al., 2018; Williams et al., 2020). However, the "publicity" and publicly reporting physical performance results is less observed within the context of football.

2.2.1 Physical performance tests

Selecting an appropriate test-battery is a critical part of physical performance testing. However, with numerous performance tests available, choosing the right test battery can be challenging. The test-battery selection process requires careful consideration of various factors, including careful consideration of necessary sport-specific abilities (Barker-Ruchti et al., 2021; Svensson & Drust, 2005), players fitness level (Nightingale et al., 2013; Svensson & Drust, 2005), testing equipment (Nightingale et al., 2013) and facilities (Barker-Ruchti et al., 2021; Svensson & Drust, 2005). Numerous factors contribute to performance fluctuations and it's important to control for as many factors as possible to obtain valid and useful test-results (Lindberg et al., 2022). Standardizing test conditions is crucial to ensure the reliability of data. For example, differences in equipment, test-surface, and environmental conditions can influence the test-results (Brechue et al., 2005; Haugen & Buchheit, 2016), and it's important to take appropriate precautions to ensure standardization (Lindberg et al., 2022). As a general recommendation, physical performance testing should be undertaken when the players are fully rested and have undergone a standardized pre-test protocol, taking external factors such as, training load, sleep, nutrition etc. into account (Lindberg et al., 2022; Nana et al., 2016; Svensson & Drust, 2005; Turner et al., 2011).

Laboratory testing, performed with standardized protocols and highly sensitive test-equipment, can provide physical trainers and sports scientists with a precise general physical profile of players and can help customize training programs or form part of player selection strategies (Modric et al., 2021). However, the availability of laboratory facilities and the high cost of such testing may pose challenges for some teams. Furthermore, laboratory testing can be time-consuming and may require multiple visits to the laboratory to achieve reliable results. There's also a question to the relevance for team sport players to perform traditional laboratory test such as VO_2-max or lactate thresholds on a treadmill (Haugen et al., 2014; Nightingale et al., 2013; Svensson & Drust, 2005). Field tests are therefore more frequently applied due to its feasibility as these tests require minimal equipment and can be conducted almost anywhere (Bok & Foster, 2021), and provide greater sport specificity and ecological validity, compared to traditional laboratory assessments (Mendez-Villanueva & Buchheit, 2013; Svensson & Drust, 2005). Typical field tests include; Yo-Yo shuttle run tests, short (20-40 m) sprint test with timing gates, counter movement- (CMJ) and squat jumps on force-plates and change of direction-tests (Mendez-Villanueva & Buchheit, 2013; Nightingale et al., 2013).

Test-protocols are often applied in studies and by practitioners and intend to be a composition of performance tests being relevant for the sport specific abilities of interest (i.e., test-battery) and including a standardized execution procedure (e.g., test order, time between tests, rest periods etc.). While researchers and practitioners such as strength and conditioning coaches may warrant large and extensive test-protocols, match preparations including field training with focus on technical and tactical aspects are typically prioritized over extensive performance testing (Barrera-Díaz et al., 2023; McQuilliam et al., 2022). Thus, compromises should be made to make physical test protocols time-effective, or included in their training regime, and cover the most relevant desired physical abilities for the specific sport (Svensson & Drust, 2005; Turner et al., 2011). Furthermore, while large parts of test-protocols in specific sports are generic across clubs and nations, specific test-batteries and protocols applied may vary between teams, leagues, and federations, as test-protocols often are designed to reflect a certain set of abilities important for the playing style, coach, or organization (Mendez-Villanueva & Buchheit, 2013; Taylor et al., 2022). For example, a variety of physical tests have been identified for ice-hockey, but there is no consensus on which tests to apply, or the use of specific test-methods and equipment, despite suggestions of standardized test-protocols being made (Nightingale et al., 2013). Therefore, a large diversity in outcome measures are observed in the published literature (Huard Pelletier et al., 2021).

Despite differences in sport specific demands (Modric et al., 2020a; Vigh-Larsen & Mohr, 2022), traditional test-protocols are generally comparable between both sports, with inclusion of high-intensity tests such as repeated sprints, change of direction tests, sprint and jumping abilities (Galati et al., 2023; Haugen et al., 2021; Taylor et al., 2022; Turner et al., 2011). However, some distinctions are also observed. For example testing of aerobic capacity has been conducted over long time within football (Haugen & Seiler, 2015; Haugen et al., 2014), and tests intended to reflect this capacity, such as the Yo-Yo IR1 shuttle test, is typically observed in football-test protocols (Svensson & Drust, 2005). Contrastingly, some tests applied within ice-hockey places higher focus on short, explosive, and strength related tests such as the Wingate test or 1RM test such as back squat and bench-press (Haugen et al., 2021). Furthermore, an important distinction for ice-hockey, is that testing of sport specific abilities, such as sprint, is performed with different biomechanical movements. E.g., sprint testing is typically performed running, compared to habitual training and match activity which is performed skating. Studies have indeed highlighted the challenges of assuming a direct relationship between sprint running and on-ice skating because of different biomechanical movements (Burr et al., 2008; Nightingale et al., 2013; Perez, Guilhem, et al., 2022; Torres-Ronda et al., 2022). In addition, off-ice sprinting is typically performed in light clothing, compared to on-ice testing, often adding ~6 kg of additional weight to the player by performing sprints wearing full gear match equipment (Thompson et al., 2020). Composing a feasible and standardized test battery is therefore a considerable challenge. Thus, coaches and practitioners are emphasized to assess the relativeness and transferability to sport specific performance before selecting and implementing a test-protocol to a player monitoring regime.

2.2.2 Physical performance assessments vs training load monitoring

Physical performance tests are typically used to evaluate the effects of interventions or other experimental studies (Svensson & Drust, 2005). Traditional laboratory-based tests are therefore typically observed in such studies where a high level of standardization or equipment sensitivity, may be needed to assess the effects of the investigated phenomenon (Svensson & Drust, 2005; Turner et al., 2011). Physical performance assessments and the effects of interventions or training periods, such as the pre-season, is often isolated to fixed moving patterns, with limited comparison to abilities relevant to match play (Huard Pelletier et al., 2021; Rice et al., 2022; Turner et al., 2011). This may explain the shift in testing methodology, where the application of field based and more sport specific performance tests has increased in modern day sport and research (Haugen et al., 2014; Taylor et al., 2022), where mentioned shuttle-run tests, such as Yo-Yo tests have replaced traditional laboratory testing of VO_2-max (Haugen & Seiler, 2015; Thomas et al., 2006).

Current assessment of physical performance is typically isolated to single test points, or a pre- and post-test if assessing the effects of training regimes such as during the pre-season or after an intervention period. Nevertheless, the timeline of changes in physical performance following such training periods is typically unknown, with limited performance testing carried out during in-season periods, except in rare cases where re-test are included to assess the longitudinal effects (Rønnestad et al., 2011).

Contrasting to physical performance testing with long historical traditions (Svensson & Drust, 2005), quantification of load via microelectronic devices has emerged in the later years. Today, devices such as running watches, cycling computers and other wearables, have become a natural part of both highly trained and recreational active athletes training regimes (Aroganam et al., 2019). In high level cycling, a recent shift in application of monitoring data is indeed observed, where training and race data has been explored as a measure to assess fitness and performance levels of the cyclists (Lamberts & van Erp, 2021). Utilizing power meters and heart rate data, cyclists generate substantial data during each training session and race. With new technological advancements and more feasible big-data analysis (Araújo et al., 2021), the necessity for frequent laboratory visits may be reduced if wearable sensor data can be used to reflect the athlete's physical performance level (Dunn et al., 2021). Indeed, training data has been suggested to predict cycling performances such as functional threshold power and time trials (Denham et al., 2020; Lamberts & van Erp, 2021).

Although largely unexplored in this context, external load from wearable tracking systems emerges as a potential tool for monitoring players performance fluctuations. Some studies have indeed started to investigate the application of tracking systems and external training and match load data in this manner, by exploring external load data as a measure of sprint performance (Lacome et al., 2019) and also in force-velocity profiling (Lacome et al., 2020). Following this note, if external training and match load data has the potential to accurately reflects a player's physical abilities, conventional physical performance testing in the team sport context could become redundant (Schimpchen et al., 2023). E.g., if some external training and match load variables accurately reflects standardized sprint performance test-results, there's no need to complete separate testing of sprint performance. The relation and effects between training and match load data and physical performance has indeed been investigated recently, however, without consistent findings (Fox et al., 2018; Jaspers et al., 2017; Rice et al., 2022). The use of external training and match load data emerges as a promising potential for coaches and practitioners to gain more nuanced insights into players' fluctuations throughout the season, mitigating the reliance on sporadic test points during the year. This approach, utilizing external training and match load data, may offer increased understanding of a player's strengths and weaknesses. Thus, this may provide a more nuanced insight to players physical fitness fluctuations and detailed insights to their capabilities and vulnerabilities, if deemed valid and reliable (Bourdon et al., 2017; Buchheit & Simpson, 2017).

2.3 The relationships between measures of physical performance and sport specific activity measures

Identification of measures that can impact or reflect sport-specific performance has received great attention (McCall et al., 2017). A major challenge is however the deamination and definition of *performance*, per se, within the context of team sports (Glazier, 2017). The performance-term is therefore often misused, as it generally lacks necessary definition within the context its being used. For instance, improvements of physical test performance are in general believed to influence sport specific performance. While physical test performance can be defined as an improvement in a certain test, such as 30 m sprint or CMJ, defining sport specific performance is more intricate (Pol et al., 2020).

2.3.1 Measuring sport performance

Performance can be defined as "how well a person, machine, etc. does a piece of work or an activity" (Cambridge University Press, n.d.). This definition is however broad and unprecise. For example, it may be argued that a good performance in sports is when the number of scored goals is higher than the ones conceded. However, winning 8-7 and 1-0 may be both a good and poor performance, depending on if it's interpreted from an attacking or defending point of view (Caldbeck & Dos'Santos, 2022). Its therefore essential to put it into context whenever assessing its relation to other measures.

The prevalent metrics used to assess sports performance typically revolve around objective outcomes such as winning or losing. However, there exists a plethora of additional quantifiable measures, encompassing both general aspects like goals (Aquino et al., 2017), assists, points (Haugen et al., 2021), and league standings (González-Rodenas et al., 2023), as well as match-specific variables including tackles (Modric et al., 2022), interceptions (Caldbeck & Dos'Santos, 2022), passes (González-Rodenas et al., 2023), touches (Caldbeck & Dos'Santos, 2022), dribbles (González-Rodenas et al., 2023), possession (González-Rodenas et al., 2023), and fouls (Gómez et al., 2012). Utilizing this comprehensive dataset, it becomes tempting to create and define sub-categorical performances measures, such as passing- or tackle performance. Moreover, external training and match load variables can also serve as specific and valid movement measures. For instance, variables like sprint running distance, extracted from external load or video-based tracking systems, may be legitimate indicators of sprint distance performance during sports-specific activities (Haugen & Buchheit, 2016). However, a significant challenge arises when assuming that these sub-performance measures directly reflect sports-specific or competitive performance. Competitive performance is a multifaceted construct influenced by an abundance of intricate variables, including physiological fitness, psychological preparedness, physical development, biomechanical expertise, and tactical smartness, among others. This complexity is further compounded by diverse factors such as nutrition, genetics, general health, sociocultural elements etc. (Glazier, 2017). Consequently, deciphering the overall sports-specific performance solely through isolated sub-performance measures remains challenging, underscoring the intricate and multifactorial nature of athletic achievement (Currell & Jeukendrup, 2008; Swann et al., 2015).

2.3.2 Relationships between physical tests performance and current measures of sport related performances

Despite the challenges in defining performance, literature has explored the relationships between physical test performance and different measures of sport specific measures. There are however some distinctions observed between the sports. For example, with the available data, research in ice-hockey has focused on physical test performance results, likely as a consequence of testing traditions (Cohen et al., 2022; Haugen et al., 2021; Huard Pelletier et al., 2021; Nightingale et al., 2013) and compared these to other available public statistics. Such objective statistical measures include playing time (Delisle-Houde et al., 2018; Green et al., 2006; Haugen et al., 2021), number of shifts, goals (Boland et al., 2019; Haugen et al., 2021), assists (Boland et al., 2019; Haugen et al., 2021), ± differential statistics (Boland et al., 2019; Delisle-Houde et al., 2018; Haugen et al., 2021; Peyer et al., 2011; Stanula et al., 2018, may), and shots (Boland et al., 2019). Despite the plethora of included measures and variables, only trivial to moderate associations were shown to physical test performance (Boland et al., 2019; Delisle-Houde et al., 2018; Green et al., 2006; Haugen et al., 2021; Peyer et al., 2011; Stanula et al., 2018, may).

Contrastingly, comparable large scale physical test performance data is currently not available in football. Instead, with application and availability of official match time-motion analysis data, research derived from the context of football has opted to focus more on data derived from such systems (Peev et al., 2019). For example, a comprehensive amount of research is published exploring the relationships between objective match statistics, such as passes, possession etc., and match outcome, however without any clear tendencies (Aquino et al., 2019). In football, associations between aerobic performance, both from laboratory- and field test, is found to be associated to match related running performance, such as total- or high intensity running distance (Aquino, Carling, Maia, et al., 2020; Modric et al., 2021). An association has also been identified between CMJ and acceleration and decelerations (Rago et al., 2018). However, there are conflicting results on these variables (Pedersen, 2021).

A suggested strength with monitoring of external load is the potential to measure players during all sporting activities (e.g., training and matches). The validity of external load variables as measures of sport performance, should be discussed as any other measure before establishing its relevance. However, an important distinction relates to the fact that these are obtained from movements during actual sporting activities. As external training and match load are intended to measure and reflect the individual efforts by a player, it can be hypnotized to be a more precise measures of sport related performance, compared to objective match statistics (Huard Pelletier et al., 2021). An example can be made from ice-hockey; Schwesig et al. (2021) assessed the relationships of physical test performance to fatigue-markers during a repeated skating test protocol, intended to simulate the physiological demands of match play. Contrastingly, Vigh-Larsen, Ermidis, et al. (2020) performed a full simulated match. While they did not include measure of physical test performance, they assessed the association of included physiological measures to measures of external load during the simulated match. For example, a strong correlation was identified between blood lactate levels and number of explosive efforts ($r = 0.71$, $p<0.05$). While both studies attempted the same, e.g., simulate match conditions, it is fair to acknowledge that actual playing an simulated game, similar to official match regulations, is a more ecological valid method. However, the research investigating relationships between physical test performance and measures of external training or match load is scarce both in ice-hockey and football (Huard Pelletier et al., 2021; Rice et al., 2022).

2.3.3. Monitoring, detecting and interpretating changes in players data

Important to effective player monitoring regimes is the ability to detect and interpret fluctuations in players performances, a task in which regular physical performance assessments are essential (Boullosa et al., 2020; Haugen et al., 2021; Rice et al., 2022). It is noteworthy that prevailing practices in both amateur and professional sports often limit physical performance evaluations to discrete test points and frequently analyze these results at the group level, despite the recognized significance of tailoring training regimens to individual athletes and closely monitoring their unique responses (Gabbett et al., 2017; Ravé et al., 2020). These evaluation is typically performed before or after competitive periods due to reluctance from coaches to incorporate physical fitness testing during the in-season phase (Rice et al., 2022; Taylor et al., 2022). Consequently, there exists an untapped potential to gain deeper insights into the dynamics of players' fitness alterations throughout a competitive season.

While external training and match load data is widely applied, limited research has delved into whether such data can reflect alterations in players' physical test performance. It may be argued that improvements in CMJ signify enhanced lower limb neuromuscular capacity, indicating heightened explosiveness and potential advancements in maximal accelerations (Gillen et al., 2020). Similarly, enhanced sprint performance directly translates to improved top speed. Such physiological advancements logically necessitate greater force for deceleration and directional changes (Cormier et al., 2020; Harper et al., 2022). Therefore, it is reasonable to argue that these physiological adaptations should be reflected in external training and match load data (Cormier et al., 2020). For example, an increase in a player's top speed would lower the relative effort required to attain generic running thresholds for high- and sprint running intensity, leading to extended distance in these running zones. Likewise, improved CMJ performance should be mirrored by an increase in number of accelerations, decelerations, and change of directions during matches, implicating the player's exposure to heightened external forces due to increased physical capacities (Suchomel et al., 2016).

The inclusion of external load data presents a promising alternative for a more comprehensive understanding and continuous monitoring of players' physical fitness during periods when traditional physical tests are not feasible (Schimpchen et al., 2023). In contrast to the meticulous standardization and extensive optimization witnessed in the field of physical performance testing over the course of several decades (Lindberg et al., 2022; Mendez-Villanueva & Buchheit, 2013; Svensson & Drust, 2005), the realm of external training and match load data lacks a comparable depth of research and understanding (Barker-Ruchti et al., 2021; Impellizzeri et al., 2023; Malone et al., 2017). While physical performance testing methodologies have been rigorously standardized and are widely emphasized in the existing literature, achieving similar uniformity in sport-specific activities poses significant challenges (Glazier, 2017; Malone et al., 2017). Notably, as match related activity variables are substantially influenced by contextual factors, match data may not be an accurate reflection of the individual player's inherent abilities, but rather an isolated measure of performed efforts in the context of the match (Ravé et al., 2020). Despite these inherent complexities, studies within the domain of football have undertaken assessments of the reliability of external training load data during small-sided games, demonstrating their viability and potential (Milanović et al., 2020; Owen et al., 2013). Consequently, these structured training drills may offer standardized contexts for the evaluation of changes in players' external load data within the spectrum of sport-related activities (Buchheit & Simpson, 2017) and may arguably be seen as a more ecological valid measure and context of players sport specific abilities (Mendez-Villanueva & Buchheit, 2013). This nuanced examination underscores the untapped potential of external training and match load data, providing valuable insights into the multifaceted dynamics of players' physical capabilities in various sporting scenarios, urging for further exploration.

When assessing changes in highly trained players, traditional hypotheses testing is often inadequate, as the changes may be interpreted as no effects (i.e., $p>0.05$), likely affected by factors such as limited sample size and variation in responses within a team of players. As such, it's important to assess the players individually, as some may experience an improvement, while others may reduce their performance, potentially falsely concluding with a "no change" at a team level. At the highest competitive level, small improvements can have significant performance effects. Therefore, its crucial to assess the meaningfulness and practicality of potential changes beyond traditional hypothesis testing (Gabbett et al., 2017). At the minimum, controlling for measurement error and calculating a threshold for a change to be deemed valid, is recommended (Hopkins, 2000; Lindberg et al., 2022). Assessment of the smallest worthwhile difference (SWD) (Hopkins, 2004; Lindberg et al., 2022), the minimum detectable change (Donoghue & Stokes, 2009; Edwards et al., 2022), and different measures of effect-sizes (Fröhlich et al., 2009; Hopkins, 2004; Lindberg et al., 2022), is further suggested as potential methods to assist both researchers and practitioners in their assessment and interpretation of results, rather than simply concluding based on raw data.

2.4 Summary and delimitations

The monitoring of players' physical training, match efforts, and an overview of their physical fitness level is essential within team sports. While physical performance tests have been employed for several decades (Cohen et al., 2022; Svensson & Drust, 2005), the emergence of external load data from wearable tracking systems in recent years has become an integral component of team sports monitoring strategies (Gualtieri et al., 2023). Despite the availability of LPS, a predominant focus of research and application is observed in outdoor field sports, such as football, with limited exploration within the context of ice-hockey (Huard Pelletier et al., 2021). The utilization of external training and match load data has facilitated the quantification of training and match demands, allowing for individualization, development, and follow-up strategies (Cardinale & Varley, 2017; Theodoropoulos et al., 2020). Nevertheless, despite the advancements in this area, recent research suggests that external training and match load data serves not only as a quantification of players' physical efforts, but such data derived from wearable tracking systems may effectively represent and capture fluctuations in players' fitness (Schimpchen et al., 2023). This may consequently obviate the necessity for traditional physical performance testing in team sports. However, despite the potential of external training and match load data in this regard, there exists a notable gap in the literature concerning the investigation of the actual relationships between measures of physical test performance and external training and match load data.

2.4.1 Delimitation of thesis

The ability to predict team success, players performance, identify talent, or foresee potential injuries within sports is regarded as the "holy grail" within player monitoring in sport sciences (McCall et al., 2017). Consequently, the exploration of external training and match load in this regard is emerging. Its however imperative to distinguish between the terminology applied, such as prediction, associations, and causation, when exploring this area (Impellizzeri et al., 2023; McCall et al., 2017). The aim of this thesis is to investigate the relationships between physical test performance and external training and match load, mainly through exploring the associations between these measures. The thesis does therefore not aim to predict or provide causation, e.g., that one variable is casually linked to another (Impellizzeri et al., 2023; Kalkhoven et al., 2021), but rather apply an exploitative approach to investigate the aims of this thesis, namely the external training and match load demands within ice-hockey, the relationships between physical test performance and external load, and how changes in physical test performance can be reflected in external load data.

3 Methods

The present chapter describes the methodologies employed to explore the aims of this PhD-project. As the global Covid-19 pandemic emerged during the start phase of this project, it is imperative to acknowledge that modifications from the original plans were made. For a brief overview, readers are directed to section 3.7 in this chapter. The completed thesis consisted of two district studies, and four related papers (**study one - paper I** and **II**, **study two - paper III** and **IV**) performed September-December 2020 (**study one**) and August-November 2021 (**study two**).

3.1 Study protocols

Study one explored the external training and match load demands within ice-hockey activities by including data from eight official matches and four scrimmages. The relationships between external load data to physical test performance was assessed by including two days of physical performance assessments.

Competitive matches and scrimmages were played in the team's home arena, equipped with a North American sized ice rink (60.96m x 25.90m). Matches were scheduled in the weekends and consisted of two games against the same opposition, played over Saturday and Sunday. Scrimmages were played over four days within a three-week period and at the same time of day (± 2.5 hours). Similar to a previous study (Vigh-Larsen, Ermidis, et al., 2020), playing time was standardized with 1-min shift and a 1:2 work/rest ratio and played in accordance to competitive match regulations. I.e., matches were played with 3 x 20 minutes periods, intercepted by 18 minutes of recovery. Within the three-week period, players completed seven physical performance tests, performed on two separated test days. A visual overview of **study one** is presented in Figure 1.

Paper I was performed with a cross-sectional approach and investigated if external match load demands could be replicated with a scrimmage design. External load variables included total distance, peak speed, slow- moderate, high- and sprint speed skating distances, PlayerLoad^{TM}, HIEs, accelerations, decelerations and change of directions.

Paper II was performed with a cross-sectional design exploring the association between physical test performance and external scrimmage load. Physical test performance assessments included 30-m running and skating sprint times, max speed, countermovement jump, standing long jump, bench-press, pullups and trap bar deadlift. External load variables from scrimmages included total distance, peak speed, slow-moderate, high- and sprint speed skating distances, number of sprints, PlayerLoad^{TM}, HIEs, accelerations, decelerations and change of directions.

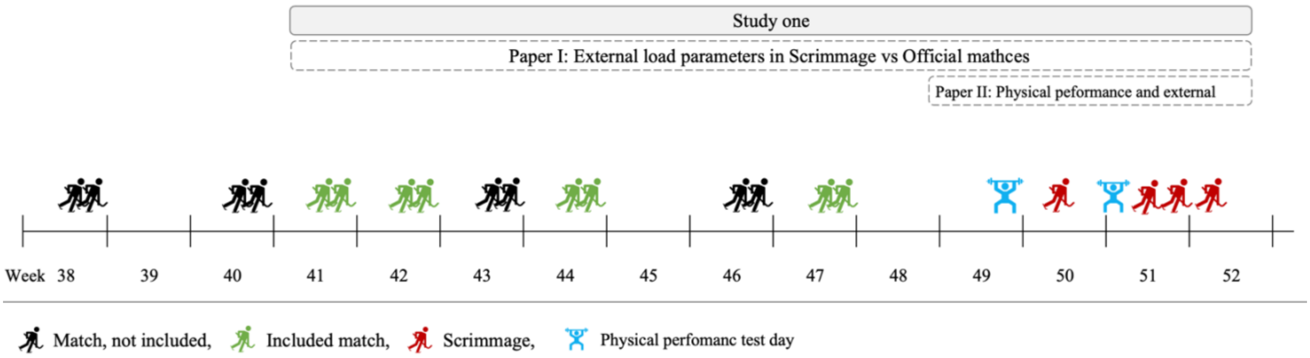

***Figure 1**: Schematic overview of **study one**, including **paper I** and **II**.*

Study two explored the effects of a strength intervention period and if external match load data could be reflective of changes in physical test performance. This study included a 10-week strength intervention, pre- and post-tests and measures of external match load, performed from August to November 2021. During the strength intervention players were randomly drawn into two groups, regulating training volume based on either an objective (AUTO-group) or subjective (SELF-group) marker during the intervention period. For the AUTO-group, high intensity running distance (HIR: >19.8 km/h) was used to determine the strength training volume for each strength training session. Contrastingly, the SELF-group self-selected their desired strength training volume for the same sessions based on their subjective readiness to train feeling. Players altered between two strength training programs (micro and regular) based on the match congestion, and strength training volume varied from one to three sets of the exercises included in the respective programs, with the aim of performing two sessions per week. Physical test performance was assessed with traditional pre- and post-assessments, while external match load data was included from ten matches in the beginning (n=5) and the end (n=5) of the study period. For a more details regarding the experimental procedures of the strength intervention, please see **paper III**.

Field training and competitive home matches were performed at the same arena, with strength training taking place in a designated strength training facility within the arena. Field training was typically conducted in the morning and afternoon (e.g., 10:00 and 14:00), while strength training was typically performed in the afternoon (~15:00). Ten competitive matches (home n=5, away n=5) with kick off between 15:00 and 20:00 are included in data-analysis from **study two**. A visual overview of **study two** is presented in Figure 2.

Paper III was performed with an experimental design and specifically investigated the group effects of the autoregulated strength training regime for the AUTO- and SELF-group. Physical test performance included 30 m sprint times, CMJ and Keiser leg press, and body composition. External match load variables included: distance per min, peak speed, PlayerLoad^{TM}, High speed and Sprint running distance and efforts, HIEs, accelerations, decelerations and change of directions.

Paper IV was performed with a case-study design and investigated the individual effects in physical test performance and external match load data for players fulfilling the strength intervention period and having sufficient external load match data. Raw and relative (%) typical error (TE) in addition to assessment of SWD were applied as criteria to categorize improvements in physical performance as meaningful, while SWD and non-overlap of all pairs (NAP) were used to assess the changes in external match load data. Physical test performance included 30 m sprint times, CMJ and Keiser leg press. External match load variables included: distance per min, peak speed, PlayerLoad^{TM}, High speed and Sprint running distance, HIEs, accelerations, decelerations and change of directions.

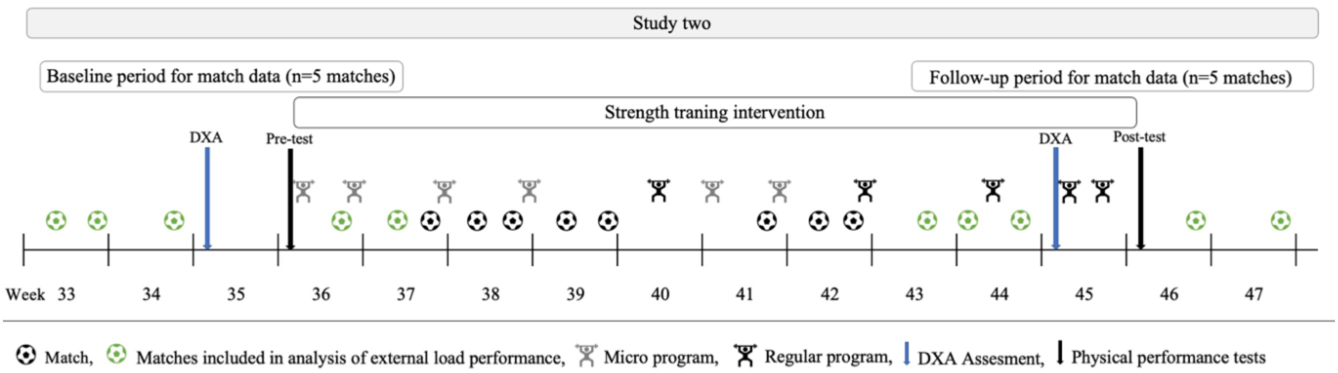

***Figure 2**: Schematic overview of **study two**, including **paper III** and **IV**.*

3.2 Participants

Based on the classification from McKay and colleagues (McKay et al., 2022), 50 highly trained male youth ice-hockey players and 30 highly trained male professional football-players initially recruited to **study one** and **study two**, respectively. During **study one**, 19 LPS devices were available for each match. To be included in analysis of external match load data, players had to participate in a minimum of four to eight competitive matches, with a minimum five minutes of ice-time from the respective match. To be included in analysis of external scrimmage load data, players had to participate in and fulfill all four scrimmages. Nine of 25 player were excluded from competitive matches (**paper I**), while four of 19 players were excluded from scrimmages (**paper I** and **II**). Six included players participated in both competitive matches and scrimmages, thus a total sample of 25 individual players were included in **paper I**. One of the 15 players fulfilling the inclusion criteria from the scrimmages, failed to complete physical performance tests, and was excluded from **paper II**, which included 14 players.

Thirty players had a contract with the respective football club and were eligible for participation in **study two**. Twenty-one of 30 players participated in and completed physical pre-testing. Five players were injured or sold during the intervention period, resulting in 16 players completing the intervention period (**paper III**). The same 16 players included in **paper III** were eligible for inclusion in **paper IV**. In addition to completing the intervention period during **study two**, the players had to participate in a minimum two matches with >60 minutes playing time either in the beginning or end of the intervention period. While ten and eleven players fulfilled these criteria for the baseline and follow-up period, respectively, only eight players fulfilled this criterion in both periods. Thus, eight players were included in **paper IV**. For a detailed description of the participants in the four studies, see Table 2.

Table 2: Overview of participants in all four papers.

Paper	Design (timeframe)	N	Age (yrs)	Height (cm)	Body mass (kg)	Sport / competitive level
I	Cross sectional (2020)	25	18.1 ± 1.1	179.5 ± 5.5	73.3 ± 6.6	Youth ice-hockey (National U20 and U18 league)
II	Cross sectional (2020)	14	17.8 ± 1.1	179.5 ± 6.5	71.2 ± 6.0	Youth ice-hockey (National U20 and U18 league)
III	Experimental (2021)	16	23.9 ± 4.1	183.4 ± 6.2	77.0 ± 7.6	Professional football (National 2nd tier)
IV	Case-study (2021)	8	25.4 ± 3.1	184.1 ± 3.4	79.3 ± 2.2	Professional football (National 2nd tier)

3.3 External load monitoring

Tracking systems from Catapult Sports (Melbourne, Australia) were applied in all four studies. **Study one** applied an LPS system (Catapult ClearSky T6) including 20 nodes installed ~20m above the ground, around the ice-rink. The system was spatially calibrated using a tachymeter (Leica Builder 509 Total Station; Leica Geosystems AG Switzerland), as recommended by the manufacturer. See setup of one LPS node in Figure 3. **Study two** applied a GNSS-based system (Catapult Vector S7), and activities were performed outdoors with GNSS-signals. In addition to an GNSS/LPS chip sampling at 10Hz, both systems were equipped with an IMU, sampling at 100Hz. Each player wore a tracking device (**Study one**; ClearSky T6, firmware version 5.6. **Study two**; Vector S7, Firmware 8.10), located between the scapulae in a custom vest supplied from the manufacturer. Data from both systems were transferred to OpenField version 1.17.2 (Catapult Sports, Melbourne, Australia), where it was edited post-match to ensure that only data from match or scrimmage participation was included (i.e., excluded time on bench/warmup, time between periods/half's).

Prior to the initiation of **study one**, familiarization of wearing the LPS devices was performed. To ensure that the players had the appropriate vest size and were comfortable with the devices under training conditions, they wore the devices in training for a period of one week. In **study two**, the utilization of tracking systems was already established as part of the team's routine training practices, thus eliminating the need for familiarization prior to the commencement of the project. See Figure 4 for an illustration of a deceive placed in a vest and worn by a player.

Figure 3*: Illustration of node/satellite mounted in the arena (**study one**).*

Figure 4*: Illustration of a custom vest including a Catapult tracking system device placed in pouch between scapulae. Copyright Catapult Sports, Melbourne, Australia.*

3.3.1 Match day procedures

Prior to match-days in **study one**, two researchers would arrive at the arena approximately two hours before face-off. They were responsible for ensuring that the LPS network was operational, the LPS devices were calibrated and set to the same clock-time. An alarm was programmed to activate the devices approximately 15 minutes before the start of the match. The devices were then handed over to a member of the coaching staff, who would place them in the wardrobe for the players to retrieve. The players, who had undergone a familiarization process with the devices, would then secure the devices in their vests. Throughout the match, the researchers monitored live data recordings and documented any incidents (e.g., injuries, faulty devices) that occurred during the match. After the match, the coaching staff would collect the LPS devices and return them to the researchers, who would then transfer the data to the system's software and cloud account.

In **study two**, the system and devices were managed by the team's strength and conditioning coach in collaboration with a researcher. On match-days, the coaching staff would place a hardcase with the devices in the wardrobe, where the players would retrieve them and secure them in their vests. The devices would automatically turn on approximately 15 minutes before the start of the game, and after the game, they would be placed back in the hardcase. The next day, the strength and conditioning coach would transfer and synchronize the data. The raw data would then be transferred to a university-computer, running the same system software, in order to analyze and edit the data without interfering with the team's original datafiles.

3.3.2 External load data processing

Speed distance thresholds in **paper I** and **II** were based on previous ice-hockey research, divided into slow (0.0-10.9 km/h), moderate (11.0-16.9 km/h), high (17.0-23.9 km/h) and sprint (>24 km/h) speed skating (Douglas & Kennedy, 2019; Vigh-Larsen, Ermidis, et al., 2020). **Paper III** and **IV** only included high speed (19.8-25.1 km/h) and sprint (>25.2 km/h) running distance, in addition to number of efforts in the respective intensity zones (**paper III**), where thresholds were in accordance with best practice (Akenhead & Nassis, 2016). Total distance, peak speed, PlayerLoad™, HIEs, accelerations, decelerations and change of directions were applied in all four studies. PlayerLoad™ is calculated by summarizing all accelerations and is expressed as the square root of the sum of the squared instantaneous rate of change in accelerations in each of the 3 vectors (x, y, and z axes), divided by 100 and scored as arbitrary units. Accelerations, decelerations, and change of directions are a summary of identified movements in the respective direction with an intensity > 2.5 m/s. The sum of accelerations, decelerations, and change of directions were displayed as HIEs. Total distance and PlayerLoad™ were also reported in relative terms (i.e., per min) in **paper I**. All included variables in **paper III** and **IV** were reported relative to playing time (i.e., per min). A comprehensive overview of all external load variables, thresholds, and metric units included in the respective papers can be found in Table 3.

Table 3: Overview of external load variables and units applied.

	Paper I	Paper II	Paper III	Paper IV
Total distance	m m/min	m	m/min	m/min
Peak speed	m/s	m/s	m/s	m/s
PlayerLoad™	au au/min	Au	au/min	au/min
Slow speed/intensity	m (0-10.9 km/h)	m (0-10.9 km/h)	-	-
Moderate speed/intensity	m (11-16.9 km/h)	m (11-16.9 km/h)	-	-
High speed/intensity	m (17.0-23.9 km/h)	m (17.0-23.9 km/h)	m/min efforts/min (19.8-25.2 km/h)	m/min efforts/min (19.8-25.2 km/h)
Sprint speed/intensity	m (>24 km/h)	m (>24 km/h)	m/min efforts/min (>25.2 km/h)	m/min efforts/min (>25.2 km/h)
High intensity events	Nr (>2.5m/s)	Nr (>2.5m/s)	Nr/min (>2.5m/s)	Nr/min (>2.5m/s)
Accelerations	Nr (>2.5m/s)	Nr (>2.5m/s)	Nr/min (>2.5m/s)	Nr/min (>2.5m/s)
Decelerations	Nr (>2.5m/s)	Nr (>2.5m/s)	Nr/min (>2.5m/s)	Nr/min (>2.5m/s)
Change of directions	Nr (>2.5m/s)	Nr (>2.5m/s)	Nr/min (>2.5m/s)	Nr/min (>2.5m/s)

Note: m: meter, m/min: meter per minute, m/s: meter per second, au: arbitrary units, Nr: number.

3.4 Physical performance measurements

Physical performance was assessed in **paper II**, **III** and **IV**. An overview of paper-specific physical performance tests and reported units is presented in Table 4. In **paper II**, the physical performance tests included CMJ, 30-m linear sprint on- and off-ice, standing long jump, pullups (max repetition number with body mass), and 1RM bench-press and trap bar (hexagonal barbell deadlifts) deadlift. Physical performance tests were conducted over two test-days, where test-day one included CMJ and 30-m sprints, and test day two included standing long jump, bench-press, pullups and trap bar deadlift. All players underwent a typical warmup procedure before the physical performance tests, included jogging, jumps, running/skating drills, sprints with increasing intensity and dynamic stretching.

In **paper III** and **IV**, physical performance and body composition was assessed pre- and post-intervention. Body composition was assessed ± 7.0 days in relation to physical performance testing, and post-assessments were completed 68.6 ± 3.8 days after the initial assessment and at the same time of day (± 40 minutes). The physical performance test-battery consisted of 10-minutes self-paced warm-up on a treadmill, 30-m linear sprint, CMJ, and Keiser leg press. The test session duration was ~1 hour and all players performed the tests in the same order pre- and post-intervention. Physical performance post-testing was completed 70.0 ± 0.0 days after pre-testing and at the same time of day (± 1.0 hours).

Table 4: Overview of included physical performance tests and reported units.

	Paper II	**Paper III**	**Paper IV**
Sprint			
10 m	s*	s	s
30 m	s*	s	s
Max speed	m/s*	m/s	m/s
CMJ	cm	cm W/kg	cm
Standing long jump	cm	-	-
Bench-press	kg	-	-
Pullups	nr	-	-
Trap-bar	kg	-	-
Legg press			
Power	-	W W/kg	W
Force	-	N N/kg	-

* Includes track running and on-ice skating sprint testing. – not included in the study. CMJ: Countermovement jump, N: Newtons, W: Watts

Body composition

In **paper I, II, III** and **IV**, height was measured without shoes to the nearest 0.5 cm using a wall-mounted centimeter scale (Seca Optima, Seca, Birmingham, UK) while body mass was measured in underwear to the nearest 0.1 kg with an electronic scale (Seca 1, model 861, Birmingham, UK). In **paper III**, body composition was assessed using dual-energy X-ray absorptiometry (DXA) (GE-Lunar Prodigy, Madison, WI, USA, EnCore software version 15) and performed according to best practice recommendations, where the players arrived in a fasting state without any fluid intake on the morning of the scan (Nana et al., 2015). The same technician performed all scans on all players.

30-m Sprint

30-m sprint test was performed in three different locations. In **paper II**, players were tested on an indoor athletic synthetic track running surface, and on the ice-rink at the home arena. In **paper III** and **IV**, sprint testing was performed on an indoor synthetic surface. At every test-point, players performed 2-4 maximal sprints with 4 minutes passive rest between each attempt. The same wireless dual-beam timing gates (Musclelab, Ergotest innovation AS, Langesund, Norway) were used at every test-point. In **paper II**, players started with a 0.5 m flying start and the timing was initiated when the foot triggered the first sensor placed at 0 m and 40 cm above the ground. The remaining sensors at 10-, 20- and 30-m were placed 120 cm above the ground. In **paper III** and **IV**, the timing was initiated when the front foot left the ground at the start line (0 m). The remaining sensors at 5-, 10-, 15-, 20-, 25- and 30-m were placed 120 cm above the ground. The trial with the best 30 m time was included in post-test analysis and max speed was calculated from 10- (**paper II**) and 5-m (**paper III** and **IV**) split times.

Counter movement jump

CMJs were performed with hands on the hips, and the depth of the squatting motion was self-selected. In **paper II**, the players performed 3-5 jumps with a 2–3-minute passive rest between each attempt. In **paper III** and **IV**, the players completed 2-3 sets of 3 jumps performed 30 s apart, followed by 2–3-minute passive rest. The CMJs were measured using a Musclelab (Ergotest innovation AS, Langesund, Norway) (**paper II**) and AMTI force plate (**paper III** and **IV**) sampling at 1000Hz (Advanced Mechanical Technology, Inc Waltham Street, Watertown, USA) with custom-written MATLAB (The MathWorks, Natric, MA) script used to process the data. The mean of the two single best attempts was included in post-test analysis (**paper II**, **III** and **IV**).

Standing long jump

Long jump was assessed in **paper II**. Players started from a standing position with both feet parallel behind a start line and jumped as far as possible in the horizontal direction. Arm swing was allowed. The jump length was measured to the nearest 0.01 m from the start line to the rear heel, using a tape measure. To qualify as a successful attempt, the subjects had to take off with two feet and maintain balance for at least two seconds upon landing. Three attempts were performed with 2-3 min rest between each attempt. The best trial was included in the post-test analysis.

Bench-press

1RM bench-press test was measured in **paper II** using a free weight Olympic bar and weights. The players were instructed to hold the bar at a position slightly greater than shoulder width. The player then lowered the bar to the chest and pushed the bar until full arm extension. The gluteal muscles had to be in contact with the bench throughout the entire lift. Players performed 3-4 warm-up sets with increasing loads (50-90% of 1RM), based on previous performance. Two to four attempts were then performed to determine 1RM. Upon successfully completing the repetition, weight was subjectively increased by 2.5-10 kg. For players that were not able to complete the lift, weight was reduced by 2.5-5 kg.

Pullups

Pullups was assessed in **paper II**. Players used an overhand grip (palms facing away from the body) and started from a dead hang (arms fully extended and locked). From this position, a pullup was performed until the chin had cleared the top of the bar. The body was then lowered until the arms where fully extended or locked out. No excessive body motion was allowed. Each player completed one trial, and the maximum number of valid repetitions was recorded.

Trap bar deadlift

Trap bar deadlift was assessed in **paper II** and performed using a standard hex bar with a weight of 32 kg. Players performed 3-4 warm-up sets with increasing load (50-90% of 1RM), based on previous performance. Two to four attempts were then performed to determine the 1RM. Upon successfully completing the repetition, weight was increased subjectively by 2.5-10 kg. If they could not complete the lift, the weight was reduced by 2.5-5 kg. Players had to stand fully erect with knees and hips locked, for the lift to be considered successful.

Keiser leg press

Lower limb strength and power was assessed in **paper III** and **IV** using a Keiser AIR300 horizontal pneumatic leg press device with an A420 software (Keiser Sport health equipment INC., Fresno, CA, USA). Average force and velocity in each repetition were derived from the Keiser software with the manufacture's standard "10-repetition force-velocity test" with incremental loads (Lindberg et al., 2021). The incremental test was performed in the seated position with a 90° knee-joint angle, starting at 41 kg and increasing to 250 kg at the tenth repetition with increased and standardized increments of approximately 20-30 kg for each attempt. If the player exceeded 250 kg at the 10^{th} repetition, the test continued with 60-s rest between attempts until failure. The rest period was 10 to 20 s for the initial five loads and 20 to 40 s for the last four loads. Keiser leg press does not cause ballistic action due to the pneumatic semi-isotonic resistance, and the entire push-off was performed with maximal intentional velocity. The leg press measures were collected from the concentric phase, and the pedals are resting in a predetermined position prior to each repetition. A linear regression was fitted to the average force and velocity data to calculate extrapolated individual force–velocity relationship variables. Theoretical maximal force and theoretical maximal velocity were defined as the intercepts of the linear regression for the corresponding force and velocity axis. The theoretical maximum power was calculated as theoretical maximal force · theoretical maximal velocity /4 and was retained for further analysis.

3.5 Ethical considerations

Before commencing the project, approval for the utilization and storage of research data being collected in the project, was obtained from the Norwegian Center for Research Data (see appendix 2) in addition to securing ethical clearance from the Faculty's Ethical Committee (FEK) at the University of Agder (see appendix 3). Owing to delays related to Covid-19, an extension of the timeline for data gathering, usage, and storage was requested and granted by the Norwegian Center for Research Data (see appendix 4).

Before commencement of **study one** and **two**, all recruited players received comprehensive verbal and written information outlining the project's objectives and emphasizing the voluntary nature of participation (see appendix 5 and 6). It was explicitly communicated that all data would be treated anonymously, and participants retained the right to withdraw from the study at any point without providing a reason, either verbally or in writing. Since all participants were above the age of sixteen, no consents from legal guardians were required (Helseforskningsloven, 2008).

The projects were designed with the explicit intention of being mutually beneficial for the participating teams. It is imperative that research endeavors to be conducted with justified constraints on inference to the subjects, guided by an overarching objective to advance knowledge and augment our collective understanding of the world, benefiting researchers and practitioners alike (Thomas et al., 2022; Wilkinson & Dokter, 2023).

The engagement in maximal physical efforts, particularly exemplified by the context of physical performance testing, inherently entails certain attendant risks of injury and the manifestation of fatigue. Nevertheless, it is pertinent to note that individuals involved in this study are integral components of highly competitive environments wherein they are habituated to and proficient in physical performance testing protocols. Consequently, their participation in the present project is not perceived as constituting an elevated level of risk or undue inconvenience compared to the rigors encountered during their routine training sessions. The teams agreed to participate with the expectation of obtaining results from performance assessments and testing. In **study one**, all players willingly shared their external training and match load data with the coaches. In **study two**, monitoring external training and match loads was a part of the habitual monitoring regime, eliminating the need for additional permission to share data with team coaches. The formal agreement for data sharing between the club included in **study two** and the university, extending beyond this project, is outlined in appendices 7 and 8.

3.6 Statistics

Descriptive results were calculated using Microsoft Excel across all studies. Data is reported as mean ± SD unless stated otherwise. Statistical analysis was performed in Mplus software (version 8.4) in **paper I**, and JASP (Jeffreys's Amazing Statistics Program) version 0.16.1 in **paper II**, **III** and **IV**. Analysis of external load match performance data were performed using non-overlap of all pairs (NAP) in **paper III** and **IV**. With the use of bayes statistics in **paper I**, the significance was assessed with 95% credibility intervals. Level of statistical significance in **study III** was set to $p < 0.05$.

In **paper I**, Bayesian 2-level regression analyses were performed to assess potential associations between match type and the dependent variables (for a comparison between Bayesian and the more traditional frequentist approaches see, for example, Stenling et al. (2015). Based on the findings in previous studies we included several co-variates potentially influencing external load match performance (Brocherie et al., 2018; Perez et al., 2020). Match type, match day (official matches) and playing time (time on ice) was used as predictor variables on the within-person level (level 1). Position was used as a predictor variable on the between-person level (level 2).

In **paper II** and **IV**, a non-parametric Bayesian correlation analysis was performed to investigate the relationship between the physical performance test variables and the external load variables. Kendall's Tau correlations in combination with Bayes Factors (BF) were calculated for each comparison (van Doorn et al., 2018). In line with previous research, the interpretation of BF_{10} were: >100=Extreme strong evidence for H1, 30-100=Very strong evidence for H1, 10-30=Strong evidence for H1, 3-10=Moderate evidence for H1, 1-3=Anecdotal evidence for H1, 1=No evidence. 0.33-1=Anecdotal evidence for H0, 0.10-0.33=Moderate evidence for H0, 0.033-0.1=Strong evidence for H0, 0.01-0.033=Very strong evidence for H0, <0.01=Extreme evidence for H0 (Schönbrodt & Wagenmakers, 2018).

In **paper III**, differences between the two autoregulation groups at each test-point were assessed using Man-Whitney U test, while the within group differences in pre- to post-test changes were analyzed using Wilcoxon signed-rank test. Between group differences from pre- to post-test were analyzed with a Friedmans test. Differences in external load match performance variables between the baseline- and follow-up period were assessed using NAP analysis in **paper III** and **IV**, with effect sizes reported according to previous recommendations: 0–.65 = week effects, .66–.92 = moderate effects, .93–1.0 = large or strong effects (Parker & Vannest, 2009).

Interpretation of meaningfulness of results were assessed by effect sizes in **paper I** and were considered trivial, small, moderate, large, and very large if <0.2, 0.2 to 0.6, 0.6 to 1.2, 1.2 to 2.0, or >2.0 (Hopkins et al., 2009). In **paper IV**, meaningfulness of results were assessed by calculated using the smallest worthwhile difference (Hopkins, 2000, 2004), applying baseline SD multiplied by 0.2 (small effect). Furthermore, individual raw and relative (% change) improvements were calculated and to be larger than raw and relative typical error (Lindberg et al., 2022) to be determined as meaningful (**paper IV**).

3.7 The consequences of Covid-19

The research project associated with this PhD thesis was initially scheduled to commence in late Q4 2019 / early Q1 2020. However, due to the outbreak of the Covid-19 pandemic, the project's specific studies underwent continuous rescheduling and replanning to adapt to the evolving situation. A brief outline of the original project plans is provided herein, with a comprehensive revision of the project detailed in Appendix 1. This appendix provides in-depth insights into the specific measures implemented in response to challenges posed by the pandemic, offering a better understanding of the project's evolution and the strategies employed to navigate during these unforeseen circumstances.

Originally, the project aimed to 1) evaluate external training and match load, 2) explore the relationships between physical test performance and external training and match load, and 3) investigate whether external training and match load data could reflect changes in physical test performance. These objectives were intended to be addressed through three sub-projects, denoted as sub-1, -2, and -3. All three sub-projects were designed to encompass junior/academy as well as senior/professional players from both ice-hockey and football.

- Sub-1 would focus on the quantification of external training and match load and the relationships to physical test performance. Sub-1 aimed to include external load data from team sport players during training, standardized drills, and matches in addition to assessments of physical test performance.

- Sub-2 aimed to improve physical test performance and explore if external training and match load data could be reflective of these changes. Sub-2 was designed to include an experimental strength intervention utilizing velocity-based strength training. The intervention would involve dividing the participants into two groups, one trained with low velocity loss and the other with high velocity loss. The physical test performance and external training and match load data would be assessed before and after the intervention period.

- Sub-3: This sub-project aimed to explore the longitudinal effects of changes in physical test performance and external training and match load data. Sub-3 overlaps with the aims of Sub-1 and intent to include regular assessments of physical test performance and external training and match load until approximately one year after the completion of Sub-2.

Despite the course of revisions from the original plan, this thesis still, in parts, managed to accomplish the objectives of sub-1 and -2. However, provoking larger changes in players data and pursuing the goals of sub-3 remain to be completed in further research.

4 Results

This section presents an overview of results and the main findings related to the overall aims for the thesis. Each paper, including specific results, can be found at the end of the thesis.

4.1 Ice-hockey external scrimmage and match load

External load data from official matches and scrimmages are presented in Table 5. Average time on ice for the respective match types was 26:28 ± 09:45 minutes during official matches and 21:00 ± 00:14 minutes during scrimmages. On average, players had 22.9 ± 7.4 and 20.0 ± 0.0 shifts per match, with the average time on ice per shift being 67.7 ± 8.7 s and 63.0 ± 0.7 s for official matches and scrimmages, respectively. Overall, a higher intensity, likely explained by the continuous play design, was observed in the data from scrimmages, compared to official matches. Credible beta-coefficients, indicating statistical difference between match types, are marked in Table 5. For specific results from the Bayesian 2-level regression analysis, please see **paper I**.

An individual assessment of players coefficient of variation (CV) in external load variables during official matches and scrimmages can be found in appendix 9. While scrimmages in general resulted in a lower CV, a large within player variance was still observed with players on average showing a CV of 12-25% (range: 1-104%) across the included variables in official matches and 9-15% (range 1-64%) from scrimmages.

Table 5: External load data from the included variables during official- and simulation matches (**study one**).

Variable	Match Type Official (n=109)	Scrimmage (n=60)	ES	95% CI
Total Distance (m)	4894 ± 1731	5015 ± 502*	0.09	-0.23 / 0.40
Peak speed (m/s)	8.50 ± 0.52	8.39 ± 0.54	-0.22	-0.53 / 0.10
Slow speed skating (m)	1228 ± 486	624 ± 166#	-1.49	-1.84 / -1.14
Moderate speed skating (m)	1547 ± 587	1775 ± 267*	0.46	0.14 / 0.77
High speed skating (m)	1744 ± 683	2164 ± 628*	0.63	0.31 / 0.95
Sprint speed skating (m)	365 ± 228	442.4 ± 285*	0.31	-0.01 / 0.63
Distance per min (m/min)	188 ± 18	239 ± 24*	2.51	2.09 / 2.92
Total PlayerLoad™ (au)	161.3 ± 59.8	143.3 ± 27.7*	-0.35	-0.67 / 0.04
PlayerLoad™ per min (au/min)	6.3 ± 1.2	6.8 ± 1.3*	0.42	0.10 / 0.74
High intensity events (nr)	237.8 ± 79.3	261.7 ± 63.7*	0.32	0.00 / 0.64
Accelerations (nr)	15.6 ± 10.1	9.3 ± 4.8	-0.73	-1.05 / -0.41
Decelerations (nr)	35.4 ± 15.2	43.3 ± 15.0*	0.52	0.20 / 0.84
Change of directions (nr)	186.7 ± 65.1	209.2 ± 56.0*	0.36	0.04 / 0.68

* Credible higher than official matches. # Credible lower than official matches. Mean ± SD. ES; Effect size, CI; Confidence interval. M; meter, au; arbitrary units, nr; number.

4.2 Autoregulation of strength training volume.

Sixteen players completed the intervention period (**paper III**). AUTO-group (n = 7) completed 1.1 ± 0.1 strength training sessions per week, while the SELF-group (n = 9) completed 1.0 ± 0.1 strength training sessions per week. On average, the AUTO-group and SELF-group completed 5.8 ± 1.2 and 6.4 ± 1.4 sets in leg extensor exercises (hip, knee, and ankle extensors) per strength training session, respectively. Associated physical performance results can be found in Table 6, with percent change presented in Figure 5. A detailed description of the calculation and application of HIR distance as an autoregulation marker can be found in appendix 10. No difference was observed between the AUTO- and SELF-group in the physical test performance measures. When assessing body composition, a significantly higher leg mass and leg lean mass was shown at post- compared to pre-test in the AUTO-group. These were the only significant differences observed, and with a SD of 2-3 kg among participants, the practical effect of this significant change should not be exaggerated. Comparing the SELF-group players HIR distance prior to the self-selection of strength training volume did not show any coherence with the applied objective autoregulation criteria, suggesting that HIR distance did not contribute to the perceived readiness to train feeling for players in the SELF-group. Nevertheless, regulating strength training volume based on external load HIR distance did not differentiate from letting players self-select training volume based on a readiness to train feeling.

Table 6: Physical performance at pre- and post-test (SELF n=9, AUTO n=7) from **study two**.

	Sprint			**CMJ**		**Leg press**			
	10 m (s)	30 m (s)	Max speed (m/s)	Height (cm)	Relative power (W/kg)	Pmax (W)	Relative Pmax (W/kg)	Fmax (N)	Relative Fmax (N/kg)
Pre-test									
SELF	1.53 ± 0.07	3.95 ± 0.17	8.75 ± 0.43	39.3 ± 6.2	31.8 ± 3.7	1487 ± 309	19.2 ± 2.7	2794 ± 377	36.2 ± 3.8
AUTO	1.52 ± 0.05	3.91 ± 0.11	8.88 ± 0.32	42.3 ± 3.6	32.8 ± 4.1	1667 ± 405	21.5 ± 4.2	3071 ± 640	40.0 ± 7.4
Mean	1.52 ± 0.06	3.93 ± 0.14	8.81 ± 0.38	40.6 ± 5.3	32.2 ± 3.8	1566 ± 353	20.2 ± 3.5	2915 ± 509	37.8 ± 5.8
Post-test									
SELF	1.52 ± 0.06	3.92 ± 0.16	8.78 ± 0.42	40.9 ± 7.1	31.6 ± 3.7	1488 ± 362	19.3 ± 4.0	2898 ± 368	37.8 ± 3.7
AUTO	1.49 ± 0.03	3.88 ± 0.10	9.06 ± 0.38	43.5 ± 6.1	32.0 ± 3.9	1650 ± 431	21.2 ± 4.5	3037 ± 647	39.3 ± 6.9
Mean	1.51 ± 0.05	3.90 ± 0.13	8.89 ± 0.42	42.0 ± 6.6	31.8 ± 3.7	1559 ± 388	20.1 ± 4.2	2959 ± 494	38.4 ± 5.2
Change pre to post									
SELF	-0.01 ± 0.04	-0.03 ± 0.08	-0.03 ± 0.18	1.7 ± 3.6	0.2 ± 2.3	1 ± 193	0.2 ± 2.3	104 ± 146	1.6 ± 2.3
AUTO	-0.02 ± 0.05	-0.03 ± 0.08	0.17 ± 0.18	1.2 ± 3.9	-0.8 ± 1.8	-17 ± 113	-0.3 ± 1.2	-34 ± 302	-0.6 ± 4.0
Mean	-0.02 ± 0.04	-0.03 ± 0.08	0.08 ± 0.19	1.5 ± 3.6	-0.5 ± 1.8	-7 ± 158	0.0 ± 1.9	44 ± 230	0.6 ± 3.2

CMJ: Countermovement jump, Pmax: Maximum power (W and W/kg total body mass) extrapolated from Keiser leg press power profile, Fmax: Maximum force (N and N/kg total body mass) extrapolated from Keiser leg press power profile.

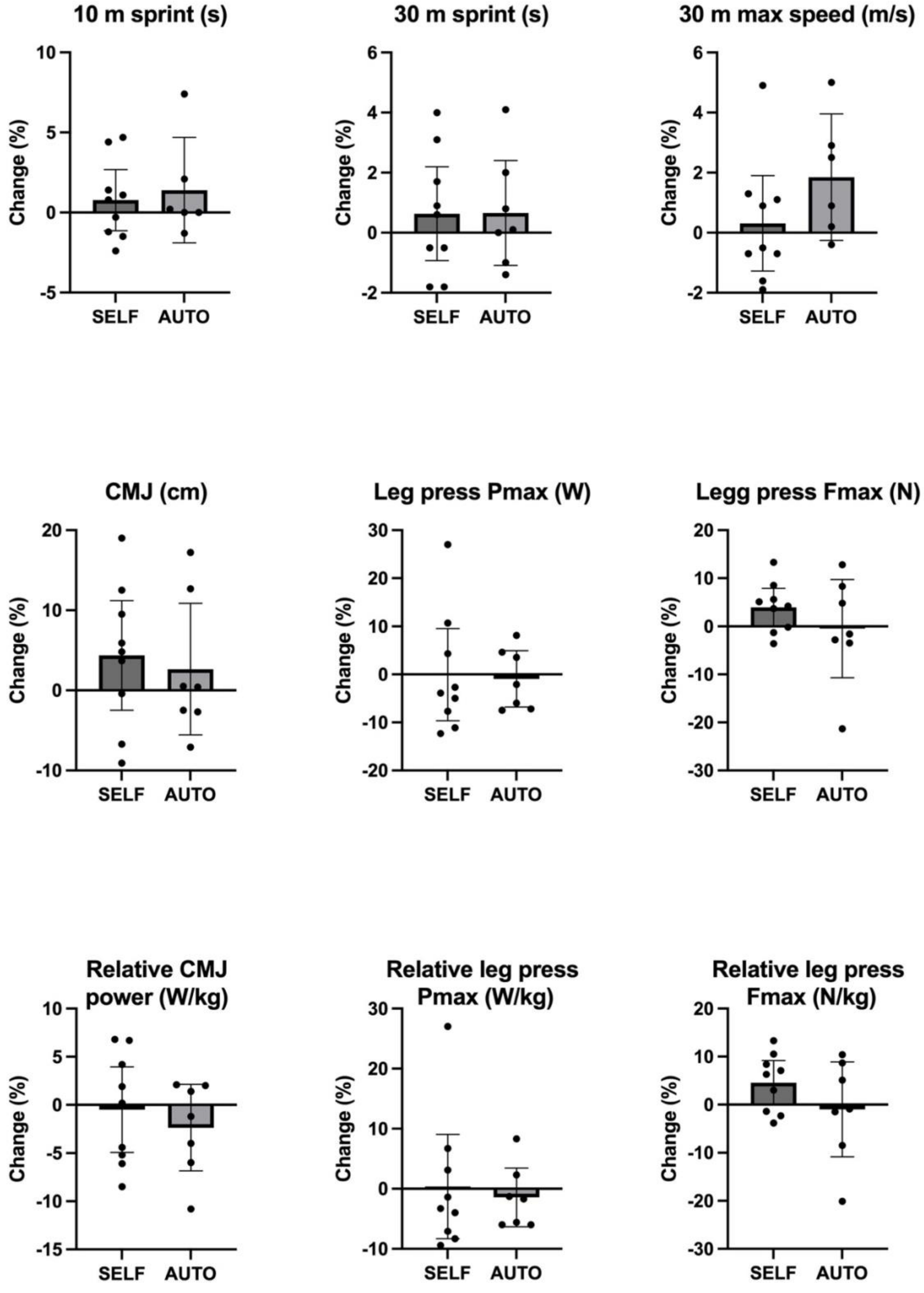

Figure 5. *Mean ±95% CI % change in physical performance tests, including individual changes from pre- to post test. 10 and 30 m; Time to 10 m and 30 m during sprint tests, Max Speed: Maximum speed (m/s) during 30-m sprint testing, CMJ: Countermovement jump, Pmax: maximum power (W and W/kg total body mass) extrapolated from Keiser leg press power profile, Fmax: maximum force (N and N/kg total body mass) extrapolated from Keiser leg press power profile. Note: positive change in 10 and 30 m times indicates improvement from pre- to post test.*

4.3 Football external match load data

Ten and eleven players completing physical performance testing fulfilled the inclusion criteria for external load data from the baseline and follow-up period, respectively. However, only eight players fulfilled the inclusion criteria for football match data from both periods (included in **paper III** and **IV)**. In total players appeared in 4.0 ± 1.3 matches (40 observations) with 89.6 ± 12.5 minutes playing time in the baseline period and in 4.1 ± 1.0 matches (45 observations) with 90.3 ± 8.8 minutes playing time in the follow-up period. Average horizontal dilution of precision and connected number of satellites was 0.90 ± 0.16 (min: 2.61 ± 0.77, max: 0.63 ± 0.12) and 14.8 ± 1.7 (min: 9.4 ± 2.5, max: 17.5 ± 1.4), in the baseline period, and 1.0 ± 0.16 (min: 3.2 ± 0.80, max: 0.69 ± 0.04) and 13.7 ± 1.1 (min: 9.1 ± 1.3, max: 16.4 ± 1.2), respectively, in the follow-up period. A summary of external match load data for players fulfilling the inclusion criteria at either period can be seen in Table 7 and results from NAP analysis of the eight players included from both time-periods can be found in Table 8. A visual presentation of players NAP can also be found in appendix 11. An individual assessment of variation (CV) in external load variables of the eight players fulfilling the inclusion criteria at both baseline- and follow-up period can be found in appendix 9.

Table 7: External match load from baseline- and follow-up period.

Variable	**Baseline period** (n=10)	**Follow-up period** (n=11)
Distance per min (m/min)	116.2 ± 10.7	121.4 ± 8.7
Peak Speed (m/s)	8.15 ± 0.32	8.34 ± 0.35
PlayerLoad^{TM} per min (au/min)	11.96 ± 1.70	12.28 ± 1.50
HSR distance (19.8-25.2 km/h) (m/min)	6.19 ± 2.16	7.10 ± 1.51
Sprint distance (>25.2 km/h) (m/min)	1.27 ± 0.70	1.67 ± 0.81
Efforts HIR (19.8-25.2 km/h) (nr/min)	0.42 ± 0.13	0.46 ± 0.10
Efforts Sprint (>25.2 km/h) (nr/min)	0.07 ± 0.04	0.09 ± 0.05
High intensity events (>2.5 m/s) (nr/min)	1.18 ± 0.31	1.38 ± 0.24
Accelerations (>2.5 m/s) (nr/min)	0.25 ± 0.08	0.33 ± 0.08
Decelerations (>2.5 m/s) (nr/min)	0.26 ± 0.08	0.26 ± 0.07
Change of directions (>2.5 m/s) (nr/min)	0.67 ± 0.20	0.79 ± 0.15

Note: The table includes players fulfilling the inclusion criteria at either time periods (i.e., pre-test and baseline period, or post-test and follow-up period. All values except Peak speed are relative to playing time (i.e., per min). Au; arbitrary units, nr; number. HSR; High speed running.

Table 8: NAP analysis between baseline and follow-up period in external match load data.

	TD (m/min)	**Peak speed** (m/s)	**PlayerLoad™** (au/min)	**HSR** (m/min)	**SPR** (m/min)	**#HIR** (nr/min)	**#SPR** (nr/min)	**HIEs** (nr/min)	**Acc** (nr/min)	**Dec** (nr/min)	**CoD** (nr/min)
Player a	.80*	.80*	.75*	.90*	.75*	.70*	.80*	.90*	.85*	.15	.80*
Player b	.27	.67*	.20	.60	.73*	.60	.73*	.60	.40	.73*	.53
Player c	.64	.40	.52	.84	.76*	.84*	.80*	.88*	1.00**	.64	.86*
Player d	.95**	.75*	.90*	1.00**	.85*	1.00**	.90*	.20	.53	.40	.25
Player e	.84*	.64	.84*	.60	.60	.44	.58	.92*	.76*	.36	.96**
Player f	.60	.40	.40	.47	.33	.33	.53	1.00**	1.00**	.87*	1.00**
Player g	.50	1.00**	.63	.88*	1.00**	.88*	1.00**	.38	.25	.00	.38
Player h	.60	.70*	.45	.43	.80*	.60	.80*	.20	.90*	.05	.20
Combined	*.67**	*.65*	*.60*	*.71**	*.72**	*.67**	*.76**	*.65*	*.74**	*.41*	*.64*
90% CI	.43 -.92	.41 -.90	.35 -.85	.47 -.96	.48 - .97	.43 -.92	.51 – 1.00	.41 -.90	.50 -.90	.16 -.65	.40 - .89

* Moderate or **strong effect in Non overlap of all pairs analysis of external load match performance between baseline and follow-up period. TD: total distance, au: arbitrary units, HSR: high speed running distance, SPR: sprint running distance, #: efforts, nr: number, HIEs: high intensity events, Acc: accelerations, Dec: decelerations, CoD: change of directions.

4.4 Association between physical performance tests and external load data.

Results from Kendall's Tau correlation analysis assessing the associations between physical performance and external load data during scrimmages in **paper II** can be found in Table 9. Body mass, max speed skate, CMJ, pull-ups, and trap bar deadlift were the only physical performance measures with a $BF_{10} > 3$ for the association with external load variables from scrimmages. Body mass had a moderate correlation with total distance. Max speed skate had a strong correlation with peak speed and a moderate correlation with sprint speed skating. CMJ had a moderate correlation with sprint speed skating and the number of sprints performed. Pull-ups had a large correlation with HIEs and a moderate correlation with change of directions. Finally, a moderate correlation was seen between trap bar deadlift and peak speed.

With ten and eleven players fulfilling the criteria for external load inclusion at either baseline or follow-up period from **paper III**, a separate Kendall's Tau correlation analysis was performed to assess the relationship between physical performance (pre/post-test) and external load match performance (baseline/follow-up period). Results can be found in Table 10 (data not reported in published papers). In summary, two sprint performance variables showed moderate (BF_{10} >3) and strong (BF_{10} >10) evidence to peak speed, namely max speed at pre-test/baseline period and 30 m time at post-test/follow-up period, respectively (not reported in published papers). Notably, peak speed was identified with credible associations towards sprint test measures in both ice-hockey (Table 9) and football-players (Table 10). A visual presentation of correlation scatterplots between sprint test measures and peak speed from scrimmages and football, can be seen in appendix 12.

4.5 Relationships between changes in physical performance tests and changes in external match load data.

Individual physical and test performance results for the eight players included in **paper IV** are presented in Table 11. In total, three players showed physical performance improvements greater than the SWD, TE and TE%, which needed to be categorized as a "meaningful improvement". All eight players showed moderate to strong effects in external load match performance from baseline to follow-up period (Table 8 and Table 11). The association between changes in physical- and external load match performance data are reported in **paper IV** and shown in Table 10. Moderate evidence was shown for max speed to number of decelerations. No other evidence (BF_{10} >3) was evident for the associations between changes in physical performance and external load match performance within the study period.

Table 9: Kendall's Tau correlation matrix between external load and physical performance variables in ice-hockey players.

		Sprint on track			Sprint on ice							
	Body mass (kg)	10 m (s)	30 m (s)	Max speed run (s)	10 m (s)	30 m (s)	Max speed skate (s)	CMJ (cm)	Long-jump (cm)	Bench-press (kg)	Pullups (nr)	Trap bar (kg)
TD (m)	0.49*	-0.01	-0.17	0.18	-0.09	-0.21	0.29	0.42	0.14	0.37	0.34	0.27
Peak Speed (m/s)	0.22	-0.28	-0.39	0.27	-0.13	-0.34	0.55**	0.42	0.36	0.16	0.10	0.45*
SlowSS (m)	-0.3	0.01	0.17	-0.13	0.18	0.21	-0.29	-0.29	-0.10	-0.25	-0.17	-0.23
ModSS (m)	-0.35	0.12	0.19	-0.24	0.11	0.28	-0.35	-0.40	-0.17	-0.25	-0.21	-0.27
HighSS (m)	0.42	0.03	-0.12	0.09	-0.09	-0.17	0.24	0.33	0.06	0.32	0.30	0.18
SprSS (m)	0.28	-0.21	-0.32	0.29	-0.16	-0.36	0.44*	0.44*	0.30	0.25	0.17	0.34
Nr of sprints (nr)	0.43	-0.04	-0.16	0.10	-0.21	-0.29	0.28	0.46*	0.13	0.22	0.34	0.15
Total PL (au)	0.29	0.11	0.00	-0.08	-0.06	-0.09	0.03	0.06	-0.09	-0.10	0.38	0.10
HIEs (nr)	0.37	0.39	0.36	-0.20	0.29	0.14	-0.16	0.02	-0.17	-0.07	0.61**	-0.14
Acc (nr)	0.27	0.22	0.33	-0.28	-0.06	-0.02	-0.17	0.03	-0.13	-0.37	0.29	-0.15
Dec (nr)	0.12	0.21	0.28	-0.40	-0.04	0.14	-0.20	-0.07	-0.25	-0.18	0.32	-0.11
CoD (nr)	0.30	0.30	0.23	-0.07	0.20	-0.03	-0.02	0.07	-0.08	0.02	0.50*	-0.02

Kendall's Tau correlations. *Moderate evidence for H1 (BF_{10} >3), **Strong evidence for H1 (BF_{10} >10). CMJ: Counter movement jump height (cm), pullups (max repetitions), bench-press (1RM), trap bar: Deadlift in a trap bar, TD: Total distance, SS: Speed skating, Mod: moderate, PL: PlayerLoad^{TM} (au), HIEs: High intensity events, Acc: Accelerations, Dec: Decelerations, CoDs, Change of directions.

Table 10: Kendal's Tau correlations matrix between physical performance tests and external match load data during **study two**.

	Sprint performance			CMJ	Leg press	
	10 m (s)	**30 m** (s)	**Max speed** (m/s)	(cm)	**Pmax** (W)	**Fmax** (N)
Pre-test and Baseline period						
TD (m/min)	0.14	0.09	-0.20	-0.20	-0.18	-0.20
Peak speed (m/s)	-0.45	-0.49	0.56*	0.11	0.05	0.02
PlayerLoad™ (au/min)	0.14	0.09	-0.11	0.07	-0.23	-0.20
HSR (m/min)	0.14	0.09	-0.11	-0.20	-0.09	-0.20
SPR (m/min)	-0.05	-0.09	0.16	0.07	-0.09	-0.11
#HSR (nr/min)	0.02	-0.02	0.00	-0.05	-0.11	-0.14
#SPR (nr/min)	-0.16	-0.21	0.27	0.18	-0.07	-0.09
HIEs (nr/min)	-0.09	-0.09	0.16	-0.29	0.32	0.24
Acc (nr/min)	-0.02	-0.02	0.09	-0.27	0.25	0.14
Dec (nr/min)	-0.05	-0.09	0.07	0.07	-0.05	0.07
CoD (nr/min)	-0.05	-0.05	0.11	-0.24	0.27	0.20
Post-test and Follow-up period						
TD (m/min)	-0.07	0.28	-0.36	-0.49	-0.38	-0.38
Peak speed (m/s)	-0.40	-0.69**	0.49	0.49	0.38	0.31
PlayerLoad™ (au/min)	-0.12	0.17	-0.27	-0.31	-0.35	-0.35
HSR (m/min)	-0.16	-0.06	0.05	-0.09	-0.06	0.09
SPR (m/min)	-0.35	-0.39	0.41	0.24	0.20	0.42
#HSR (nr/min)	-0.27	-0.14	0.24	0.06	0.02	0.17
#SPR (nr/min)	-0.24	-0.33	0.35	0.17	0.13	0.36
HIEs (nr/min)	-0.33	0.15	0.43	-0.18	-0.04	-0.07
Acc (nr/min)	-0.14	0.08	0.41	0.04	0.15	-0.15
Dec (nr/min)	-0.05	0.30	0.39	-0.15	-0.26	-0.11
CoD (nr/min)	-0.26	0.02	0.40	-0.06	0.06	-0.09
Change						
TD (m/min)	0.07	0.07	0.14	0.07	0.21	-0.14
Peak speed (m/s)	0.22	0.57	0.36	0.43	0.14	-0.21
PlayerLoad™ (au/min)	0.15	0.21	0.29	0.07	0.36	-0.29
HSR (m/min)	-0.30	-0.07	0.00	-0.21	-0.07	-0.29
SPR (m/min)	-0.22	0.14	0.36	0.00	0.14	0.21
#HSR (nr/min)	-0.57	-0.18	0.04	-0.33	-0.18	-0.11
#SPR (nr/min)	-0.36	0.00	0.08	-0.15	0.15	0.23
HIEs (nr/min)	0.15	-0.26	-0.47	-0.11	0.11	-0.04
Acc (nr/min)	0.52	0.07	0.00	-0.07	0.21	-0.14
Dec (nr/min)	-0.04	-0.40	-0.62*	-0.33	-0.33	-0.26
CoD (nr/min)	0.30	-0.14	-0.50	0.00	0.29	-0.07

Kendall's Tau correlations. * Moderate evidence for H1 (BF_{10} >3). ** Strong evidence for H1 (BF_{10} >10). 10 and 30 m; Time to 10 m and 30 m during sprint tests, Max Speed: Maximum speed (m/s) during 30-m sprint testing, CMJ: Countermovement jump, Pmax: maximum power (W) extrapolated from Keiser leg press power profile, Fmax: maximum force (N) extrapolated from Keiser leg press power profile, TD: Total distance, au: arbitrary units, HIR: High speed running, SPR: Sprint running, #: efforts, nr: number, HIEs: High intensity events, Acc: accelerations, Dec: decelerations, CoD: Change of directions.

Table 11: Individual results and change from baseline to post/follow-up in physical test performance and external match load data.

	Physical performance					External match load								
	10 m s	**30 m** s	**Max speed** m/s	**CMJ** cm	**Pmax** W	**TD** m/min	**Peak speed** m/s	**Player-Load** PL/min	**HSR** m/min	**SPR** m/min	**HIEs** nr/min	**Acc** (>2.5) nr/min	**Dec** (>2.5) nr/min	**CoD** (>2.5) nr/min
Pre-test/baseline														
Player a	1.60	4.04	8.64	41.5	1534	106.6	7.96	10.6	3.31	0.55	1.03	0.21	0.21	0.61
Player b	1.65	4.27	7.97	27.4	1165	132.4	7.56	13.7	7.92	0.66	1.01	0.25	0.19	0.58
Player c	1.44	3.71	9.42	46.9	1164	112.2	8.74	12.0	6.62	1.90	0.93	0.21	0.24	0.47
Player d	1.49	3.85	9.06	44.0	1902	100.4	8.01	9.7	2.28	0.51	1.44	0.41	0.22	0.81
Player e	1.49	3.80	9.36	47.5	2098	121.0	8.29	12.9	7.19	1.60	1.21	0.28	0.27	0.66
Player f	1.54	3.93	8.77	42.7	1597	128.6	8.25	13.3	7.94	1.98	1.26	0.23	0.35	0.68
Player g	1.46	3.79	9.09	38.7	1719	127.0	8.33	11.3	7.61	1.01	1.59	0.36	0.33	0.90
Player h	1.52	3.92	8.87	39.0	1673	110.3	8.32	10.4	8.40	2.47	1.51	0.24	0.31	0.96
Post-test/follow-up														
Player a	1.53	3.88	9.06	49.4	1599	111.8	8.58	11.2	5.08	1.16	1.17	0.30	0.18	0.70
Player b	1.67	4.29	7.94	28.7	1035	130.4	7.70	12.5	8.72	0.90	1.04	0.20	0.22	0.61
Player c	1.47	3.78	9.35	43.8	1105	115.3	8.59	12.1	8.30	2.50	1.19	0.27#	0.26	0.65
Player d	1.51	3.89	9.14	42.8	1764	107.8#	8.31	10.4	4.93#	0.93	1.30	0.39	0.21	0.69
Player e	1.46	3.72	9.60	55.7	2267	126.5	8.57	13.3	7.45	1.77	1.42	0.33	0.25	0.84#
Player f	n/a	3.99	n/a	39.6	1478	130.3	8.26	13.4	7.93	1.67	1.77#	0.34#	0.42	1.00#
Player g	1.46	3.79	9.06	38.9	1683	126.6	8.81#	11.7	8.73	2.08#	1.39	0.32	0.20	0.86
Player h	1.52	3.88	9.31	43.9	1573	110.0	8.45	10.2	8.38	3.25	1.30	0.27	0.23	0.81

Change pre/baseline – post/follow-up														
Player a	**0.08***	**0.16***	**0.42***	**7.9***	65	5.3†	0.62†	0.7†	1.77†	0.61†	0.14†	0.08†	-0.03	0.09†
Player b	-0.02	-0.02	-0.04	1.3	-130	-2.0	0.14†	-1.3	0.80†	0.24†	0.02	-0.05	0.04†	0.03
Player c	-0.03	-0.07	-0.07	-3.1	-59	3.1†	-0.14	0.1	1.68†	0.60†	0.26†	0.06†	0.02†	0.18†
Player d	-0.02	-0.04	0.08	-1.2	-138	7.4†	0.30†	0.7†	2.65†	0.42†	-0.14	-0.02	-0.01	-0.12
Player e	**0.03***	**0.08***	**0.23***	**8.2***	**169***	5.5†	0.28†	0.4†	0.25	0.17†	0.22†	0.05†	-0.03	0.19†
Player f	n/a	-0.05	n/a	-3.0	-119	1.7	0.00	0.0	-0.01	-0.32	0.51†	0.11†	0.07†	0.32†
Player g	0.00	0.00	-0.03	0.2	-36	-0.4	0.48†	0.4†	1.12†	1.06†	-0.20	-0.04	-0.13	-0.03
Player h	0.00	0.03	**0.45***	**5.0***	-100	-0.3	0.13†	-0.3	-0.03	0.78†	-0.20	0.03†	-0.08	-0.15

Note: Positive change in 10 and 30 m times indicate improved performance from pre to post. N/a; missing data.

* Bold text indicates that physical performance changes were larger than SWD, raw and relative (%) TE. #Strong effects in Non overlap of all pair analysis (in follow-up compared to baseline period). †Larger than SWD calculated from baseline results. CMJ: Countermovement jump, Pmax: Max power (W), TD: total distance, HSR: high speed running distance, SPR: sprint running distance, HIEs: high intensity events, Acc: accelerations, Dec: decelerations, CoD: change of directions.

5 Discussion

This chapter provides an overview of the objectives and outcomes of the present thesis, through the completion of two distinct studies, resulting in four included papers. The following chapter will firstly address the main findings in relation to the overall research aims of the present thesis, namely external training and match load demands within ice-hockey, the relationships between physical test performance and external training and match load data, and if changes in physical test performance can be reflected in external training and match load data. The second part consists of a methodological discussion of the thesis and overarching aims related to the findings.

5.1 Discussion of main findings

This thesis highlights the complexities of assessing team sport players physical test performance and the potential relationships to external training and match load data. However, the thesis provided more detailed insight into the application of external training load data within ice-hockey. Specifically, **paper I** indicated that competitive demands could be effectively replicated in training through the implementation of scrimmages. Notable differences were observed in the scrimmages, displaying a higher relative intensity with increased distance in the high intensity-, and less distance in the slow intensity locomotive categories.

When exploring the association between physical test performance and external scrimmage and match load data in **paper II**, a limited number of associations between physical tests performance and external scrimmage match load was observed. Coherent results were observed when exploring the same relationships between football players physical performance and external match load during **study two** (data not reported in papers).

Paper III showed no differences between objectively and subjectively regulating professional football players strength training volume during an in-season strength intervention period. Lastly, the primary finding of **paper IV**, indicated that three of eight players were categorized with a meaningful improvement in physical test performance following the intervention period presented in **paper III**, however, these improvements were not consistently reflected in changes in external match load data.

5.1.1 Ice-hockey external match load

After the introduction of LPS systems, studies have started to provide a description of competitive external training and match load demands in ice-hockey (Huard Pelletier et al., 2021). However, the body of literature is still scarce and to the author's knowledge, there has only been a handful of studies applying LPS within ice-hockey training and match analysis (Douglas & Kennedy, 2019; Gamble et al., 2022; Gamble et al., 2023; Vigh-Larsen, Ermidis, et al., 2020). Notably, there are also some studies exploring external training and match load demands in ice-hockey by applying IMU-data, (Allard et al., 2020; Douglas, Johnston, et al., 2019; Douglas, Rotondi, et al., 2019; Douglas et al., 2020; Perez, Brocherie, et al., 2022; Rago et al., 2022). In **paper I** we provide novel insight to external match load demands in a team of highly trained male youth ice-hockey players. When comparing the results from the official matches to previous research, the observed total distance seems to fit within previous observations, suggesting that this measure is somewhat uniform, with 4-7 km reported from junior level to elite NHL level players (Douglas & Kennedy, 2019; Lignell et al., 2018; Vigh-Larsen, Ermidis, et al., 2020; Vigh-Larsen & Mohr, 2022). However, when assessing different locomotive speed categories, higher caliber players tend to cover more distance in the higher intensity zones. For example, we observed 1744 ± 683 m and 365 ± 228 m in the high and sprint speed skating zones during matches. While similar distances have been observed in the high intensity zone among national team youth players and elite senior players, sprint distance skating is reported to be higher, with >500 m covered in this zone (Douglas & Kennedy, 2019; Lignell et al., 2018). This finding is coherent to previous observations in football, where total distance is quite uniform across competitive levels, while a distinction is made when assessing more intensified measures, such as sprint distance (Bradley et al., 2016; Sæterbakken et al., 2019).

5.1.2 Ice-hockey external scrimmage load

To the best of the authors knowledge, only Vigh-Larsen, Ermidis, et al. (2020) have replicated and assessed simulated match demands with a LPS system. Indeed, skating protocols and other measures to provoke a match-like intensity has been previously attempted (Schwesig et al., 2021; Steeves & Campagna, 2019). However, use of standardized game formats, such as observed in football (Owen et al., 2013; Sarmento et al., 2018), is currently unexplored in ice-hockey (Huard Pelletier et al., 2021). The adoption of the simulated game design from Vigh-Larsen, Ermidis, et al. (2020) allowed for a standardized match-format that was preferable for the aims of **paper II**, exploring the relationships between physical test performance and external scrimmage load. Compared to Vigh-Larsen, Ermidis, et al. (2020), our scrimmage load data displayed a lower total distance (~5 vs 6 km). This may be attributed to methodological differences as we included a continuous play design and show a significantly lower slow speed distance (~600 m vs 1400 m), and higher distance covered with sprint speed (442 vs 309 m), in our study.

When comparing the external scrimmage load data to the external match load data, a higher relative intensity is observed, with distance per min reported as 239 ± 24 m vs 188 ± 18 m during official matches. This was displayed by a lower distance in the slow intensity zone (~600 m vs 1200 m) and increased distance in the high (~2200 vs ~1700 m) and sprint (365 vs 442 m) skating intensity zones. Although some similarities are also observed in our results between the two playing conditions, scrimmages, including a non-stop playing design, do not conform to a typical playing format. For example, the removal of stops and puck drops eliminates an essential component of ice-hockey match play and may also explain the lower number of accelerations observed during scrimmages (9.3 ± 4.8 vs 15.6 ± 10.1).

The applied scrimmage design enables standardization of the physical load imposed on players, as all players are exposed to the same playing time. Accordingly, this design may be suitable in training situations where its desirable to "overload" players with an intensity superior to that of official match demands. This design was indeed applied in coherence with the team coaches, to simulate match activity due to postponement of official match activity during the study period. Thus, while the standardized scrimmages may not be a true representation of the technical and tactical performance, the design can be applied to mimic match play intensity and standardize the physical load across all players. Besides being used as a training modality for simulating match play, the design can also be used as a tool to induce training stimulus and potential adaptations relevant for ice-hockey specific abilities.

5.1.3 Physical test performance and external scrimmage load in ice-hockey

The associations between physical test performance and external scrimmage load were explored in **paper II**. Overall, a limited number (8 of 144) of credible associations were identified. An important distinction between typical field-based sports and ice-hockey, is the translation of off-ice-measures to on-ice movements. While off-ice measures may be correlated with specific skills (Schwesig et al., 2021; Thompson et al., 2020), it does not guarantee an corresponding on-ice performance (Burr et al., 2008). Transferability between specific task-abilities, such as off and on-ice test has been debated as the physiological demands of different measures, such as sprint running vs skating, may not be relatable (Huard Pelletier et al., 2021; Thompson et al., 2020; Young, 2006). For example, distance related measures in ice-hockey are often less associated to the physiological stress, as a significant part of players movements relates to gliding or coasting across the ice (Vigh-Larsen & Mohr, 2022). As reported in **paper II**, an association between max speed from on-ice sprinting and peak speed and sprint skating distance was observed, while no associations were displayed for off-ice sprint testing and measures of external scrimmage load data. While off-ice sprinting may be suggested as a feasible training method to induce certain training stimulus (Delisle-Houde et al., 2019; Wagner et al., 2021), our results suggest that practitioners should be cautious with postulating a relevance between these off- and on-ice measures of sprinting abilities.

Leg extensor strength is central for acceleration of the body during sprints or with change of directions in a variety of sports (Gillen et al., 2020; Suchomel et al., 2016), whereas upper body pulling muscles, such as those used during pull-ups, are less involved in ice-hockey movements. The displayed association for CMJ towards external scrimmage load sprinting abilities was therefore expected. On the contrary, it was somewhat surprising to observe that IMU data (HIEs and change of directions), showed evidence for an association towards pullups. Logically, we were expecting the IMU data to show an association toward lower body extensor strength, such as trap bar deadlifts. The observed associations between pullups and

IMU data could be explained by strength relative to body mass. However, no meaningful relationships were observed when trap bar deadlift strength was expressed relative to body mass (data not reported).

It is noteworthy that a high level of physical exertion is achieved during puck battles in the corners of the rink, along the boards, and in front of the opposing goal. These isometric actions impose significant demands on the players. However, existing wearable tracking systems currently lacks the capability to accurately quantify these specific types of actions (Torres-Ronda et al., 2022). Although the test protocol used in **paper II** comprises physical performance tests considered important in ice-hockey (Haugen et al., 2021; Nightingale et al., 2013), it does not include any measurement of isometric strength. Future studies should strive to incorporate such measurements and explore potential ways to quantify these isometric demands during match-specific conditions.

5.1.4 Physical test performance and external match load in football

The association between physical test performance and external match load data is not reported in any of the papers. However, the thesis included a separate analysis utilizing the dataset from **study two**. Specifically, a correlation analysis exploring the associations between physical test performance and external match load data for players fulfilling the physical performance testing and external match load inclusion criteria at two separate time points (pre-test/baseline period and post-test/follow-up period) was included. Only two credible associations (one at each time-point) were identified when examining the relationship between physical test performance and external load match performance, namely max speed and 30 m sprint time to peak speed (Table 10). Notably, peak speed demonstrated associations with the results of sprint test performance in both ice-hockey and football. This observation is coherent with some recent studies suggesting that peak speed from external load data may be a valid measure of maximal sprinting abilities (Cormier et al., 2022; Reinhardt et al., 2019). Indeed, a similar study by Pedersen and colleagues performed on 36 Norwegian female football players identified peak speed from friendly matches as a marker strongly associated to sprint test performance ($r = 0.56$) and CMJ ($r = 0.50$). In addition, a moderate association between sprint test and accelerations were found ($r = 0.43$) (Pedersen et al., 2022). While some relationships between physical test performance and external match load were found in their study, the majority of associations were non-significant and in line with our findings.

5.1.5 Changes in physical test performance and external match load

During **study two**, a strength intervention period was implemented. This intervention, presented in **paper III**, utilized two different methods of autoregulation, namely objective (AUTO-group) and subjective (SELF-group) autoregulation. With a similar (5.8 ± 1.2 and 6.4 ± 1.4 sets in leg extensor exercises pr session), and overall low strength training volume (~1 session pr week), the lack of differences within or between the groups from pre- to post-test was not unexpected. Furthermore, the inclusion of one-weekly session and maintained physical performance during in-season intervention period, as presented in **paper III**, is not uncommon (Otero-Esquina et al., 2017; Rønnestad et al., 2011; Silva et al., 2015). However, the effects of this training compared to solely performing field-based training is unknown with the lack of a control-group. This is typical whenever working with high-level or professional players as no coach or organization will willingly accept some of their players being placed in a control-group, prescribed with less training stimulus compared to other players (Cormier et al., 2020; Cuthbert et al., 2021; Silva et al., 2015).

While the current thesis, and specifically **paper IV**, aimed to provide new insight into the relationships between changes in physical test performance and external match load data, there are some challenges within the dataset. Specifically, players training responses was, to a large extent, restricted by the methods applied during the intervention period (**paper III**). We aimed for two strength session per week and regulating strength training to two, four or six sets per exercise, however the average number of sessions was 1.1 session per week with one, two or three sets pr exercise. This is not unique whenever working with professional sport players within the in-season period (Beato, Maroto-Izquierdo, et al., 2021; Rønnestad et al., 2011; Silva et al., 2015). Consequently, this likely restricted the potential for change in physical test performance results in our group, challenging the process and aims of **paper IV**, as the potential for improvement was limited by the overall low strength training stimuli.

In **paper IV**, three players (player a, e, and h) demonstrated a meaningful improvement in physical performance tests (Table 11). On the contrary, three other players (d, g, and f) exhibited notable NAP effects when comparing the baseline and follow-up periods' external load match performance data (Table 8). In fact, all eight players displayed moderate to strong NAP effects, in their external load match performance between the two periods. We do, however, argue to categorize the observed NAP-effects as practically unsignificant, as the observed difference in external match load data was below the typical match variations in these variables (Carling et al., 2016; Gregson et al., 2010). Exploring the associations between changes in physical test performance and external match load underlined this finding with only one credible association identified (Table 10).

5.2 Methodological discussion, strengths, and limitations

The present thesis encompasses four distinct studies, employing different research designs and methodologies. **Paper I** and **II** from **study one** adopted cross-sectional analysis, albeit with a longitudinal approach in the data sampling, to explore the relationship between physical test performance and external training and match load in ice-hockey players. Conversely, **paper III** from **study two** utilized a randomized trial approach to investigate the effects of two autoregulation strength training methods. Notably, cross-sectional analysis of data from **study two** was also incorporated into the thesis. Finally, **paper III** served as the foundation for the case study presented in **paper IV**, investigating the changes between to time-periods.

5.2.1 External load data

Similar to physical performance tests, external load aims to quantify aspects related to sport-specific performance, such as those encountered during training or match situations (Theodoropoulos et al., 2020). While external load, per se, is intended to be a representation of the completed work performed by a player (e.g., number of kg lifted or distance covered) (Impellizzeri et al., 2022), applying tracking systems in sport specific activities does not make the associated external load monitoring data a valid measure of sport specific performance (Currell & Jeukendrup, 2008). Additionally, a measure may be discriminative without necessarily indicating increased performance or level of success. For example, high intensity running is commonly used to monitor external match load (Akenhead & Nassis, 2016), and higher-caliber players tend to cover more distance in high intensity running zones (Carling, 2013; Sæterbakken et al., 2019). However, when factors related to winning or losing are assessed, high intensity running seems unrelated to the level of success (Carling, 2013).

The accuracy of external training and match load data has been debated in the recent years, with reference to the numerous manufactures and overwhelming data variables (Barker-Ruchti et al., 2021; Bourdon et al., 2017; Cardinale & Varley, 2017; Malone et al., 2017). Regarding the systems utilized in this thesis, the Catapult ClearSky T6 system applied during **study one** has been found to have acceptable validity and reliability, albeit with reduced reliability during higher intensity and more complex movements (Luteberget et al., 2017). Similarly, the Catapult Vector S7 system used during **study two** has been rated as both acceptable and questionable in terms of the validity and reliability of certain measures (Cormier et al., 2022; Crang et al., 2022; Ellens et al., 2022). Generally, locomotive measures such as total distance and distance covered in low and moderate intensity zones appear to provide good and acceptable reliability for both LPS and GNSS-based tracking systems, while caution should be taken when interpreting data from the highest intensity zones (Crang et al., 2021; Cummins et al., 2013). For instance, 30-40% CV have been reported for high-speed and sprint running distances, and similar values are observed in our data from both ice-hockey and football (appendix 8) (Gualtieri et al., 2023). Interestingly, these measures are frequently used by practitioners to evaluate external load performance in both training and matches (Akenhead & Nassis, 2016).

In recent years, there has been increased focus on acceleration-based external load variables (Akenhead et al., 2016; Teixeira et al., 2021). These variables can be calculated from positional data (e.g., GNSS/LPS) as well as regular accelerometer-derived data. However, it is important to distinguish between these variables due to their varying reported accuracy (Varley et al., 2017). Contrasting to 10Hz GNSS data derived from doppler shift calculations (Rico-González et al., 2020), IMU uses raw accelerometer and gyroscope data sampling at 100Hz to create a nongravitational acceleration vector (or data) based on Kalman filtering algorithms (Luteberget et al., 2017). These algorithms detect specific acceleration events, which can be defined as an instant 1-step movement effort. The magnitude of an event is calculated as the area under the curve, based on the sum of anterior–posterior and mediolateral accelerations. The magnitude is expressed as delta velocity (in $m \cdot s^{-1}$). The direction of an event is calculated relative to the device's orientation at the time of the step and is based on the angle of the applied acceleration and is measured in degrees (±180°) (Luteberget et al., 2017). Consequently, IMU derived acceleration-based variables has been suggested to be more accurate compared to GNSS/LPS based acceleration variables (Luteberget et al., 2017; Sandmæl & Dalen, 2023). For instance, GNSS-derived measures of the most intense acceleration and decelerations have been shown to have a CV of 25-74% (Crang et al., 2022), whereas comparable measures from IMU devices exhibit a CV of 12-22% (Luteberget et al., 2017).

While these findings are in line with our observation from football, a CV of 9-42% was shown in IMU variables from ice-hockey matches and scrimmages (appendix 9). It is important to note that while IMU-variables may be more precise, both methods and calculation approaches can either increase or decrease reliability depending on the variable calculation. Acceleration-derived measures such as accelerations, decelerations, and changes of direction above 2.5 m/s have demonstrated acceptable reliability (CV <11%) during task specific movements, with further improvements if expressed as an overall sum, such as HIEs (CV <4%). However, dividing and reporting the same variables within specific thresholds, such as low (<1.5 m/s), moderate (1.5-2.5 m/s), high (2.5-3.5 m/s), and very high (>3.5 m/s), has been associated with poorer reliability, with similar findings observed for PlayerLoad™ (Luteberget et al., 2017). Thus, the rationale behind selecting specific external load variables in this thesis and the four related papers, is based on the known implications of subdividing locomotive and IMU measures.

External load data in ice-hockey

In contrast to field-based team sports, there is a lack of previous research applying tracking systems within ice-hockey. However, comparable challenges in the methodology and design employed in prior research (Buchheit & Simpson, 2017) is observed, with inconsistent methods applied also in ice-hockey (Allard et al., 2020; Buchheit & Simpson, 2017; Douglas, Johnston, et al., 2019; Douglas & Kennedy, 2019). For example, while effective playing time is utilized in ice-hockey, previous studies have opted to include whole match time, while excluding only the time between periods (i.e., including data from time on bench) (Douglas et al., 2020), or solely incorporating effective playing time data (i.e., data while the puck is in play and the players are on the ice) (Douglas & Kennedy, 2019). In the analysis of external match load data in **paper I**, we chose to include all accumulated time on the ice, which involved the time and distance between stops in play and restarts with puck-drops during competitive matches, including standing still or gliding across the ice with limited effort. While these seconds are typically unrelated to sport-specific performance, it represents a short time where players can recover within the shift (Montgomery, 1988; Vigh-Larsen & Mohr, 2022). This does however complicate comparison of data across studies. For example, we report PlayerLoad™ values of 140-160 au. In other studies, this measure varies from ~110 to >250 au (Allard et al., 2020; Douglas, Johnston, et al., 2019; Douglas, Rotondi, et al., 2019; Douglas et al., 2020; Neeld et al., 2021;

Perez, Brocherie, et al., 2022). Its therefore challenging to interpret if this is attributed to differences in data sampling or playing level and player caliber (Perez et al., 2020).

Caution should however be taken whenever trying to generalize the findings to other populations, sports or environments, as certain aspects of the findings may be limited to the specific sample studied. For example, the ice-rink was the only one in Norway with NHL dimensions (26 vs 61m). Thus, the conditional circumstances for competitive match play monitoring may differ when comparing our results to a different team, solely due to rink dimensions, as typical rinks in Norway follows international standards and are 4 m wider, equivalent to ~25 m^2 more area per player (Staunton & Björklund, 2023). This difference also increases during special team-play (e.g., power play / penalty kill), and its known from football that area per player influences the physical demands and thus likely affecting external load data (Douglas & Kennedy, 2019; Sarmento et al., 2018). Researchers should work closely with practitioners to identify and develop more unified methods for external training and match load applications within ice-hockey, and specifically explore how different manipulations of rink size/area per player and rule regulations affects external training and match load.

External football match load

Despite its integrated application in modern football, the are several challenges arising from the use of external load data. For example, the abundance of variables and different metrics complicates the identification of the most valuable metrics and their reliability and validity within a sport-specific context (Barker-Ruchti et al., 2021; Gabbett et al., 2017; Impellizzeri et al., 2023). Attention should be directed towards the manufacturers of wearable tracking systems, as they frequently release new systems, devices, software, and variables claiming to be leading in their domain (Bourdon et al., 2017; Miguel et al., 2021). Unfortunately, little to no scientific evidence or independent research accompanies these releases, and the first published studies assessing the validity or reliability of these new features often come years later, coinciding with the release of newer systems, software, or variables. Recent publications emphasize the autonomy of practitioners and encourage them to critically evaluate their needs and objectives before incorporating new systems, updates, or variables into their monitoring protocols (Barker-Ruchti et al., 2021; Buchheit & Simpson, 2017; Gabbett et al., 2017; Impellizzeri et al., 2023; Torres-Ronda et al., 2022). Additionally, a holistic approach involving several important variables is recommended, rather than relying solely on a single measure when making causal decisions (Torres-Ronda et al., 2022).

Consequently, the methodological approach and data selection employed in **paper III** and **IV** converge to the majority of existing research in football. Although discrepancies exist in the calculation and incorporation of acceleration data (IMU vs GNSS), the literature consistently emphasizes the significance and standardization of high-intensity activities such as high intensity running (≥19.8 km/h) and sprinting (≥25.2 km/h) (Akenhead & Nassis, 2016; Beato, Drust, et al., 2021; Gualtieri et al., 2023). Nonetheless, challenges related to variations in manufacturing, data processing, and filtering techniques may still pose issues (Buchheit & Simpson, 2017). Furthermore, the contextual variance of official match demands complicates the standardization of data. Indeed, contextual factors (match score, opposition) were reported, however, this does not overcome the fact that there's a large variance within the included data (appendix 9).

5.2.2 Physical performance testing

Ensuring the precision of test equipment is a critical aspect of evaluating physical test performance, particularly when attempting to identify potential changes (Svensson & Drust, 2005). Furthermore, while specific systems or protocols have been reported to be reliable, it is important to evaluate their validity within the specific environment in which they are applied. A recent study assessed the test-retest reliability of typical physical performance tests using the same laboratory facility and equipment as the present thesis, reporting acceptable reliability, with a raw and relative typical error (%TE) of less than 5%, for sprint times, CMJ, and Keiser leg press assessments (Lindberg et al., 2022). As for the remaining tests employed in **paper II** (pull-ups, deadlift, bench press, and long jump), studies have suggested acceptable reliability for pull-ups and long jump with CV <3% and intraclass correlation coefficient ≥0.75, respectively (Coyne et al., 2015; Henriques-Neto et al., 2020). However, a reduction in reliability has been observed in testing maximal strength exercises such as bench press and deadlift, although they are generally considered to have acceptable reliability with CV ~5% (Grgic et al., 2020; Stock et al., 2011). Notably, it doesn't help if the test measure is sensitive and reliable if not properly performed by the test-leader, as meaningful differences indeed has been reported from test-centers utilizing the same systems and test-protocols (Lindberg et al., 2022). Additional factors such as music and verbal encouragement is also know to influence the test results (Currell & Jeukendrup, 2008). While thorough planning and standardizations were made, we cannot rule out that other factors, such as test leader variability, might influence the results when comparing our results to other studies.

5.2.3 External match load as a measure of physical test performance

External training and match load are suggested as a potential tool to individually assess players fitness (Rice et al., 2022; Schimpchen et al., 2023), and its suggested that physical performance testing may be redundant, if physical fitness may be accurately assessed during training and match activities (Cummins et al., 2013; Massard et al., 2018; Schimpchen et al., 2023). In contrast, our findings indicate a limited number of associations between physical test performance and external training and match load data, in both ice-hockey and football. It's highlighted that the complexities and coherent variability of training and match activities, due to technical/tactical and other contextual variables may compromise the detection of such relationships (Dalton-Barron et al., 2020; Modric et al., 2022). In addition, there's an underlying challenge with the variability in the included external training and match load variables. E.g., while the physical performance tests included in the thesis has proven reliable with CV <5% (Lindberg et al., 2022), included external scrimmage and match load variables displayed much higher CV (appendix 9). For example, our findings demonstrate substantial individual variations, with CV reaching up to 100% for certain variables. In addition, while a standardized match design such as scrimmages may provide standardization, a large within player variation is still observed with CV of >50% in measures such as sprint skating distance and number of accelerations. Exploring the relationships between measures with such large variability is challenging as its uncertain whether we explore the actual signal in the data or just correlate the associated noise (Currell & Jeukendrup, 2008). Notably, peak speed from both ice-hockey and football was observed to have good reliability (CV of ~5%). Peak speed was indeed identified with credible associations to sprint test measures, however with variation to which specific measure (e.g., 30 m/max peed: Table 9 and 10). The construct validity of peak speed in this context should be further explored (Currell & Jeukendrup, 2008).

Contemporary research has delved into the intricate relationship between training prescription and performance outcomes, with a particular emphasis on comparing the associations between exposure/dose and their corresponding outcomes/effects (Impellizzeri et al., 2023). Analogous to pharmaceutical drugs, training exposure can be tailored to target specific internal factors to achieve desired performance outcomes. Ultimately, coaches and practitioners strive to identify the optimal method to administer a precise dose of training, intended to facilitate enhanced performance (Impellizzeri et al., 2023; Suchomel et al., 2016).

As direct effects are challenging to assess, research typically applies surrogate or indirect measures to address the effects on the outcome of interest. For instance, decrements in CMJ height are deemed a valid surrogate measure when evaluating neuromuscular fatigue (Clarke et al., 2015; Hader et al., 2019). However, while the application of surrogate outcomes seems straightforward in theory, real-world challenges can influence these measures. For instance, several unmeasured confounders may affect the measured outcome, thereby compromising the validity towards the intended performance outcome measure (Currell & Jeukendrup, 2008; Impellizzeri et al., 2023). As an example, CMJ is highlighted as an appropriate test measuring changes in strength and power performance of the lower extremities. It is however uncertain to what degree the improvements reflect physiological changes (e.g.., changes in muscle morphology, tendons and so on), and what is due to improved technique and coordination of activated muscles (Lindberg, 2023). Following this argument, HIEs is intended to reflect high intensity actions, such as rapid changes of speed, decelerations, or changes of directions (Luteberget & Spencer, 2017). Such actions are typically associated with increased external force, thus requiring a high physical effort by the players to perform or withstand forces during these efforts (McBurnie et al., 2022). Hence, it’s natural to assume that many of the same physical efforts contribute to players efforts during traditional physical performance tests. Thus, with the potential overlap in contributing muscle efforts between these measures, it’s natural to assume that one could reflect the other. However, while changes in muscle physiology, measured by changes in CMJ, may be influenced by extraneous factors, there are numerous contextual factors affecting external training and match load variables. These factors complicates the process of identifying what degree changes in CMJ is related to observed changes in external training and match load variables, such as HIEs.

The complicated proses of identifying the transferability between measures has been emphasized (Young, 2006). As an example, 8 weeks of strength training improved 1RM squat and vertical jump height with 21%, however the associated change in 40 m sprint performance was only 2.3% (Wilson et al., 1996). It may therefore be suggested that substantial increase in isolated physical performance tests, beyond what's observed in the current thesis, is needed before a transferable effect is observed in more sport-specific movement measures. Consequently, with the significance of even minor improvements on sport related performance (Gabbett et al., 2017; Hopkins, 2004), we suggest that current measures of external training and match load are unsuitable as markers for alterations in physical performance tests.

Indeed, external training and match load monitoring emerges as a potential tool to monitor players physical fitness fluctuations. However, we suggest that our findings provide a foundational basis for future investigations and underscore the importance of expanding both researchers and practitioners understanding of how training adaptations and changes in strength and physical test performance can impact various aspects of sport-specific performance (Suchomel et al., 2016), including measures of external training and match load. It is imperative for coaches and practitioners to exercise caution when ascertaining the relevance and significance of any improvements in physical performance. Extrapolating a direct sport-specific performance effect between measures without sufficient supporting knowledge is unwarranted.

The observed absence of a relationship between physical test performance and different markers of match performance is not unique. As previously noted, identifying these relationships is complex (Huard Pelletier et al., 2021; Impellizzeri et al., 2023; McCall et al., 2017; Rice et al., 2022). Theoretically, these observations may indeed reflect the actual dynamics within ice-hockey and football environments, suggesting that external load data is unsuitable as a marker to reflect players physical fitness capacity and fluctuations. Alternatively, it can be argued that external match load data variables are unsensitive to capture the players physical abilities attributing to sport specific performance (Currell & Jeukendrup, 2008). Thus, physical test performance may indeed be associated to match specific activities, however not expressed through external scrimmage and match load data included in this thesis.

It is essential to recognize that the findings are likely influenced by the number of included players and their homogeneity. For instance, a larger and more heterogeneous sample, encompassing both senior/professional and junior/academy level players from both sports, may increase the likelihood of identifying a relationship between physical test performance and external training and match load data. This association could be solely attributed to the augmented sample size and increased diversity. This is exemplified by aerobic fitness; in a diverse population, there is a well-established link between VO_2-max and aerobic performance, however the identification of such relationships diminishes when results are compared across players competing at the same level, such as among elite endurance athletes (Morgan & Daniels, 1994; Rodrigo-Carranza et al., 2022).

5.2.4 The detection of changes in players physical test performance and external match load

Whenever interpreting changes, whether in physical test performance, external load or other variables in players monitoring data, it's imperative to evaluate the meaningfulness of such changes within the context its identified (Lindberg et al., 2022; Svensson & Drust, 2005). In **paper IV**, TE, %TE, and SWD were employed as criteria to categorize changes in physical test performance as meaningful. Additionally, SWD and NAP were utilized to evaluate changes in external match load data. The selection of these measures as criteria to assess changes were based on previous research (Hopkins, 2004; Lindberg et al., 2022) and recommendations by a statistician within the research group. However, it's important to emphasize that this selection was made with the aim of exploring a practical and feasible alternative to interpret changes in players performances, potentially relevant and easy to use for sport practitioners. Consequently, the criteria applied in the research related to this thesis should not be interpreted as a more correct way of interpreting results, however rather as an alternative and practical method in "real life" situations building on the current knowledge for assessing high level players (Hopkins, 2004; Lindberg et al., 2022).

SWD emerged as an alternative approach for assessing elite athletes due to the importance of even subtle changes for successful performance (Hopkins, 2004; Malcata & Hopkins, 2014). There's however an unresolved question to the optimal way of interpreting changes in external training and match load data. As mentioned, several contextual factors affect players performance (Glazier, 2017; Ravé et al., 2020), and its currently difficult to "isolate" the data in a similar and standardized manner, as with physical performance tests with long traditions. Following this note, the influence or practicality of a >0.2SD change in external match load data is unknown. However, based on our data, SWD as an approach to analyze match data with large inherent variations seems unfit. In this context, different controlled training drills, such as small-sided games have been suggested as a standardized and reliable context for evaluating external training load data (Owen et al., 2013). Thus, increased research on how to standardize the context of external training and match load monitoring and interpretation, comparable to the evolution of physical performance testing, is warranted.

While considerations of reliability and the exploration of SWD have been addressed in sport science research (Lindberg et al., 2022), less attention has been given to NAP. Although it may be considered an unconventional approach, NAP provides the opportunity for individual case assessments between two phases, in addition to group calculations (Table 8 and appendix 11). Given the significance of tailoring training and monitoring to individual players, NAP can serve as an additional measure when evaluating player development between periods, for instance when comparing performance between seasons. Moreover, NAP offers a graphical visualization that facilitates interpretations by coaches and practitioners (see appendix 11). While NAP is employed as an additional method to categorize changes in this thesis, it is not without limitations. For instance, the methods associated with calculating confidence limits for NAP are subject to debate (Parker & Vannest, 2009). Therefore, it is reasonable to assume that NAP is an appropriate measure in this context; however, its application within the realm of sport science warrants further examination. Coaches and practitioners should evaluate NAP and additional measures in comparison with additional measures of players performance and be careful in postulating effects solely based on one specific variable.

While we included external match load in the beginning and the end of the intervention period (Figure 2), five of the included matches were within the strength intervention period itself, and only six strength training sessions were performed after the last match in the baseline-period, before the first match in the follow-up period. Accordingly, the strength training stimulus potentially influencing the external match load data, is limited. In addition, while a substantial load of football-specific field training took place during the intervention period, which likely stimulated external match load data variables, it is unlikely that the overall stimulus of ~1 weekly strength training session and field/match exposure were any different to the general stimulus during the competitive season. Consequently, taken together with the variation in the data, the lack of change in external match load data is not unexpected.

5.2.5 External load and autoregulation

Autoregulation has become a common training modality (Greig et al., 2020). Previous studies have applied pre-session measures of readiness such as neuromuscular fatigue (Silva et al., 2018) or wellness-scales (Lopes Dos Santos et al., 2020). However, to the authors best knowledge, current application of autoregulation places focus on in-session measures, such as lifting velocity or reps in reserve (Greig et al., 2020). Thus, a novelty of **study two**, was the inclusion of HIR distance as an objective marker to regulate strength training volume. To compare this objective autoregulation, we chose to compare this to a subjective, self-selecting approach. This subjective approach was related to the typical routines of the players during the in-season period, where they self-reflected on their readiness to train, and selected their training volume accordingly. Such subjective regulations methods are, however questioned as they may be misused by players to influence the training to their preference (Bourdon et al., 2017). With an overall low training volume, we did not observe any difference between the groups in **paper III**. However, we hypothesized that a discrepancy would have been observed with larger training volumes as some players indeed consequently self-selected the lowest possible training volume. Comparable to wellness-scales or rate of perceived exertion measures, the applied self-selection and other subjective methods are dependent on factors such as standardizations (e.g., when and how data is collected) and athlete buy-in for the implementation to work as intended (Abbott & Taber, 2021). Thus, while our observation may be attributed to our applied methodology, we recommend coaches and practitioners to consider a combination of subjective and objective markers when prescribing or regulating training (Bourdon et al., 2017).

HIR as a regulating variable was selected based on the findings of Hader et al. (2019), which found an association between increased HIR distance and fatigue. However, it is important to note that the specific thresholds employed in **paper III** were solely derived from the team's repository data, not adjusting for changes in the squad during the time course of **study two**. Consequently, while the HIR observations during this period was comparable to the repository data (appendix 10), the repository data may not accurately reflect the team's HIR abilities during this period. Furthermore, the HIR distance may be influenced by positional demands rather than a player's inherent ability (Di Salvo et al., 2009), and individualized high- and sprinting speed thresholds have indeed been suggested to provide a more accurate insight to the relative effort by the players (Rago et al., 2020; Scott & Lovell, 2018). Thus, the generic thresholds may overestimate or underestimate the actual fatigue experienced by the players. To address this variation, we propose exploring the implementation of individualized thresholds, wherein a player's common HIR distance and typical variation is established, and their training volume is accordingly regulated if there are significant increases or decreases in the data.

5.2.6 Statistical analysis

In addition to employing different research designs, the four studies encompass a range of statistical analyses. Specifically, with a limited sample across the two study-periods this thesis opted to include a Bayesian statistics approach, as this approach is not based on large samples and may elicit reasonable results even with small samples (Van de Schoot & Miočević, 2020). While the objective of **paper I** could have been evaluated through traditional between-group analysis, the incorporation of Bayesian two-level regression analysis allowed for a more comprehensive and robust examination. This approach enabled the inclusion of a greater number of observations, with 109 and 60 data points respectively, for the official matches and scrimmages, as opposed to comparing means based on 16 and 15 players. Furthermore, unlike traditional frequentist analysis, which typically utilizes Pearson's correlation coefficient and associated p-values to assess relationships, the present thesis and **paper II** and **IV** adopted Kendall's Tau correlation, accompanied by a Bayes Factor (BF) (Van de Schoot & Miocević, 2020). This analytical approach exhibits robustness in scenarios with limited sample sizes and violations of parametric assumptions (van Doorn et al., 2018). Moreover, Bayesian estimation, unlike the Neyman-Pearson approach, does not necessitate a pre-specified sample size (Berger & Wolpert, 1988). The inclusion of BF, in conjunction with Kendall's Tau correlation, allows for a qualitative interpretation of the credibility of the association, as opposed to traditional null-hypothesis testing (Van de Schoot & Miocević, 2020; van Doorn et al., 2018; Wagenmakers et al., 2018). It is important to note that while the applied analyses may be suitable for small sample sizes, small samples are likely to contain less information compared to analyses conducted with larger sample sizes (Mengersen et al., 2016), and thus harder to replicate (Cohen, 1962; Van de Schoot & Miocević, 2020).

5.2.7 Covid-19

Lastly, conducting these projects amidst the Covid-19 pandemic has posed significant challenges, which have influenced the study designs and the number of participants included in the respective papers and the overall project. It is essential to acknowledge that the exceptional circumstances during the project period may have had an impact on the data presented in this thesis. During both **study one** and **two**, players lived under Covid-protocols, which entailed regular Covid-testing and restrictions on the number of individuals in their vicinity. Generally, the Covid-19 period was associated with heightened levels of perceived anxiety and diminished sleep quality (Bigalke et al., 2020; Gupta et al., 2020). Although these factors may have influenced the players, it is also plausible that engaging in sporting activities provided a stress-free outlet that mirrored "normal" everyday life, potentially exerting a positive influence on the players. It should be noted anecdotally that several unmeasured and confounding factors are known to impact players' performance, and it is unlikely that Covid-19 itself represents a more substantial influence than other factors, albeit limited to speculation. Despite the encountered challenges, the researchers have maintained close collaboration with coaches and practitioners from the respective teams, and firmly believe that the thesis and specific papers offer applied and relevant and applicable information for practitioners.

6 Perspectives and practical applications

The findings of the present thesis may have useful implications for both researchers and practitioners. Firstly, while external training and match load is commonly assessed in almost every competitive level in football, a scarcity of external training and match load data is evident in ice-hockey. Thus, our description of external load demands during competitive match play provided more empirical data into the field and the application of a scrimmage design may be feasible for coaches and practitioners under specific circumstances. Comparable to the development within outdoor field sports, we believe that this is just the beginning for external training and match load monitoring within ice-hockey. Hopefully this thesis can contribute to increased awareness of the challenges of postulating relationships between measures of physical fitness and external training and match load data, bridging the gap between research and practice, and assist towards a more unified approach in the future. We encourage coaches and practitioners to take ownership towards their application and utilization of different types of data in their player monitoring regime.

The findings of the current thesis emphasize the challenges of assuming a relationship between physical tests and external training and match load data from sport-specific activities. While external training and match load data may be seen as a feasible method for monitoring players physical fitness and fluctuations over time, such as during the competitive period, these relationships are complex. Contrastingly, the emergence of new variables without any conceptual support are frequently observed within the field of player monitoring. Essentially, these variables lack a theoretical foundation, shifting the verification of relevance onto the practitioners. Rather than being theory-driven, they present measures of exposure, leaving it to others to decipher their actual meaning and utility. The sophistication or apparent advancement of a metric becomes irrelevant if it cannot be linked to a plausible mechanism or relevant responses. In practical terms, such variables are likely of little use in supporting and optimizing the training process. Consequently, before embracing external training and match load data as a valid marker to assess fluctuations in players performance, the link, e.g., proof of construct validity, between these measures need to be established (Impellizzeri et al., 2023).

The importance of physical performance testing or external load monitoring, per se, should not be neglected based on the lack of empirical support for the relationships between these measures. Physical performance testing serves as a valuable tool in assessing players general fitness, individualization of training, longitudinal development and follow-up, injury prevention, setting standards for competitive levels etc. Likewise, external training and match load monitoring has been implemented as a feasible and low-effort inclusion of a vast amount of data from training and match situations, allowing for better understanding of players efforts, aid in training programming and optimization, and give insight to the individuality of each single player (Boullosa et al., 2020; Buchheit & Simpson, 2017). For any practitioner, club, or organization considering investing in and utilizing such systems, it is crucial to thoroughly assess how they intend to apply these systems. Key personnel responsible for managing the system and associated data should be identified, and a comprehensive plan for how the information is to be applied and communicated to players and coaches should be developed in order to ensure a successful implementation (Barker-Ruchti et al., 2021). Lastly, we emphasize the notion that "less is more" in a world of data overload (Bourdon et al., 2017) and recommend practitioners to carefully select a minimum number of relevant variables and thoroughly evaluate their accuracy and relevance before making any decisions based on the data provided (Gabbett et al., 2017).

7 Conclusions

The overall aim of the thesis was to explore how physical test performance is related to measures of external training and match load. To fulfill this aim, the thesis was conducted across two study periods, exploring the physical test performance and external training and match load within highly trained youth ice-hockey players (**study one**) and highly trained male professional football players (**study two**). The main conclusions of this thesis are summarized below.

- Scrimmages, with a continuous play design, provoked a higher relative intensity in external load measures. Specifically, higher distance per min, less slow speed skating distance and more distance covered in the moderate-, high-, and sprinting speed skating zones was observed in the scrimmages.

- While some physical performance test variables were associated with external scrimmage load data in ice-hockey, the low number of identified meaningful associations indicates that external load data cannot be reflected by players physical tests performance alone.

- Overall, and comparable to ice-hockey, external match load from two 4-week periods during the competitive seasons were not associated to physical performance test results within the same time-periods.

- When individually exploring players' change in physical test performance from the intervention period, three of eight players were categorized with a meaningful improvement in physical test performance. However, improvements in physical test performance were not consistently reflected in external match load data.

In conclusion, this thesis highlights the complexity of the relationships between physical test performance and external training and match load data in youth ice-hockey and professional football players. While some associations were found between physical test performance and external load variables, the overall number of meaningful associations was limited, suggesting that physical test performance may not be reflected in external training and match load data. Notably, peak speed was found to be associated to sprint test measures across football and ice-hockey, and this variable should be further explored. With the limited associations between physical test performance and external load data, the lack of associations between changes within the same measures is to be expected.

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Paper I-IV

Paper I

Simulated game-based ice hockey match design (scrimmage) elicits greater intensity in external load parameters compared with official matches.

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Simulated Game-Based Ice Hockey Match Design (Scrimmage) Elicits Greater Intensity in External Load Parameters Compared With Official Matches

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Objective: A limited number of studies have explored the external load experienced in indoor sports such as ice hockey, and few the link between training and match performance. As a paucity exists within this topic, this study explored whether a simulated match design (i.e., scrimmage) could be representative of official match demands and elicit similar external loads as in official matches in a group of elite youth male ice hockey players.

Methods: A total of 26 players were monitored during eight official and four simulation matches using a Local Positioning System. Total distance, max velocity, slow (0–10.9 km/h), moderate (11–16.9 km/h), high (17.0–23.9 km/h), and sprint (>24 km/h) speed skating distance, distance per min, PlayerLoad^{TM}, PlayerLoad^{TM} per min, high-intensity events (HIEs) (>2.5 m/s^{-2}), acceleration (ACCs), decelerations (DECs), and change of directions (CODs) were extracted from the tracking devices. A two-level regression analysis was conducted to compare the difference between match types when controlling for time on ice, match day, and position.

Results: Between match-type results showed a credible difference in all variables except max velocity and ACCs. Distance per min was 27.3% higher during simulation matches and was explained by a 21.3, 24.1, and 14.8% higher distance in sprint-, high-, and moderate speed skating distance, while slow speed-skating distance was 49.2% lower and total distance only trivially different from official to simulation matches. Total PlayerLoad^{TM} was 11.2% lower, while PlayerLoad^{TM} per min was 8.5% higher during simulation matches. HIEs, CODs, and DECs were 10.0, 11.9, and 22.3% higher during simulation matches.

Conclusion: The simulated match design is related to official match demands with comparable match-time, playing time, number of shifts, and shift duration. However, simulation matches provoked a higher external load output compared with official matches, possibly explained by a more continuous movement design. A game-based simulation match design can therefore be utilized when match-related actions at high intensity are warranted.

Keywords: Local Positioning System (LPS), game-based training, team sports, inertial measurements units (IMU), athlete monitoring

INTRODUCTION

Quantification of the external load has allowed for more extensive monitoring of training practices and can be used as an objective tool to optimize training and prepare for competitive performance. Match demands can be quantified at a team-, position- or individual-specific level. Recent studies of match-demands in ice hockey players have shown that players typically cover 50% of total distance in high-velocity zones (>17.0 km/h) (Lignell et al., 2018; Douglas and Kennedy, 2019). This is in contrast to running-based field sports, where most of the distance covered is in moderate-to-low-intensity zones, and only 10–20% in high-intensity zones (Bradley and Ade, 2018; Johnston et al., 2018; Kapteijns et al., 2021). The intermittent style of play with short, high-intensity shifts being performed throughout the match may be a reason for this. A typical shift lasts 45–60 s and involves 5–7 high-intensity actions, followed by 2–5 mins of rest on the bench before the subsequent shift (Brocherie et al., 2018; Vigh-Larsen et al., 2020; Wagner et al., 2021).

Further analysis of ice hockey match demands has revealed significant differences in intensity distribution between positions, periods, and odd-man situations (Douglas and Kennedy, 2019). Typically, forwards cover more distance in high-intensity zones (>17 km/h) compared with defensive players (Lignell et al., 2018; Douglas and Kennedy, 2019; Allard et al., 2020) and both total distance and intensity have been shown to decline from 1st to 3rd period (Brocherie et al., 2018; Lignell et al., 2018; Douglas and Kennedy, 2019; Douglas et al., 2019a; Allard et al., 2020). Interestingly, one study by Douglas et al. (2019b) compared the external load difference between training and matches in a group of elite female players. They found a clear mismatch in both intensity and volume between training and matches, which may partly explain the decline in match intensity across periods, as training seemed to be performed with an insufficient intensity level. This is supported by the findings of Spiering et al. (2003) as they demonstrated significantly lower heart rate distribution in training compared with matches (76 ± 3 vs. 90 ± 2% of HR_{max}). Furthermore, Allard et al. (2020) recommended more match-like intensity during training drills, after assessing intensity distribution across a whole season.

Game-based training drills and scrimmage have been adopted in several sports to mimic specific match demands to address the experienced match complexity during training (Aguiar et al., 2012; Luteberget et al., 2018; Vazquez-Guerrero et al., 2021). However, there seems to be a lack of research on this topic within ice hockey. Lachaume et al. (2017) investigated energy expenditure during different drills by using heart rate, however, they only compared the drills between each other and not to match intensity. Other studies have used repeated-sprint protocols in an attempt to simulate ice hockey match performance in order to assess the physiological impact (Palmer et al., 2017a,b; Steeves and Campagna, 2019). To the authors knowledge, only Vigh-Larsen et al. (2020) have applied an actual game-based design in their attempt to replicate physical match demands. In a standardized simulation match, each player performed eight 1-min shifts per period and thereby total match time of ∼24 min. Even though total distance was somewhat higher than previously reported, an intensity distribution similar to Douglas and Kennedy (2019), where ∼50% of total distance was covered in high-intensity zones, was evident. Notably, the previously reported intensity decline toward the end of the match, was not evident in the simulation match. As previous studies have shown that there appears to be a mismatch between training- and match intensity, and a paucity exists in the ice hockey literature regarding the match transferability of game-based training drills, we wanted to explore if a simulated match design could be representative of match-like intensities. Furthermore, as there have been few studies examining the external load demands of modern-day ice hockey, we wanted to add further insights to the actual in season on-ice physical performance of male ice hockey players. Thus, the aim of this study was to assess whether a simulated match design could be representative of official match demands and elicit similar external loads as in official matches.

METHODS

In this study, we investigated the on-ice external load of official ice hockey matches and compared it to simulation matches. The study was conducted from September to December 2020 and included eight official matches and four simulation matches.

Subjects

A group of 48 male players from a U21- and U18 team volunteered to participate in this study. Players had to wear an Local Positioning System (LPS) unit and participate in a minimum of four official matches, with a minimum of 5 min time on ice per match and/or all the four simulation matches to be included in the study. In total, 25 players were involved in official matches, where nine of the 25 players did not fulfill the inclusion criteria for official matches. Simulation matches initially included a squad of 34 players. Eleven players were excluded because of an insufficient number of LPS devices. Eight players were excluded due to promotion to the senior team (n = 1), injury (n = 3), and not participating in all matches (n = 4). Thus, 16 players (age: 18.7 ± 0.9 years, height 179.3 ± 4.8 cm, body mass 73.6 ± 4.9 kg) are included from the official matches and 15 players (age: 17.9 ± 1.1 years, height: 179.7 ± 6.4 cm, body mass: 72.3 ± 7.2 kg) are included from the simulation matches. Only U21 players are included from the official matches, while simulation matches included players from both teams ($n = 8$ U21 players and $n = 7$ U18 players). Of all the included players, six U21 players participated in both official and simulation matches. Thus, a total sample of 25 players ($n = 9$ DEF, $n = 16$ FWD) is included in this study. Written informed consent was obtained from all the players before initiating the study. The study was performed according to the ethical standards established by the Helsinki declaration of 1975 and was approved by the local ethical committee at the University of Agder, Kristiansand, Norway.

Design

All the matches were played at the same arena, housing a North American-sized ice-rink (∼60.96 × 25.9 m). An LPS system (Catapult Clearsky T6, Catapult Sports, Australia) was installed in the arena. A total of 20 anchor nodes were mounted ∼20 m above the ice-surface. The system was spatially calibrated using a tachymeter (Leica Builder 509 Total Station; Leica Geosystems AG Switzerland), as recommended by the manufacturer. For both simulation and official matches, each player was equipped with an LPS unit (Catapult Clearsky T6, Catapult Sports, Australia: firmware version 5.6). The LPS unit was located between the scapulae in a specialized sewn vest supplied from the manufacturer.

Official Matches

Data from official matches were obtained from eight home matches played between September to November. Apart from wearing the LPS-unit, the study did not intervene with any aspect of the normal match or match preparation for players. The data collection was monitored in real-time using Catapult Openfield (Catapult Sports, Australia) Software (version 1.17.2). Interchanges were manually tracked using the software to ensure that only on-ice time was included in the analyses.

Simulation Matches

The simulation matches were standardized by modifying official match regulations, comparable to the simulation match in the study by Vigh-Larsen et al. (2020) Such gameplay replication may also be referred to as scrimmage (Vazquez-Guerrero et al., 2021). Accordingly, the simulated matches consisted of 3 × 20 min periods, interspersed by 18 min of recovery, in compliance with official match regulations. However, to standardize playing time, periods consisted of 20 min continuous play, without interference or stoppages. Changes of lines were performed every 1 min with a whistle-signal from the coach. At the whistle, all players on the ice performed a rapid change before the new line-up could enter the ice and immediately continue the play, resulting in a 1:2 work to rest ratio. Thus, the playing time for each player was ∼20 min per match. In total, each match lasted 1 h and 36 min, including intermissions. To avoid odd-man situations, no penalties were given. However, to standardize play to normal match regulations and avoid reckless play, fictive penalties were used: for every second minor foul committed by the same team (i.e., 2-min penalty fouls), a goal was awarded to the opposition. If an offside or icing-situation occurred, the defensive team would gain possession of the puck. When a goal was scored, the play was immediately restarted by the goalkeeper taking out the puck from the net.

The players were allocated by the team coaches into two separate teams to give a balanced opposition for the simulation matches. Each team consisted of 15 players making three line-ups, where the best players (1st and 2nd line of each team) wore an LPS unit. The four simulation matches were arranged within a two-week period and played at the same time of day (±2.5 h). Players were verbally coached during every match and were given a tactical and motivational talk between periods, as in the official match situations. The data collection was monitored in real-time, and interchanges were manually tracked in the same way as in official matches.

Data Processing

Total distance, distance per min, distance in speed skating zones, max velocity (max vel), PlayerLoad™, PlayerLoad™ per min, accelerations (ACCs), decelerations (DECs), and change of directions (CODs) were extracted from the Openfield software. Speed skating zones thresholds were chosen in accordance with previous research (Douglas and Kennedy, 2019; Vigh-Larsen et al., 2020) divided into slow (0–10.9 km/h), moderate (11.0–16.9 km/h), high (17.0–23.9 km/h), and sprinting (> 24 km/h) speed skating. PlayerLoad™, high-intensity events (HIEs), ACCs, DECs, and CODs were applied as previously reported by Luteberget and Spencer (Luteberget and Spencer, 2017). Briefly, PlayerLoad™ is calculated by taking the square root of the sum of the squared instantaneous rate of change in acceleration in each of the 3 vectors (x, y, and z axes), divided by 100 (Boyd et al., 2011). PlayerLoad™ per min is calculated by dividing PlayerLoad™ by the duration of the activity. ACCs, DECs, and CODs is a summary of identified movements in the respective direction with an intensity > 2.5 m/s^{-2}. The sum of ACCs, DECs, and CODs was displayed as HIE. The data were edited postmatch to remove time between periods and time on the bench (i.e., only time on ice was included in the analysis). Data were extracted from the manufactures software and organized in Microsoft Excel (Microsoft Corp, Redmond, WA, USA).

Statistics

Descriptive results were calculated using Microsoft Excel. Effect size of < 0.2, 0.2 to 0.6, 0.6 to 1.2, 1.2 to 2.0, and > 2.0 were considered trivial, small, moderate, large, and very large, respectively (Hopkins et al., 2009). Data are presented as mean ± SD and 95% CI. A 95% CI without crossing zero was decided to indicate a statistically significant result.

Bayesian 2-level regression analyses were performed in MPlus software (Muthén & Muthén. Los Angeles, CA, version 8.4) to assess potential associations between match type and the dependent variables. In the 2-level regression analyses, aimed to analyze data that contains an inherent hierarchical structure, every match data point for each player was set at level 1 (within a person) and is nested within individuals on level 2. Covariates can then be regressed on both levels. The advantages of using the Bayesian approach, in comparison to the more traditional frequentist approach are, for example, the increased likelihood of producing reliable estimates in small samples and the less restrictive distributional assumptions [for a more comprehensive comparison between the two approaches see, for example, Stenling et al. (2015)].

We applied the potential scale reduction factor to assess the model convergence and < 1.1 was considered as evidence of convergence (Kaplan and Depaoli, 2012). Model convergence was assessed using both statistical criteria and visual inspection of trace plots to ensure that multiple chains converged toward a similar target distribution (McArdle and Nesselroade, 2014). Bayesian models were implemented using Markov chain Monte Carlo simulation procedures with a Gibbs sampler and specified a fixed number of 150.000 iterations (the first half is used as the burn-in phase, which is the default in Mplus).

We used the posterior predictive *p* (PPp) value and the 95% CI to assess model fit. A well-fitting model should have a PP*p*-value around 0.50 in combination with asymmetric 95% CI centering on zero. We also inspected the root mean square error of approximation, comparative fit index, and Tucker Lewis Index to determine the models fit to data. For each parameter, a credibility interval was estimated. If the 95% credibility interval does not include zero, the null hypothesis was rejected as improbable, and the parameter estimate is considered credible (Zyphur and Oswald, 2015). For all parameters default, priors in Mplus were used (Muthén and Asparouhov, 2012).

Based on the findings in the previous studies, we included several covariates potentially influencing match physical performance (Brocherie et al., 2018; Perez et al., 2020). Match type, match day (only official matches), and playing time (time on ice) was used as predictor variables within level (level 1). Playing position was used as a predictor variable between level (level 2) and defensive/forward players were coded “0/1”, respectively. Interpretation of results from the regression analysis should be done by comparing beta-coefficients (e.g., a beta-coefficient value of −0.6 is stronger than −0.5).

RESULTS

A summary of the included external load variables during official and simulation matches can be found in **Table 1**. Players appeared in 6.8 ± 1.5 official matches and 4.0 ± 0.0 simulation matches. Average time on ice for the respective match types was 26:28 ± 09:45 min (range: 05:02–44:40) during official matches and 21:00 ± 00:14 min (range 20:13–21:22) during simulation matches. On average, players had 22.9 ± 7.4 and 20.0 ± 0.0 shifts per match, with the average time on ice per shift being 67.7 ± 8.7 s and 63.0 ± 0.7 s for official and simulation matches, respectively. When excluding intermissions, official and simulation matches lasted 88.3 ± 7.2 and 60.0 ± 0.0 min, respectively.

The model fit from the 2-level regression had an acceptable PP*p*-value for all variables (range 0.467 to 0.474) and results can be found in **Table 2**. Match type had a credible impact on all dependent variables, except max vel and ACCs when controlling for match day and time on ice. Total distance was strongly related to time on ice, and a trivial difference can be observed between match types (**Tables 1**, **2**). When comparing the impact of match type on the included variables, a stronger impact was evident for high speed skating, distance per min, and sprint speed skating, which was 24.1, 27.3, and 21.3% higher during simulation matches. Furthermore, a weaker impact was evident for slow- and moderate speed skating distance which, compared to official matches, were 49.2% lower and 14.8% higher in simulation matches. For inertial measurement unit data, match type seems to have a stronger impact on CODs, HIEs, and DECs (11.9, 10.0, and 22.3% higher during simulation matches), compared to total PlayerLoad™ and PlayerLoad™ per min (11.2% lower and 8.5 higher during simulation matches, respectively). ACCs had a 40.6%, but noncredible, lower value for official- in comparison to simulation matches. The position had a credible between-level influence on all variables except ACCs and CODs. Data for each position is shown in **Figure 1**.

DISCUSSION

The main aim of this study was to assess if a simulated match design could be representative of official match demands and elicit similar external loads as in the official matches. We are, to the knowledge of the authors, the first to compare external load measurements from a simulated match design to external load from official matches in ice hockey. With similar match time, playing time, a number of shifts, and shift duration, the simulated match design provides an environment comparable to official matches. However, our results show differences in on-ice physical performance, with players eliciting a higher intensity in simulation matches. The results of this study provide practitioners with a game-based training drill applying a matching design that could be used in training situations where match-specific tasks at high intensity are warranted.

We observed a very large difference in distance per min, which can be seen in relation to the small-to-large difference in distance covered in speed skating zones. While slow speed skating was lower, moderate-, high-, and sprinting speed skating distance were all higher in simulation matches, compared to official matches. With a similar total distance covered between match types, our results, therefore, suggest that during simulation matches, a portion of distance covered in the low-intensity zone is replaced with more distance in higher speed zones. Naturally, a higher distance per min is undertaken in simulation matches because of the opportunity to continuously be on the move and chase the puck with opposition pressure. In contrast, the lower distance per min observed in official matches is explained by the inclusion of low activity data during stoppage time. Similar findings are, for example, also shown in basketball (Svilar et al., 2019). However, when comparing effective playing time from simulation matches to time on ice in official matches, the relative playing time is ∼30–35% of total match time in both match conditions. Thus, our official match data, including playing time, number of shifts, and shift duration, are comparable to previously reported observations

TABLE 1 | Match data from the included variables during official and simulation matches.

	Match Type			
Variable	**Official (*n* = 109)**	**Simulation (*n* = 60)**	**ES**	**95% CI**
Total distance	4,894 ± 1,731	5,015 ± 502	0.09	−0.23/0.40
Max Vel	8.50 ± 0.52	8.39 ± 0.54	−0.22	−0.53/0.10
Slow speed skating	1,228 ± 486	624 ± 166	−1.49	−1.84/−1.14
Moderate speed skating	1,547 ± 587	1,775 ± 267	0.46	0.14/0.77
High speed skating	1,744 ± 683	2,164 ± 628	0.63	0.31/0.95
Sprint speed skating	365 ± 228	442.4 ± 285	0.31	−0.01/0.63
Distance per min	188 ± 18	239 ± 24	2.51	2.09/2.92
Total PlayerLoad™	161.3 ± 59.8	143.3 ± 27.7	−0.35	−0.67/0.04
PlayerLoad™ per min	6.3 ± 1.2	6.8 ± 1.3	0.42	0.10/0.74
HIE	237.8 ± 79.3	261.7 ± 63.7	0.32	0.00/0.64
ACC	15.6 ± 10.1	9.3 ± 4.8	−0.73	−1.05/−0.41
DEC	35.4 ± 15.2	43.3 ± 15.0	0.52	0.20/0.84
COD	186.7 ± 65.1	209.2 ± 56.0	0.36	0.04/0.68

Mean ± SD.
HIE, high-intensity event; ACC, acceleration; DEC, deceleration; COD, change of direction.

TABLE 2 | Results from the 2-level regression analysis.

	TD	Max Vel	SlowSS	ModSS	HighSS	SprSS	Dist min	Tot PL	PL min	HIE	ACC	DEC	COD
MT^{WI}	-0.55	*-0.29*	0.47	-0.65	-0.97	-0.78	-0.91	-0.28	-0.34	-0.66	*0.18*	-0.62	-0.67
MD^{WI}	-0.11	*-0.20*	0.13	-0.15	-0.21	*-0.10*	-0.12	-0.16	-0.24	-0.21	*0.01*	-0.25	-0.20
TOI^{WI}	1.03	0.38	0.80	0.97	0.74	0.31	-0.27	1.00	-0.60	0.84	0.37	0.72	0.81
POS^{BW}	0.53	0.51	0.46	-0.78	0.61	0.51	0.48	0.48	0.45	0.43	*-0.10*	0.42	*0.40*

-1.0 0.0 1.0

Model explanation													
R^2_{WI}	0.96	0.15	0.96	0.88	0.79	0.45	0.87	0.92	0.46	0.69	0.22	0.51	0.64
R^2_{BW}	0.28	0.26	0.21	0.60	0.37	0.26	0.23	0.23	0.21	0.19	0.03	0.18	0.16

0.0 1.0

Significant beta-coefficient- (range: −1.0 to 1.0) and R2 (range: 0.0 to 1.0) strength is displayed by graded color backgrounds. Gray italic font numbers on white background are indicating not credible estimates.
MT, match type; MD, match day; TOI, time on ice; POS, position; WI, with-in level; BW, between-level; TD, total distance; SS, speed skating; Dist min, distance per min; PL, PlayerLoad™; PL min, PlayerLoad™ per min; HIE, high-intensity event; ACC, acceleration; DEC, deceleration; COD, change of direction.

from official matches (Brocherie et al., 2018; Lignell et al., 2018; Douglas and Kennedy, 2019). Our simulation match design, therefore, seems appropriate when coaches wish to address high-intensity actions, avoiding low-intensity actions, while at the same time keeping a game-based design in training situations.

When comparing our results from the simulation match to the results from the simulation match of Vigh Larsen et al., the intensity distribution between the two studies is similar, with the exception of a higher distance in the slow intensity skating sone in the study of Vigh-Larsen et al. (2020) This may be due to inclusion of stoppage in play. In contrast, the same authors displayed a markedly higher total distance compared with our study (Vigh-Larsen et al., 2020). However, if comparing total distance related to playing time, distance per min is quite comparable. The observed difference in total distance might be due to their design, applying 24 min periods compared to our 20 min periods, allowing each player to complete ∼4 min higher match time, and thus a higher total distance. Notably, our design, using less time and no stoppages, while eliciting

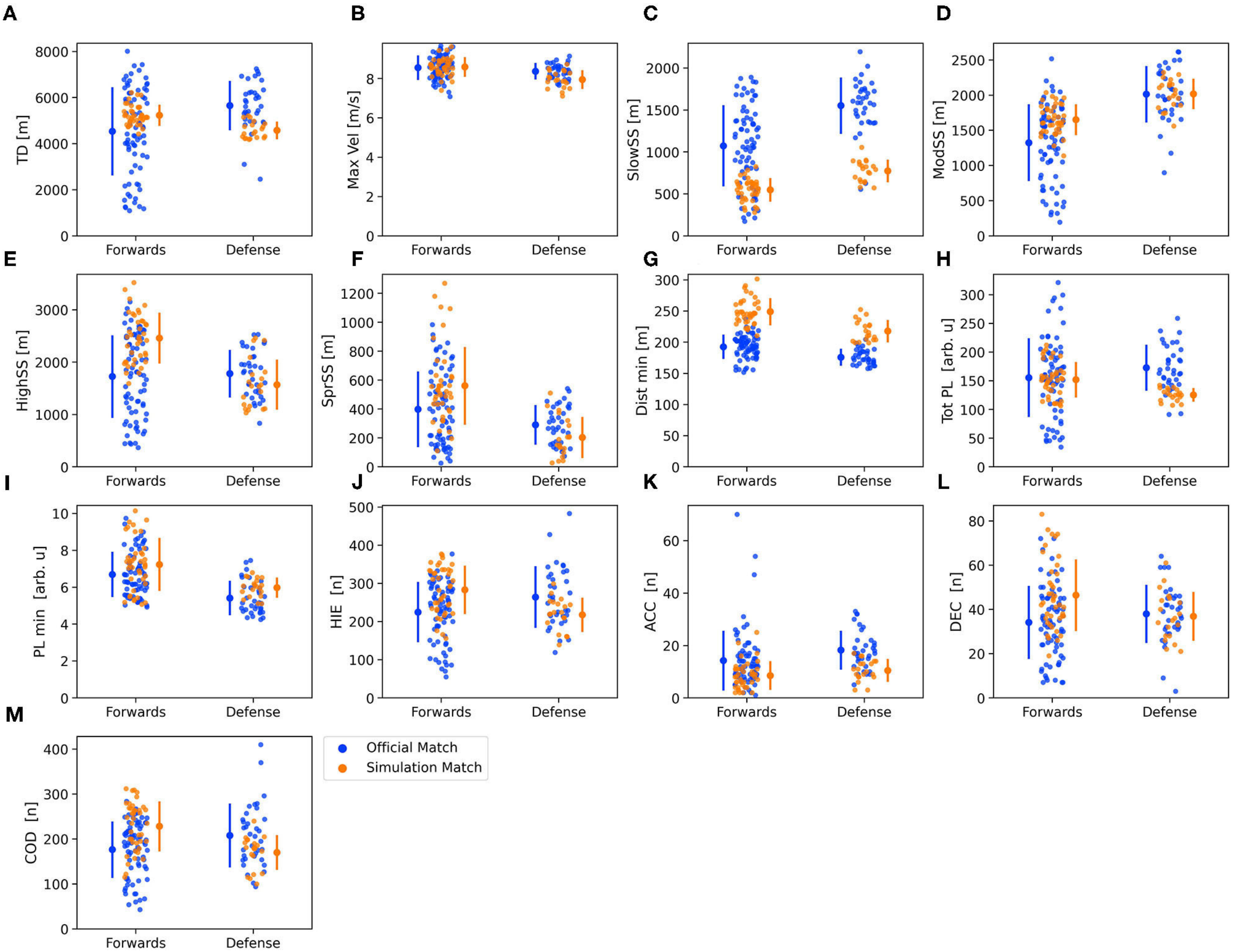

FIGURE 1 | Positional differences between official- (blue) and simulation (yellow) matches for the included locomotive and inertial sensor variables. Data are presented as mean ± SD and individual plots for each variable. **(A)** Total distance, **(B)** Max vel, **(C)** Slow speed skating, **(D)** Moderate speed skating, **(E)** High speed skating, **(F** Sprint speed skating, **(G)** Distance per min, **(H)** Total PlayerLoad^{TM}, **(I)** Total PlayerLoad^{TM} per min, **(J)** High intensity events, **(K)** Acceleration, **(L)** Deceleration, and **(M)** Change of direction. TD, total distance; SS, speed skating; Dist min, distance per min; PL, PlayerLoad^{TM}; PL min, PlayerLoad^{TM} per min; HIE, high-intensity event; ACC, acceleration; DEC, deceleration; COD, change of direction.

similar high-intensity distance and distance per min as Vigh-Larsen et al. (2020), therefore, seems to be a sufficient method to time-effectively simulate game play in training situations.

Our results show a small difference in total PlayerLoad^{TM} and PlayerLoad^{TM} per min. While total PlayerLoad^{TM} was lower, PlayerLoad^{TM} per min was higher during simulation matches. This is likely explained by the premises of match play, as an increased relative intensity has also been shown during no stop match play compared with the official rule match play in basketball (Svilar et al., 2019). As PlayerLoad^{TM} measure is a measure of the sum of forces (x, y, and z axes) generated through the accelerometer, the lack of start/stops that typically occurs when stopping the play or dropping the puck in official matches, might be the reason for this decline in total PlayerLoad^{TM}. Similar to distance per min, the more continuous movement and only obtaining data while the puck is in play, seems like the logical explanation for the small increase in PlayerLoad^{TM} per min during simulation matches. When comparing PlayerLoad^{TM} from matches, our results are lower than Neeld et al. (2021) reported in collegiate level male players (total PlayerLoad^{TM} 220–234 [DEF-FWD]) and what Douglas et al. (2019b) reported in two other studies in elite female players; 230–239 [DEF-FWD] and Douglas et al. (2020); 228–246, [DEF-FWD]). This difference might be attributed to the methodological differences (inclusion of data), however, playing level and athlete caliber (Perez et al., 2020) could also contribute to the observed differences. Contrastingly, elite and subelite female players have also displayed a total PlayerLoad^{TM} comparable to our results [total PlayerLoad^{TM} 153–159 [DEF-FWD] Douglas et al. (2019a); and 160–183 [FWD-DEF] Douglas et al. (2020)]. PlayerLoad^{TM} per min has been reported in three of the studies (Douglas et al., 2019b, 2020; Neeld et al., 2021), however, none of them excluded time on the bench, which makes it challenging to compare this metric to our results. Similar to our study, however solely using the inertial movement unit-device within the Clearsky T6-unit, Allard et al. (2020) applied on ice load to quantify external load in a group of fifty male American Hockey League players over an entire season. On ice load was intended to be a more representative and precise measure of PlayerLoad™ in ice hockey, removing all low ACCs (<0.3 m/s^{-2}) that typically occur (i.e., time on the bench, substitutions, coasting, gliding, standing, and resting) but at the same time comparable (Pearson correlation: $R^2 = 0.98$). Assuming that PlayerLoad™ can be compared to on ice load, the match results from Allard et al. (2020) were comparable to total PlayerLoad™ in our and previous studies (total on ice load 139–151 [DEF-FWD]). However, on ice load per min was 11.8–13.8 (DEF-FWD), which is markedly higher than our results. No other studies have reported comparable measures for HIEs, DECs, or CODs in ice hockey, however, the higher number of observed actions from official to simulation matches strengthens the assumptions of an overall higher intensity during simulation matches.

ACCs was not different between match types. Increased focus on acceleration has been highlighted in other sports due to the metabolic demands and power output needed to increase speed compared to maintaining a constant high speed (Cardinale and Varley, 2017), and it is natural to think that this measure is highly transferable to ice hockey. In contrast to running-based sports such as soccer, handball, rugby, American/Australian football, basketball, etc., it is relatively easy to remain at high speed because of the low friction on the ice. Therefore, the importance of acceleration in addition to locomotive speed distance measures should be highlighted in future studies applying LPS systems. Furthermore, even though a continuous play design has been applied in other sports, the consequence and the potential interference this has on acceleration-derived data, should be further investigated within ice hockey.

Douglas and Kennedy (2019) only included effective playing time when assessing the performance of the male Canadian U20 team during international matches. Interestingly, slow speed skating distance seems comparable, while moderate- and high speed skating distance is higher during our simulation matches. Contrastingly, sprint skating distance is higher during the international matches compared to our simulation matches. Athlete caliber, in addition to variations in methodology, seems like a possible explanation for this observed difference. The methodology is an important debate, as our match data during both match types shows comparable or higher distances covered in high-intensity zones (>17 km/h) compared to professional National Hockey League players (Lignell et al., 2018). Even though our official match results included distance covered while the puck was out of play, its unlikely to think that this is the reason for the superior distance covered in the high-intensity distance zones. A suggested explanation is an increased sensitivity when applying an LPS system compared with a semiautomated tracking system.

There are some limitations that should be considered. At first, in contrast to other studies on ice hockey, our design allows players to accumulate time on the ice when the puck is out of play (in official matches). This approach has also been used in other team sports (Luteberget and Spencer, 2017) and takes into account all load when players are on-ice. However, this approach will allow players to reach higher playing time and affect parameters such as distance- and PlayerLoad™ per min. In our study, we find the percentage on-ice time (26:28 ± 9:45: 19–41% of total time) to be in line with previous literature reporting 15–25 min of effective playing time (25–42% of total match time). Therefore, we think this approach is appropriate, although the difference from other studies could affect the direct comparability. Second, our official match data only included the home team. Furthermore, the within-level performance seems to be negatively impacted by the second matchday during consecutive matches during official matches, as this is a significant predictor in all variables except max vel, sprint speed skating, and ACCs. However, even though the impact is weak (beta-coefficient range −0.24 to .13), and this schedule is typical for this team, playing against the same opposition over two back-to-back match days may differ from other match schedules and complicate data comparison. Furthermore, the match score is an important factor as players are likely to improve their efforts if there is an even score or when chasing an equalizer, compared with leading 10–3 the last minutes of the game, which was the case in one of the included matches (Brocherie et al., 2018). This will further influence the tactical decisions, such as player rotations, playing time, etc. Caution should be taken when trying to generalize the findings as many factors contribute to the overall physical performance (overall fitness level, technical skills, athlete caliber, tactical strategies, etc.). Furthermore, the study was conducted in the middle of a pandemic. Lack of gym facilities during preseason, no ice during the summer period, psychological factors (stress, anxiety), etc., are all the factors influencing overall performance in this time period. However, this unique situation also gave a special opportunity (e.g., if the players performed well, a promotion to the senior team was more likely to occur due to injuries, quarantines, etc.). Therefore, the players had to remain fit and fully motivated for the entire period. At last, different calculations of acceleration load (i.e., PlayerLoad™, on ice load, Accel'Rate) used in the literature complicate comparison and interpretation of the results. Indeed, the PlayerLoad™ calculations have recently been suggested to have limitations for estimating whole-body mechanical load (Hollville et al., 2021), and its relevance in ice hockey is not investigated. Implementation of Accel'Rate has been suggested as a more sensitive measure (Hollville et al., 2021) and has indeed been applied in ice hockey (Perez et al., 2020) and future studies should assess its relevance compared to the traditional use of PlayerLoad™.

Practical Applications

This study suggests that a game-based match design can be adopted when practitioners wish to address match-like performance with intensity- and high-speed skating distance (> 17 km/h) superior to official matches during training drills. Within the field of game-based training-drills in ice hockey, more research is needed to assess the external load and intensity when the drill design is manipulated (number of players, rink size, etc.) and how this is linked to external load during official matches. Some caution should be taken when interpreting the results. Even though a simulation match design is comparable to the official matches, there are large individual variations. For example, during the official matches players are exposed to as much as 44 min or as little as 5 min time on the ice. Accordingly, simulation matches, with a standardized time on the ice, will be an over or underrepresentation of actual match demands for some players. It is, however, a feasible way of eliciting the match-like intensity that has been lacking in the previous studies.

CONCLUSION

This study shows that there is a difference in the external load parameters between official and simulation matches. Specifically, a higher distance per min and more distance covered in the moderate-, high-, and sprinting speed skating zones is observed in the simulation matches, compared with official matches. This difference seems to be associated with the continuous play design, allowing players to always be on the move and thus display a higher intensity during simulated matches. Our findings provide practitioners with a game-based match design that can be adopted during training situations when match-specific training is desired.

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

DATA AVAILABILITY STATEMENT

The raw data supporting the conclusions of this article will be made available by the authors, without undue reservation.

ETHICS STATEMENT

The studies involving human participants were reviewed and approved by Fakultetets etiske komité (FEK) ved Faktultetet for helse- og idrettsvitenskap, Universitetet i Agder. The patients/participants provided their written informed consent to participate in this study. Written informed consent was obtained from the individual(s) for the publication of any potentially identifiable images or data included in this article.

AUTHOR CONTRIBUTIONS

PB, LL, TB, and MS contributed to the conceptions and design of the study. PB, LL, and TB executed the study and collected data. AI and PB performed the statistical analysis. PB wrote the first draft of the manuscript. All the authors contributed to manuscript revision, read, and approved the submitted version.

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Paper II

Association Between Physical Performance Tests and External Load During Scrimmages in Highly Trained Youth Ice Hockey Players

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Abstract

Purpose: To investigate the relationship between physical performance tests and on-ice external load from simulated games (scrimmages) in ice hockey. **Methods:** 14 players completed a physical performance test battery consisting of 30-m sprint test – run and 30-m sprint test - skate (including 10-m split times and max speed), countermovement jump (CMJ), standing long jump, bench-press, pullups and trap bar deadlift, and participated in four scrimmages. External load variables from scrimmages included total distance, peak speed, slow- (<11.0 km/h), moderate- (11.0-16.9 km/h), high- (17.0-23.9 km/h) and sprint (>24.0 km/h) speed skating distance, number of sprints, PlayerLoad^{TM} and number of high intensity events (HIEs; >2.5 m/s), accelerations, decelerations and change of directions (CODs). Bayesian pairwise correlation analyses were performed to assess the relationship between physical performance tests and external load performance variables. **Results:** The results showed strong evidence (Bayes Factor >10) for associations between pullups and HIEs (τ=0.61), and between max speed skate and peak speed (τ=0.55). There was moderate evidence (Bayes Factor >3 to <10) for six associations; both max speed skate (τ=0.44) and CMJ (τ=0.44) with sprint speed skating distance, CMJ with number of sprints (τ=0.46), pullups with CODs (τ=0.50), trap bar with peak speed (τ=0.45), and body mass with total distance (τ=0.49). **Conclusion:** This study found physical performance tests to be associated with some of the external load variables from scrimmages. Nevertheless, the majority of correlations did not display meaningful associations, possibly influenced by the selection of physical performance tests.

Keywords: Local Positioning Systems, Athlete monitoring, Simulated games, Match performance, Strength training

INTRODUCTION

Physical off-ice testing for ice hockey players has been completed for decades, with the North American National Hockey League (NHL) being a large-scale pioneer of their implementation of the NHL Combine test battery, annually conducting large scale testing of worldwide youngsters potentially eligible for the NHL in the future.[1] Physical performance tests aim to reflect the most relevant physical capabilities underlying ice hockey performance,[2-4] and the results can be useful to monitor longitudinal development, in injury follow-up, and are implemented to set thresholds for fitness requirements in positional, team and/or competitive playing levels.[3,5-8] Enhanced physical capabilities can be beneficial for players' game-related performance, as an increased fitness-level can contribute to players' likelihood of success in explosive efforts such as during puck battle, body checks and breaking free from the opposition to score a goal.[8] In addition, superior fitness contributes to reduced physical and mental exhaustion, affecting players decision making, technical/tactical skills, injury risk etc.[3,9] While there is an inconsistency in the specific physical performance tests applied both on- and off-ice, the majority of tests intent to measure physical abilities such as aerobic and anaerobic power, speed, agility, and upper- and lower body strength.[1-3,8]

How well these physical performance assessments represent game-playing performance is, however, debatable.[8] Measures of on-ice game performance seem to vary and have for example, been limited to pre-defined skating- and puck handling courses.[6,10] Additionally, there is considerable test-retest variability in all physical and game-related performance measurements, which will confound the investigation of potential relationships between specific parameters.[11] Nevertheless, the search for an association or "predictiveness" of game performance is ongoing. Some have explored the association to the draft selection, however without any clear associations between physical test performance and draft round entry.[1,4,12,13] Furthermore, there are a plethora of factors that determines draft selections, and physical performance is only a minor part of those.[1,2,12] In other studies, trivial to moderate associations have been shown between off- and on-ice tests and game performance markers such as; points, goals, assists, shots, scoring chances, ± differential statistics, playing time, shift time, or games played across a variety of player caliber, sex and playing level.[3,7,14,15] The lack of any clear association can be explained by the nature of physical game performances, involving highly complex tasks with great performance variabilities across players competing at the same level. It is therefore, unlikely that any on- or off-ice physical performance test can be the true representative of the current markers of match performance.[10] Hence, the lack of strong associations is more or less expected.

Despite the comprehensive search for relevant physical performance tests that relate to markers of game performance, it is surprising to observe the lack of studies including any on-ice external load measures from gameplay situations. Comparison between physical fitness and external load from official game situations is, however, shown in sports such as soccer.[16] In contrast to outdoor field sports, the limited availability of locomotive characterization research in ice hockey may partly explain this observed research gap.[17] Accordingly, the association between physical performance tests and external load performance from indoor gameplay situations remains to be determined. Notably, recent developments and application of Local Positioning Systems (LPS) and other player tracking technologies have made external load monitoring available in indoor conditions and has indeed provided insight to both official- and scrimmage situations (simulated gameplay replication) in ice hockey.[18-20] Implementation of such technology is suggested to provide helpful information in narrowing this research gap by its potential to accurately quantify specific game demands.[8,17] Based on these previous research recommendations and the obvious gap in the literature, this study aims to explore the association between physical performance tests and external load from on-ice play situations by the application of LPS. Specifically, the purpose of this study is to assess physical fitness of highly trained male youth players and explore the association with on-ice external load from scrimmages.

METHODS

SUBJECTS

Highly trained youth players from a professional ice hockey club, competing at a national level, were invited to participate. To be included in the study, the players were required to complete a physical performance test battery. Furthermore, and to minimize game-to-game variability and single player efforts, players had to participate in all four scrimmages with a LPS-unit to be included in the analysis. 14 players (age: 17.8 ± 1.1 yrs, height: 179.5 ± 6.5 cm, body mass: 71.2 ± 6.0 kg, n=4 defensive, n=10 forwards) completed all measurements and are included in this study. Nineteen players were initially recruited to participate in the present study, but one of these players was excluded for not completing all physical performance tests (injury), while four players were excluded for not participating in all four scrimmages (promotion to senior team: n=1, injury: n=3). Additional players not included in the study were participating in the scrimmages to ensure enough players for each team. Written informed consent was obtained from all players before the study commenced. The study was performed according to the Helsinki declaration of 1975 and was approved by the local ethical committee at the University of Agder, Kristiansand, Norway.

DESIGN

In the present study, assessment of on- and off-ice physical test performance was conducted over two separate test days and four scrimmages were played to assess external load performance. The study was completed over a three-week period during the first half of the regular season.

Physical performance testing

The physical performance tests included counter movement jump (CMJ), 30-m linear running and skating sprint test, standing long jump, pullups (max repetition number with body mass), and 1RM bench-press and trap bar (hexagonal barbell deadlifts) deadlift, performed over two separate days. The test battery was chosen to include physical performance abilities important for ice-hockey and selected based on previous studies involving high-level athletes.[2,3] The specific tests were included as they were a part of the team's regular physical assessment test battery and all players were familiar with the tests. CMJ and sprint assessment were completed on day one, with CMJ and 30-m sprint test - run performed in the morning, and 30-m sprint test – skate performed 6 ± 1 hours later. Strength test, performed on a separate day, were completed in the following order: standing long jump, bench-press, pullups and trap bar deadlift. All participants underwent a typical warmup procedure before the physical performance tests, included jogging, jumps, running/skating drills, sprints with increasing intensity and dynamic stretching.

CMJ

CMJs were performed with hands on the hips, and the depth of the squatting motion was self-selected. The athletes performed 3-5 jumps with a 2-3 min passive rest between each attempt. The CMJs were measured using a force plate (Musclelab; Ergotest AS, Porsgrunn, Norway) and calculated from its accompanying software. The mean jump height (cm) of the two best attempts was included in post-test analysis.

30-m sprint test - run

Sprint test – run were performed wearing light clothing on an indoor athletic synthetic track running surface. Participants performed 2-4 maximal sprints during the test with 4 min passive rest between each attempt. Wireless timing gates were used to measure time at each 10-m interval (Musclelab, Ergotest innovation AS, Langesund, Norway). The timing was initiated when the foot triggered the first sensor, placed 50 cm in front of the start line and 40 cm above the ground. The remaining sensors at 10-, 20- and 30-m were placed 120 cm above the ground. The trial with the best 30-m time was included in post-test analysis and max speed was calculated from the 10-m split-times.

30-m sprint test - skate

Sprint test – skate were performed in full match-kit, including stick. During the test, participants performed 2-4 maximal sprints with 4 min passive rest between each attempt. The same wireless timing gates and setup were used for the sprint test - run and sprint test - skate. Players started from a stationary sideways position holding the stick in front of the photocells, making sure the sensors weren't obstructed by anything other than the body. The timing was initiated when the foot triggered the first sensor, placed 50 cm in front of the start line and 40 cm above the ground. The players were instructed to keep the stick in contact with the ice to avoid prematurely breaking the photocells [5]. The trial with the best 30-m time was included in post-test analysis and max speed was calculated from the 10-m split-times.

Standing long jump

For the long jump, subjects started from a standing position with both feet parallel behind a start line and jumped as far as possible in the horizontal direction. Arm swing was allowed. The jump length was measured to the nearest 0.01 m from the start line to the rear heel, using a tape measure. To qualify as a successful attempt, the subjects had to take off with two feet and maintain balance for at least two seconds upon landing. Three attempts were performed, where the best trial was included in the post-test analysis.

Bench-press

One-repetition maximum (1RM) bench-press test was measured using a free weight Olympic bar and weights. The participants were instructed to hold the bar at a position slightly greater than shoulder width. The subject then lowered the bar to the chest and pushed the bar until full arm extension. The gluteal muscles had to be in contact with the bench throughout the entire lift. Participants performed 3-4 warm-up sets with increasing loads (50-90% of 1RM), based on previous performance. Two to four attempts were then performed to determine 1RM. Upon successfully completing the repetition, weight was subjectively increased by 2.5-10 kg. For subjects that were not able to complete the lift, weight was reduced by 2.5-5 kg.

Pullups

Subjects used an overhand grip (palms facing away from the body) and started from a dead hang (arms fully extended and locked). From this position, a pullup was performed until the chin had cleared the top of the bar. The body was then lowered until the arms where fully extended or locked out. No excessive body motion was allowed. Each subject completed one trial, and the maximum number of valid repetitions was recorded.

Trap bar deadlift

Trap bar deadlift was performed using a standard hex bar with a weight of 32 kg. Participants performed 3-4 warm-up sets with increasing load (50-90% of 1RM), based on previous performance. Two to four attempts were then performed to determine the 1RM. Upon successfully completing the repetition, weight was increased subjectively by 2.5-10 kg. If they could not complete the lift, the weight was reduced by 2.5-5 kg. Participants had to stand fully erect with knees and hips locked, for the lift to be considered successful.

Measurements of external load

Scrimmages and sprint test – skate were performed in the same arena, housing a North American sized ice-rink (60.96 m x 25.90 m). A LPS (Catapult Clearsky T6, Catapult Sports, Australia) with twenty anchor nodes was mounted ~20 meters above the ice-surface. The system was spatially calibrated using a tachymeter (Leica Builder 509 Total Station; Leica Geosystems AG Switzerland), as recommended by the manufacturer. Each player was equipped with an LPS-unit (Catapult Clearsky T6, Catapult Sports, Australia: firmware version 5.6). The LPS-unit was located between the scapulae in a specialized sewn vest supplied by the manufacturer. The data collection was monitored in real time using Catapult OpenField Software (version 1.17.2). Interchanges were manually tracked using the software to ensure that only on-ice time and data were included in the analyses.

To ensure comparable playing time and avoid single player efforts, the scrimmages were standardized by modifying official game regulations, as described in Byrkjedal et al.[20] Briefly, scrimmages were played in accordance with full-game regulations with 3 x 20 min continuous play periods, with 18 min of recovery between periods. Entire line shifts were performed for both teams every 1-min by a whistle signal from the coach, resulting in 1:2 work to rest ratio and ~20 min of ice time per player. No penalties were given and if an offside or icing-situation occurred, the defensive team would gain possession of the puck. When a goal was scored, the play was immediately restarted by the goalkeeper taking out the puck from the net.

30 players were allocated by the team coaches into two separate teams to give a balanced opposition for the scrimmages. Each team consisted of 15 players making three line-ups, where the 1st and 2nd line of each team wore a LPS-unit due to a restricted number of LPS devices. The four scrimmages were arranged within a two-week period and played at the same time of day (± 2.5 hours) with the players allocated to the same teams each time. To ensure maximal efforts, the players were verbally coached during every scrimmage and were given a tactical and motivational-talk between periods, as in official game situations and score tabs was kept between the teams (total and line vs line). Furthermore, as regular league games were postponed due to a covid-outbreak in other regions, the scrimmages were the main competitive arena for the players in this period. The players were aware that if they performed well during the scrimmages, they could be promoted to the elite team.

SCRIMMAGE VARIABLES

Total distance, distance in speed skating zones, peak speed (m/s), PlayerLoad™, accelerations (ACCs), decelerations (DECs) and change of direction (CODs) were extracted from the

OpenField software. Speed skating zones thresholds were chosen in accordance with previous research[18,19], divided into slow- (<11.0 km/h), moderate- (11.0-16.9 km/h), high- (17.0-23.9 km/h) and sprinting (>24.0 km/h) speed skating. PlayerLoad™, high-intensity events (HIEs), ACCs, DECs and CODs were applied as previously reported by Luteberget and Spencer.[21] Briefly, PlayerLoad™ is calculated by summarizing all accelerations and is expressed as the square root of the sum of the squared instantaneous rate of change in acceleration in each of the 3 vectors (x, y and z axes), divided by 100 and scored as arbitrary units (au). ACCs, DECs and CODs is a summary of identified movements in the respective direction with an intensity >2.5 m/s. The sum of ACCs, DECs and CODs were displayed as HIEs. The data were edited post-match to remove time between periods and time on the bench (i.e., only time on ice was included in the analysis). Results from test day one and scrimmage data were extracted from the respective manufactures software and organized in Microsoft Excel (version 16.59 Microsoft Corp. Redmond, WA, USA) together with the results from test day two.

STATISTICS

Descriptive results were calculated using Microsoft Excel and are presented as mean ± SD. The main analyses were conducted in JASP (Jeffreys's Amazing Statistics Program) version 0.16.1. A non-parametric Bayesian correlation analysis was performed to investigate the relationship between the physical performance test variables and the external load variables from scrimmages. The Kendall's Tau correlations in combination with Bayes Factors (BF) were calculated for each comparison.[22] The BF is one method to quantify the likelihood of an alternative hypothesis (H1) compared to the null-hypothesis (H0), and is expressed as BF_{10}.[23] For example, a BF_{10} of 3 should be interpreted as the H1 (e.g., an effect) is 3 times as likely compared to H0 (no effect). For a more comprehensive description of the advantages applying this analysis over more traditional correlation analysis, see Ivarsson et al.[24]; Wagenmakers et al.[25] For each pairwise comparison, a BF was calculated. In line with previous research, the interpretation of BF_{10} were: >100=Extreme strong evidence for H1, 30-100=Very strong evidence for H1, 10-30=Strong evidence for H1, 3-10=Moderate evidence for H1, 1-3=Anecdotal evidence for H1, 1=No evidence. 0.33-1=Anecdotal evidence for H0, 0.10-0.33=Moderate evidence for H0, 0.033-0.1=Strong evidence for H0, 0.01-0.033=Very strong evidence for H0, <0.01=Extreme evidence for H0.[26]

RESULTS

The results from the physical performance tests can be found in Table 1, with a summary of the included variables from the scrimmages presented in Table 2. During scrimmages, players performed 20.0 ± 0.0 shifts and had a total game time of 21:00 ± 00:06 min per match.

A matrix Table of Kendall's Tau correlations are reported in Table 3. Only the pairwise comparison correlations between physical performance tests and external load parameters are reported. Body mass, max speed skate, CMJ, pullups and trap bar deadlift were the only physical performance measures with a BF_{10} >3 for the association with external load variables from scrimmages. Body mass had a moderate correlation to total distance. Max speed skate had a strong correlation with peak speed and a moderate correlation with sprint speed skating. CMJ had a moderate correlation with sprint speed skating and the number of sprints performed. Pullups had a large correlation with HIEs and a moderate correlation with CODs. Finally, a moderate correlation was seen between trap bar deadlift and peak speed. Correlations scatterplots including 95% confidence intervals are shown in Figure 1. No correlations with BF_{10}>3 were shown to the physical performance tests variables 10-m and 30-m max speed run and -skate measures, long jump or bench-press. For the external load variables, no correlations with $BF_{10}>3$ were shown to the slow-, moderate- and high speed skating distance zones, PlayerLoad™, ACCs or DECs. Relative strength was assessed for the 1RM bench-press and trap bar results by dividing max weight lifted on the player's body mass. No difference was seen between relative and absolute measures for these variables and relative data is therefore not included.

(Insert Table 1, 2 and 3 here)
(Insert Figure 1 here)

DISCUSSION

The aim of the current study was to explore the potential associations between physical performance tests and external load variables from ice hockey scrimmages. We found eight meaningful associations across our data including 12 performance test variables and 12 external load variables. Whereas previous studies only compared physical performance to objective game statistics or pre-defined courses during on-ice tests, this is, to the best of the authors knowledge, the first study to explore the relationship between physical fitness and external load performance from scrimmages in ice hockey.

The difficulties with measurements of sport specific sprinting abilities and the complexity of physical game performance complicate the comparisons between game related physical performance and general physical tests. The current study applies external load data from a tracking system as a new marker of game performance, not previously used in the literature when comparing game performance and physical fitness.[8] Generally, sprinting ability is considered highly important within ice-hockey.[17,27] Nevertheless, the relationship between standardized sprinting measurements and game-related sprint skating performance has been unclear.[8] While previous studies have shown associations between off- and on-ice sprinting times,[28] on-ice sprints have generally been suggested as a more valid method to predict sprinting abilities in ice hockey.[17,29] This hypothesis is supported by our findings where max speed skate was associated with sprint speed skating distance and peak speed during scrimmages. Furthermore, a positive association was also seen between CMJ and both sprint speed skating distance and the number of sprints performed. However, we did not observe evidence for any other sprint related performance tests, supporting the limited associations observed between physical performance test and external load as markers of physical game performance.

When assessing the external load performance measures from the inertial measurement data, only pullups showed any evidence for the displayed association, with strong correlations to HIEs and CODs. Leg extensor strength is central for acceleration of the body during sprints or with change of directions in a variety of sports[9] whereas upper body pulling muscles, such as those used during pullups, are less involved in ice hockey performance. Logically, we were therefore expecting inertial measurement data to show some association towards lower body extensor strength, such as trap bar deadlifts. The observed associations could be explained by strength relative to body mass. However, we did not observe any meaningful relationships when trap bar deadlift strength was expressed relative to body mass (data not reported). Notably, body mass tended to be positively correlated to many of the included external load performance variables, which may explain why there were no associations between external load variables and relative strength in trap bar deadlift. Furthermore, technique and the experience may vary more among these youth players which can impact test scores. Thus, while the number of pullups might be related to HIEs and CODs in our study and across our limited number of participants this could potentially be the result of some underlaying factors that we were unable to detect. However, pullups is most likely not a good marker of game performance in other samples of elite senior players. For example, a reversed relationship was shown between upper body maximal strength and playing time and game points when assessing long term career performance.[2] This does not necessarily conclude that players with reduced upper body strength are more likely to have longitudinal success in NHL. On the contrary, players typically reach the top of their careers 7-10 years after the combine testing where the reason for increased performance is more likely due to matureness, technical skill improvements, players game intelligence etc. This highlights the need for more research into the association between physical fitness and game performance at specific points within the same timeframe, and not several years after fitness assessment.[2]

Apart from the association between trap bar deadlift and peak speed, no evidence is shown between bench-press, trap bar deadlift and long jump, and the external load variables from scrimmages. Trap bar deadlift biomechanics have somewhat lower moments at the lumbar spine, hip, and ankle, and higher moments at the knee than conventional straight bar deadlifts,[30] reminiscent to conventional back squat. Our findings are comparable to the findings of Haugen et al.,[3] where trivial to small associations were shown between bench-press and squat strength to the game related statistics included in their study. In addition, longitudinal follow-up of combine test results did not find any predictive ability of standing long jump or bench-press to players NHL-performance.[2] Notably, the standing long jump length (~250 cm) is quite uniform between several studies with varying performance level of the athletes, which may partly explain the lack of association for this jump ability measurement.[2,4,6,13,17]

Finally, if simply assessing the correlations, without considering BF, total PlayerLoad™ had the lowest displayed association to the performance tests with τ=<0.11 for all measures, except for pullups. PlayerLoad™ and other whole-body measures of mechanical load are widely used in field sports such a football and rugby and have been found to be strongly correlated to running distance,[31] but no uniform approach has been applied in ice-hockey.[20] Anecdotally, some of the players eliciting the highest PlayerLoad™ scores in this study, were the lowest ranked players in the team (3rd or 4th lineup). Based on these data, one could speculate if a higher PlayerLoad™ is shown in less efficient players during the scrimmages, as visual observations suggest greater upper body movement, compared to better ranked players. However, compared to official matches, the scrimmages were performed with less high intensity actions, such as tackles and hits, which also influences the data and PlayerLoad™ score. Therefore, the specific use of this kind of workload variable in ice hockey and its relationship to physical performance tests should be further explored.

LIMITATIONS

There are some limitations that needs to be addressed. Firstly, we did not include external load data from official games. However, our scrimmage design has been shown to be comparable to official games, with the main difference being a higher relative intensity during scrimmages due to the continuous play design.[20] Thus, the association between physical performance tests and external load performance in this study may therefore be relevant to official games. Secondly, only sprint test - skate was used as an on-ice physical performance measure. Further studies should assess the relationship to other on-ice tests. In addition, while we adopted specific tests previously applied in high-level and elite players[2,3], there was a restricted number of tests included, and we did not include any measure of endurance. A more comprehensive test battery could have potentially provided a more thorough overview of physical performance. Finally, we included a limited number of high-level athletes. Small samples are a limitation because it provides restricted information. We have, however, used statistical methods suggested for small sample research. Further studies should, however, include a lager sample to provide more information into the analyses.

PRACTICAL APPLICATIONS

Physical game performance is a complex measure, difficult to decipher by fixed moving patterns, such as those included in traditional physical performance test batteries. The association between physical performance tests and markers of game performance seem to vary, both in relation to objective statistics and external load performance. This is reflected in our results, where evidence (BF_{10} >3) is shown for 8 of 144 associations. Coaches and practitioners should assess the relevance and importance of any physical test and external load measure thoroughly before including in a test- and monitoring regime. In addition, the low association between physical tests and external load measures indicate that they should not be used to monitor an athlete's performance level interchangeably or in isolation, but rather include a variety of relevant performance markers to cover the complex nature of abilities underlying game performance. Lastly, while scrimmages differ from official matches, the standardized design could be favorable when exploring associations to physical performance, as external load in official matches is affected by factors such as level of opposition, differences in playing time, stops, puck-drops and penalties etc, influencing the intensity of the match. Future studies should, however compare the differences to official game data and include players from different competitive levels.

CONCLUSION

While some physical performance test variables were associated with external load variables, the low number of meaningful associations in this study indicate that external load performance cannot be explained by the performance in physical tests alone. Several factors could affect these finding, such as a limited test-battery and limited number of specific on-ice tests. Thus, more research is needed to explore the association between physical performance tests and external load measures, both in training- and match situations.

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Figure 1: Scatterplots between physical performance tests and external load variables for the meaningful associations (BF >3). Including trend line (solid) and 95 % confidence limits (dotted lines). SS: Speed skating, CMJ: Countermovement jump, HIEs: High intensity events, Change of directions.

Table 1: Results from physical performance tests (n=14).

Physical Test	**Mean ± SD**
Sprint test - run	
10-m (s)	1.66 ± 0.06
30-m (s)	4.19 ± 0.15
Max speed run (m/s)*	8.21 ± 0.33
Sprint test - skate	
10-m (s)	1.77 ± 0.09
30-m (s)	4.29 ± 0.15
Max speed skate (m/s)*	8.41 ± 0.30
CMJ height (cm)	39.5 ± 5.1
Standing long jump (cm)	253.6 ± 13.7
Bench-press 1RM (kg)	86.1 ± 7.6
Pullups (nr)	17.1 ± 5.7
Trap bar deadlift 1RM (kg)	162.1 ± 24.9

*Max speed was calculated using the 20-30m spilt time
Nr: Number.

Table 2: Game data from the included variables during scrimmages (n=14).

Game variable	**Mean ± SD**
Total distance (m)	5072.0 ± 458.9
Peak speed (m/s)	8.45 ± 0.41
Slow Speed Skating (m)	607.3 ± 149.3
Moderate Speed Skating (m)	1744.8 ± 225.9
High Speed Skating (m)	2240.0 ± 565.5
Sprint Speed Skating (m)	470.3 ± 266.0
Number of sprints	19.9 ± 7.6
Total PlayerLoad^{TM} (au)	145.6 ± 27.4
High Intensity Events (nr)	269.3 ± 56.3
Accelerations (nr)	9.0 ± 3.2
Decelerations (nr)	44.2 ± 13.7
Change of Directions (nr)	216.1 ± 49.5

Nr: Number, au: arbitrary units. Mean ± SD was calculated from the players' average score after the four scrimmages

Table 3: Kendall's Tau correlation matrix

		Sprint test - run			Sprint test - skate							
	Body mass	10-m	30-m	Max speed run	10-m	30-m	Max speed skate	CMJ	Long-jump	Bench-press	Pullups	Trap bar
TD	0.49*	-0.01	-0.17	0.18	-0.09	-0.21	0.29	0.42	0.14	0.37	0.34	0.27
Peak Speed	0.22	-0.28	-0.39	0.27	-0.13	-0.34	0.55**	0.42	0.36	0.16	0.10	0.45*
SlowSS	-0.30	0.01	0.17	-0.13	0.18	0.21	-0.29	-0.29	-0.10	-0.25	-0.17	-0.23
ModSS	-0.35	0.12	0.19	-0.24	0.11	0.28	-0.35	-0.40	-0.17	-0.25	-0.21	-0.27
HighSS	0.42	0.03	-0.12	0.09	-0.09	-0.17	0.24	0.33	0.06	0.32	0.30	0.18
SprSS	0.28	-0.21	-0.32	0.29	-0.16	-0.36	0.44*	0.44*	0.30	0.25	0.17	0.34
Nr of sprints	0.43	-0.04	-0.16	0.10	-0.21	-0.29	0.28	0.46*	0.13	0.22	0.34	0.15
Total PL	0.29	0.11	0.00	-0.08	-0.06	-0.09	0.03	0.06	-0.09	-0.10	0.38	0.10
HIEs	0.37	0.39	0.36	-0.20	0.29	0.14	-0.16	0.02	-0.17	-0.07	0.61**	-0.14
ACCs	0.27	0.22	0.33	-0.28	-0.06	-0.02	-0.17	0.03	-0.13	-0.37	0.29	-0.15
DECs	0.12	0.21	0.28	-0.40	-0.04	0.14	-0.20	-0.07	-0.25	-0.18	0.32	-0.11
CODs	0.30	0.30	0.23	-0.07	0.20	-0.03	-0.02	0.07	-0.08	0.02	0.50*	-0.02

-1.0 0.0 1.0

Kendall's Tau correlations are displayed by graded color backgrounds. *Moderate evidence for H1 (BF_{10} >3), **Strong evidence for H1 (BF_{10} >10).

CMJ: Counter movement jump height (cm), pullups (max repetitions), bench-press (1RM), trap bar: Deadlift in a trap bar, TD: Total distance, SS: Speed skating, PL: PlayerLoad^{TM} (au), HIEs: High intensity events, ACCs: Accelerations, DECs: Decelerations, CODs, Change of directions.

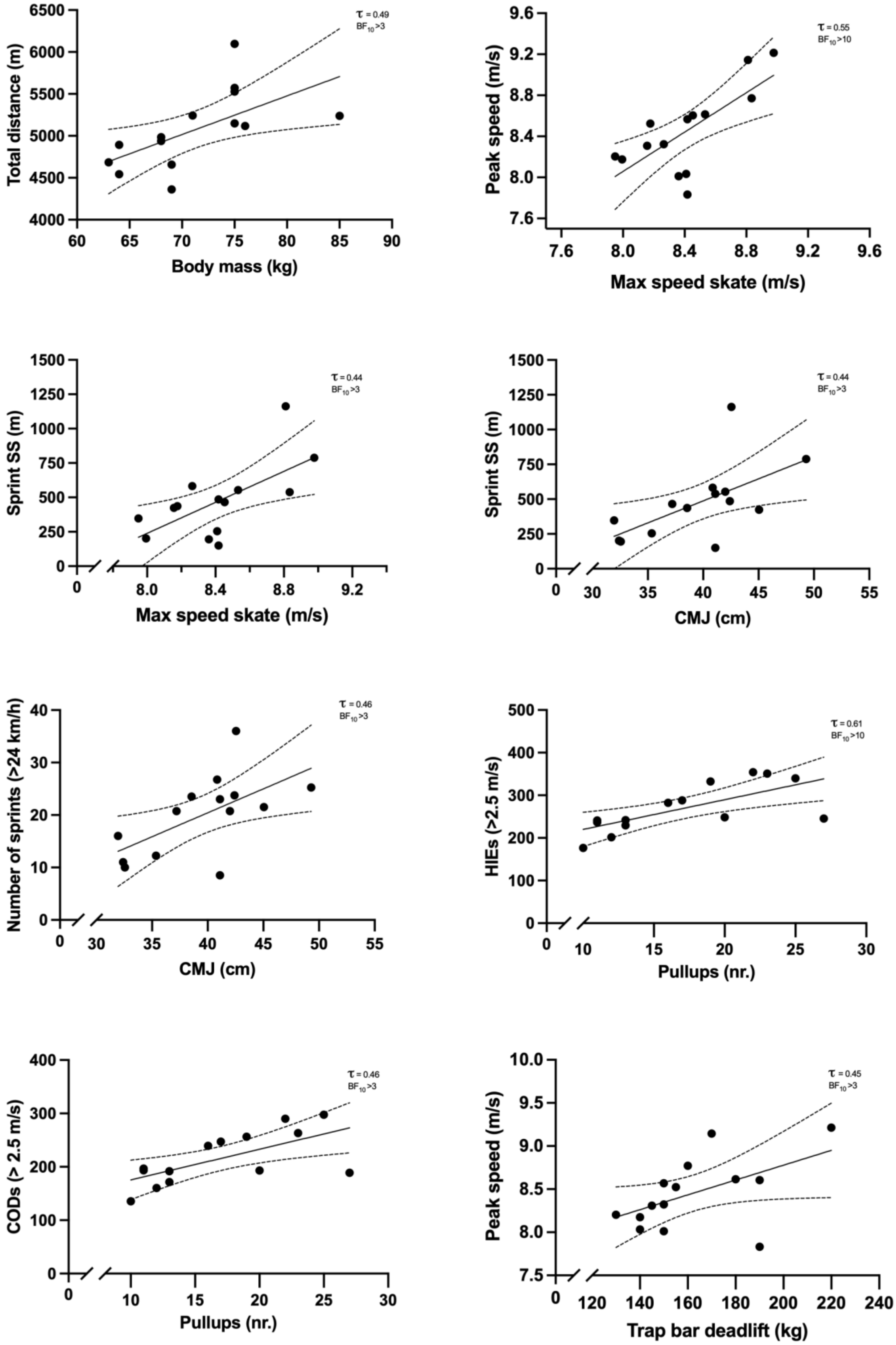

Figure 2 Scatterplots between physical performance tests and external load variables for the meaningful associations (BF>3), including trendline (solid) and 95% confidence limits (dotted lines). BF indicates Bayes Factors; CMJ, countermovement jump; CODs, change of directions; HIEs, high- intensity events; nr, number; SS, speed skating.

Paper III

In-season autoregulation of one weekly strength training session maintains physical and external load match performance in professional male football players.

Byrkjedal, P. T., Thunshelle, A., Spencer, M., Luteberget, L. S., Ivarsson, A., Vårvik. F., Lindberg, K., & Bjørnsen, T.

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In-season autoregulation of one weekly strength training session maintains physical and external load match performance in professional male football players

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ABSTRACT

The aim of this study was to compare the effects of autoregulating strength training volume based on an objective (external load match performance) versus a subjective (self-selected) method in professional male football players. Sixteen players completed a 10-week strength training programme where the number of sets was regulated based on football match high-intensity running distance (HIR >19.8 km/h, AUTO, $n = 7$), or self-selected (SELF, $n = 9$). In addition to traditional physical performance assessments (30-m sprint, countermovement jump, leg-strength, and body composition), external load match performance was assessed with five matches in the beginning and in the end of the study period. Both groups performed ~ 1 weekly bout of ~ 6 sets in leg extensor exercises during the 10-week period, and maintained physical performance during the competitive season, with no group differences detected after the training period. Non-overlap of all pairs (NAP) analysis showed weak-to-moderate effects in external load match performance from before to after the study period, suggesting that players maintained or improved their performance. In conclusion, no group differences were observed, suggesting that both external load autoregulated and self-selected, low-volume in-season strength training maintained physical, and external load match performance in professional male football players.

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Resistance training; Athlete monitoring; GPS; Soccer

Introduction

Physical fitness is an important component of football performance and several studies have addressed the issue of optimizing strength training to prepare for match performance (Cross et al., 2019; Rønnestad et al., 2011; Styles et al., 2016; Suchomel et al., 2016). General recommendations for highly strength-trained athletes suggest performing strength training ≥ 2 times per week with a total of ~ 10–30 sets per muscle group, per week (Beato, Maroto-Izquierdo, et al., 2021; Schoenfeld et al., 2021). However, timing of in-season strength training is challenging, as professional teams often participate in numerous competitions, regularly playing several matches per week. With focus on adequate recovery, travel, and other match preparations, strength and conditioning coaches in team sports must compromise their strength training focus due to these time constraints (McQuilliam et al., 2022; Rønnestad et al., 2011; Silva et al., 2015). Thus, high strength training volumes are often not achievable or not prioritized during the competitive season. Intriguingly, as little as one strength training session per week during the competitive season has been reported to maintain initial pre-season gains in strength, jump and sprinting performance, compared to de-training effects observed without in-season strength training (Rønnestad et al., 2011; Silva et al., 2015). Contrastingly, a higher training volume should be prioritized if the overall aim is to improve physical performance (Beato, Maroto-Izquierdo, et al., 2021; Silva et al., 2015). Nevertheless, the aim of in-season strength training is often not to improve players physical capabilities, but rather to maintain strength and physical performance, in addition to reduce the risk of injury (Beato, Maroto-Izquierdo, et al., 2021; McQuilliam et al., 2022; Suchomel et al., 2016). Naturally, the effect of in-season strength training programming can therefore differ from strength training interventions that are performed during pre-season training periods (Silva et al., 2015). Thus, the inclusion of one session per week is often practiced during the competitive season (Beato, Maroto-Izquierdo, et al., 2021; Rønnestad et al., 2011; Silva et al., 2015).

Where team sport players previously were treated collectively, researchers and practitioners have acknowledged the need for individualization also within team sports (Boullosa et al., 2020). For example, differences in dose-response, fitness-level, recovery status, and so on, plays an important role for training prescription and programming (Boullosa et al., 2020; Ravé et al., 2020; Wing, 2018). Several methods have been applied to optimize individual training load adjustment, including autoregulation. Autoregulation refers to adjustment of training based on measurements of physical performance (objective autoregulation) or the athletes perceived capability to perform (subjective autoregulation) (Greig et al., 2020). Current practice of objective autoregulation methods in

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strength training seem to mainly focus on in-session measurements for adjustments in training intensity or volume (Zhang et al., 2021). For example, velocity-based autoregulation applies thresholds for velocity during each repetition (e.g., lifting within a certain velocity target or ending the set after a given velocity reduction between repetitions). Alternatively, subjective autoregulation can be applied by measures of rating of perceived exertion (RPE), reps in reserve (RIR), readiness scores or self-selection of training load and intensity, hereby adjusting for individual factors such as sleep, stress, fatigue etc (Greig et al., 2020; Lopes Dos Santos et al., 2020). In addition, alternative measures of readiness, such as pre-session assessment of neuromuscular fatigue or heart rate responses have also been applied to regulate training (Lacome et al., 2018; Silva et al., 2018).

As football players do most of their training on the field, with tracking systems widely applied as a player monitoring tool, it's interesting to note the limited research investigating the link between these external workload variables and individual adjustment of strength training intensity and volume. High intensity running (>19.8 km/h; HIR) and sprint running distances have become increasingly important in modern day football and are among the most applied performance measures from tracking systems when assessing both training and match performance (Akenhead & Nassis, 2016; Bush et al., 2015). Interestingly, a meaningful relationship is shown between HIR distance and post-match fatigue (Beattie et al., 2021), and a recent review has shown HIR distance to be associated with increased fatigue 24 hours post-match, with increased creatine kinase and lower countermovement (CMJ) peak power output (Hader et al., 2019). Furthermore, HIR distance exposure has been related to soft tissue injuries, while simultaneously being suggested as a tool in injury prevention strategies (Beato, Drust, et al., 2021). Despite these findings, the use of tracking systems as an objective marker in regulating strength training load seems unexplored. Hence, the aim of this study was to compare the effects of in-season strength training volume autoregulated based on football match HIR distance with self-selection of strength training volume, in professional male football players. Furthermore, in addition to typical pre-post assessments, we also included measures of external load match performance before and after the study period to explore possible changes in physical match performance following the strength intervention period. Based on the findings by Hader et al. (2019), we hypothesized that autoregulating strength training with an objective marker would induce superior changes in physical and external load performance compared to self-selection of strength training volume.

Methods

Design

This study was conducted over 15 weeks during the second half of the regular season (Figure 1). Within this period, the team performed a 10-week strength training intervention. During the intervention, players alternated training between a micro-dose strength training programme (grey strength icons) and a regular-dose programme (black strength icons). Physical performance (black arrows, 30-m sprint, CMJ and leg press strength and power) and body composition (blue arrows, via dual-energy X-ray absorptiometry: DXA) were tested pre- and post-intervention. During the study period, the team played 18 matches (football-icons), 5 matches at the beginning ("baseline") and 5 matches at the end of the study period ("follow-up"), were included to explore the effects in external load match performance after the study-period (green football icons).

Participants

A professional football club, playing in the Norwegian 2nd tier was invited to participate in the study. Initially, 30 out-field players were eligible for participation in the study. Nine players did not participate in pre-testing, due to injuries and not being a part of the senior team squad. Thus, 21 players were randomly assigned to an external load autoregulated group (AUTO-group, $n = 10$) or a subjectively regulated group (SELF-group, $n = 11$). During the intervention period, five players were injured and were unable to participate in the post tests ($n = 3$ AUTO, $n = 2$ SELF). Sixteen players between 16 and 30 years (AUTO [$n = 7$: 24.1 ± 4.7 yrs, 181.4 ± 5.1 cm, 76.6 ± 7.1 kg], SELF [$n = 9$: 23.7 ± 3.9 yrs, 185.0 ± 6.9 cm, 77.4 ± 8.4 kg]) consisting of 12 defensive players (AUTO: $n = 3$, SELF: $n = 6$), 5 midfielders (AUTO: $n = 3$, SELF: $n = 2$) and 2 attackers (AUTO: $n = 1$, SELF: $n = 1$) completed the intervention period and all pre- and post-laboratory measurements. Written informed consent was

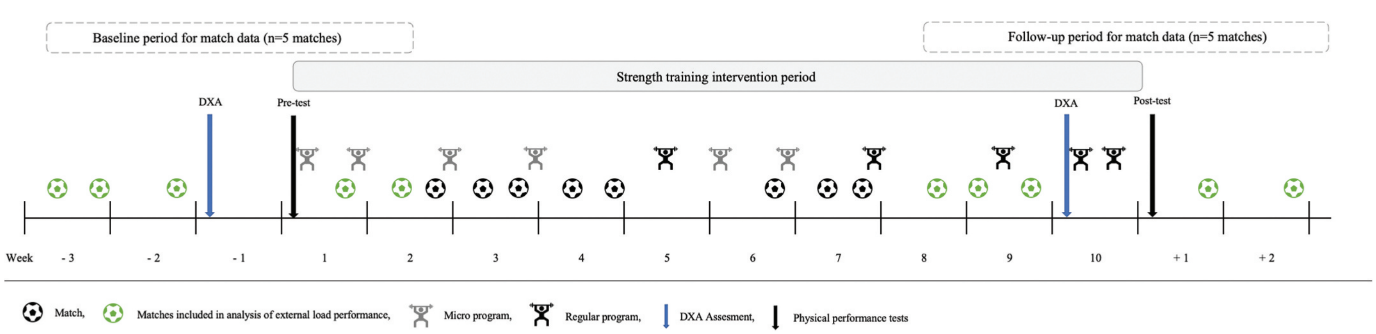

Figure 1. Overview of the intervention period. Football-icons: Matchday; Green football-icons: match data included in analysis of external load performance; Blue arrow: Dual X-ray absorptiometry (DXA) Body composition assessment; Black arrow: Physical performance tests; Strength icon: strength training session for both groups; Black strength training icon: AUTO-group performed the regular strength training program; Gray strength training icon: AUTO-group performed the micro strength training program.

obtained from all players before the study commenced. The study was performed according to the Helsinki declaration of 1975, approved by the local ethical committee at the University of Agder, Kristiansand, Norway, and Norwegian Center for Research Data (approval reference: 464080).

Experimental procedure

During the intervention period all players performed two different strength training programmes: *Regular* and *Micro*. Each program was designed to be feasible in-season sessions with exercises that players were well familiarized with prior to the present study. For the AUTO-group, the micro programme was applied in more congested periods (i.e., ~2 matches per week) while the regular programme was applied in normal weeks (e.g., ~1 match per week). SELF-group was able to self-select both programme and number of sets during the same sessions. Exercises included in the respective programmes are presented in Table 1. All players performed 1–3 sets per exercise of the regular programme, and 1–2 sets per exercise with the micro programme. The players performed one to two strength training sessions per week, with an aim of performing two sessions per week as often as the football training and match schedule allowed for. The head coach decided when strength training sessions could be implemented, and the training schedule was similar for both groups (Figure 1).

The regulation of training volume in the AUTO-group was based on HIR distance, and the SELF-group self-selected their number of sets based on a subjective feeling of readiness to train. For the AUTO-group, the calculation of a player's HIR distance was dependent on time between the strength training session and the last match, and match participation. Specifically, if a strength training session was performed <3 days after a match, and the player had ≥ 60 playing time, HIR distance from that specific match was used to calculated training volume. In all other circumstances, the accumulated HIR distance the previous 72 hours prior to the strength training session was applied to calculate the player's HIR distance.

The selection of HIR distance as a variable to regulate strength training volume was based on the findings from Hader et al. (2019), which demonstrated that HIR distance represented the most sensitive post-match monitoring variable associated with markers of neuromuscular fatigue across 165 semi-professional to elite level soccer players.

To calculate the specific thresholds applied in the AUTO-group of the present study, repository HIR distance data from the team's field activity (i.e., training and matches) during the ongoing season (243 data points) was applied. By design, we aimed to divide the players into three "groups", which regulated the players to low (1 set), moderate (2 sets) or high (2 sets in micro programme, 3 sets in regular programme) strength training volumes. Accordingly, an upper and lower HIR distance threshold of 687 m and 421 m, was calculated, which corresponds to the team's previous field activity HIR distance data's mean ±0.5 SD (554 ± 133 m). This distribution of our repository data in the present study and threshold categorization, was in our interpretation comparable to the distribution of the data across players in Hader et al. (2019). Thus, for the AUTO-group in the present study, the strength training volume was regulated to either 1, 2 or 3 sets (2 sets in the micro-programme), when the player had a HIR distance >687 m, between 421–687 m or <421 m, respectively.

Before every strength training session, the AUTO-group received information on which programme and specific number of sets to perform, according to the HIR criteria. The SELF-group performed training on the same days as the AUTO-group. The SELF-group were instructed to reflect on their subjective feeling and readiness to train and base selection of programme and set number on their subjective rating of readiness. For example, if they felt fresh and ready to train, they were encouraged to select a higher training volume. Thereafter, players selected the programme and number of sets accordingly. Typically, strength training sessions were conducted the day after a match and/or ~4 days prior to upcoming match-days (Figure 1). The SELF-group selected their desired programme and number of sets before initiating each training session, to ensure that they chose the self-selected appropriate training volume prior to exercising in the same environment as the AUTO-group. The same researcher supervised all training sessions for all athletes.

Testing procedure

Physical performance testing was completed over one test-day, pre- and post-intervention, whereas body composition was

Table 1. Strength training programmes during the intervention period.

Programme/Exercise	Sets	Reps	RIR	Rest	Comment
MICRO-DOSE					
A1 Back squats	1–2	6	1–2	2–3 min	Full range of motion
A2 Assisted band jumps		4			Bodyweight, pause 2 s at bottom
B1 Hip Thrust	1–2	6	1–2	2–3 min	Instructed to jump as high as possible
B2 Depth jump		4			
REGULAR-DOSE					
Back squats	1–3	6	1–2	2–3 min	Full range of motion
Hip Thrust	1–3	6	1–2	2–3 min	
Bulgarian split squat	1–3	6	1–2	2–3 min	Sets x reps per side
Seated calf raises	1–3	6	1–2	2–3 min	
Side-plank	1–3	8		2–3 min	Sideways w/knee kicks (8 knee kicks). Sets x reps/side. ~15 s per side.
Pallof-press	1–3	8		2–3 min	Standing in cable machine. Sets x reps/side. Hold ~3 s per side.

Exercises included in the specific programs. All participants performed the same programs. RIR: Reps in reserve. A1 and A2, or B1 and B2: superset between exercises, 1 and 2 were performed without a rest period.

completed on a separate test day, with no moderate to hard physical activity the previous 48 h prior to testing. The physical performance test-battery consisted of 10-min self-paced warm-up on a treadmill, 30-m linear sprint, CMJ, and Keiser leg press. All players were familiar to the test battery and had previous experience from similar test protocol movements. The test session duration was ~ 1 hour and all players performed the tests in the same order pre- and post-intervention between 08:00 and 15:00. Physical performance post-testing was completed 70.0 ± 0.0 days after pre-testing and at the same time of day (±1.0 hours). Body composition was assessed ±7.0 days in relation to physical performance testing, and post-assessments were completed 68.6 ± 3.8 days after the initial assessment and at the same time of day (±40 min) between 08.00 and 12.00.

Body composition (DXA)

Height was measured without shoes to the nearest 0.5 cm using a wall-mounted centimetre scale (Seca Optima, Seca, Birmingham, UK). Body mass was measured in underwear to the nearest 0.1 kg with an electronic scale (Seca 1, model 861, Birmingham, UK). Body composition was assessed using dual-energy X-ray absorptiometry (DXA) (GE-Lunar Prodigy, Madison, WI, USA, EnCore software version 15) and performed according to best practice recommendations, were the players arrived in a fasting state without any fluid intake on the morning of the scan (Nana et al., 2015). The same technician performed all scans on all players. This protocol is categorized with excellent reliability scores (CV < 0.8%) for both total body and regional (i.e., legs) body composition measures (Shiel et al., 2018).

30-m sprint

30-m Sprint test was performed on an indoor synthetic surface. Players performed 2–4 maximal sprints during the test with 4 min passive rest between each attempt. The timing started when the front foot left the ground at 0 cm and wireless dual-beam timing gates were used to measure time at each 5-m interval (Musclelab, Ergotest innovation AS, Langesund, Norway). The sensors at 5-, 10-, 15-, 20-, 25- and 30-m were placed 120 cm above the ground. The trial with the best 30-m time was included in post-test analysis and maximum speed was calculated from the 5-m split-times. TE of 0.03–0.05 s is reported for 10–30 m sprint times and 0.18 m/s for max speed (Lindberg et al., 2022).

Counter movement jump (CMJ)

CMJs were performed with hands on the hips, and the depth of the squatting motion was self-selected. The players completed 2–3 sets of 3 jumps performed 30 s apart, followed by 2–3 min passive rest. The CMJs were measured using an AMTI force plate sampling at 1000 Hz (Advanced Mechanical Technology, Inc Waltham Street, Watertown, USA) with custom-written MATLAB (The MathWorks, Natric, MA) script used to process the data. The mean jump height and power of the two single best attempts was included in post-test analysis. Jump height was calculated through the impulse – momentum theorem and registered with a minimum of 1 decimal (e.g., 0.1 cm). Power was calculated as time average (mean) instantaneous power (product of force and velocity) from the entire push-off phase for each respective jump, that is, from peak force, obtained at the deepest position, until take-off. The power was obtained as watts (Lindberg et al., 2021). A TE of 1.7 cm and 121 W is reported for CMJ height and power, respectively (Lindberg et al., 2022).

Keiser leg press

Lower limb strength and power was assessed using a Keiser AIR300 horizontal pneumatic leg press device with an A420 software (Keiser Sport health equipment INC., Fresno, CA, USA). Average force and velocity in each repetition were derived from the Keiser software with the manufacturer's standard “10-repetition force-velocity test” with incremental loads (Lindberg et al., 2021). The incremental test was performed in the seated position with a 90° knee-joint angle, starting at 41 kg and increasing to 250 kg at the tenth repetition with increased and standardized increments of approximately 20–30 kg for each attempt. If the participant exceeded 250 kg, the test continued with 60-s rest between attempts until failure. The rest period was 10–20 s for the initial 5 loads and 20–40 s for the last 4 loads. The players were encouraged to push as explosively as possible until failure. Keiser leg press does not cause ballistic action due to the pneumatic semi-isotonic resistance, and the entire push-off was performed with maximal intentional velocity. The leg press was performed as a concentric only action without countermovement, as the pedals are resting in a predetermined position prior to each repetition. A linear regression was fitted to the average force and velocity data to calculate individual force–velocity variables. Theoretical maximal force and theoretical maximal velocity were defined as the intercepts of the linear regression for the corresponding force and velocity axis. The theoretical maximum power was calculated as theoretical maximal force · theoretical maximal velocity/4 (Lindberg et al., 2021) and was retained for further analysis. Test-retest analysis of the Keiser leg press have revealed a CV of 4.2% for both Pmax and Fmax (Lindberg et al., 2021)

External load match data

HIR distance from training and external load match performance was assessed with a tracking system from Catapult Sports (Vector S7, Firmware 8.10, Catapult Sports, Melbourne, Australia). Catapult Vector uses the Doppler shift methods for GPS positional calculations, while inertial measurement analysis is performed based on Kalman filtering algorithms (Luteberget et al., 2017). Each player wore a tracking device, located between the scapulae in a custom vest supplied from the manufacturer. Data was collected via a 10 Hz global navigation satellite system and an inertial measurement unit including a three-dimensional accelerometer, magnetometer, and gyroscope sampling at 100 Hz. Devices were turned on ~15 min prior to training/matches, and all players used the same designated device throughout the study period. A total of 10 matches were included to explore the effect of external load match performance after the intervention period. Five matches played over 28 days at the beginning of the study period were used as a baseline reference for match performance (baseline-period), while the five last matches, played over 29 days, at the end of the intervention period were used to assess the effect of the intervention (follow-up-period). All included matches were played on an artificial grass surface with kick off between 15:00–20:00. To be included in the analysis of external load match performance, the players had to participate in a minimum of two matches with ≥60 min of playing time in both the baseline- and follow-up period. Eight ($n = 5$ AUTO, $n = 3$ SELF) of the 16 players completing the intervention period, fulfilled these inclusion criteria for external load match data. Average number of connected satellites and horizontal dilution of precision was 14.8 ± 1.7 and 0.9 ± 0.2 during the baseline period and 13.7 ± 1.1 and 1.0 ± 0.1 during the follow-up period, respectively.

Match data were extracted from the tracking devices post-match and edited in Catapult OpenField (Catapult Sports, Melbourne, Australia) software (version 1.17.2) to only include data from playing time in the match. Locomotive variables from the matches included distance per min, peak speed, HIR distance (19.8–25.2 km/h), sprint running distance (>25.2 km/h) and number of HIR and sprint efforts. PlayerLoad™, high intensity events, accelerations, decelerations and change of directions were applied as previously reported by Luteberget and Spencer (Luteberget & Spencer, 2017). Accelerations, decelerations and change of directions are a summary of identified movements in the respective direction with an intensity >2.5 m/s where the sum of accelerations, decelerations and change of directions is displayed as high intensity events. External load variables were re-calculated and expressed relative to player's playing time. All external load variables have shown acceptable reliability (Crang et al., 2022; Luteberget et al., 2017).

Factor influencing match performance

Level of the opposition and match score are factors that potentially can influence the team's performance (Bradley et al., 2013; Lago et al., 2010; Lago-Peñas, 2012; Moalla et al., 2018). To address these potential confounders, we used table ranking and final match score to classify match difficulty and match outcome. Final table ranking of the included season was used to classify match difficulty, where the match was ranked as hard, moderate, or easy when facing a top 6, middle 5 or bottom 5 team, respectively. Match score was classified as "win/loss" when there was a ≥ 2 goal difference, or even (draw/single goal difference), in the final score. The included team ended among the middle-ranked teams. The matches were classified as easy ($n = 1$) and hard ($n = 4$) in the baseline period, and easy ($n = 2$), moderate ($n = 1$) and hard ($n = 2$) in the follow-up period. Two matches, 1 in each period, were classified as "win", with the remaining 8 matches classified as "even".

Statistics

Descriptive results were calculated using Microsoft Excel (version 16.67, 255 Microsoft Corp. Redmond, WA, USA) and are reported as Mean ± SD. The main statistical analysis was conducted in Jeffreys's Amazing Statistics Programme (JASP) version 0.16.1. Differences between the AUTO- and SELF-group were assessed at pre-test and post-test using Mann–Whitney U test, while the within group differences in pre- to post-test changes were analysed using Wilcoxon signed-rank test. Between group differences from pre- to post-test was analysed with a Friedmans test.

Differences in external load match performance variables between the baseline and follow-up period were analysed using non-overlap of all pairs (NAP). NAP is a nonparametric technique for measuring nonoverlap or "dominance" for two phases. It does not include data trend. NAP is appropriate for nearly all data types and distributions, including dichotomous data. NAP has good power efficiency, approximately 91–94% that of linear regression for "conforming" data, and greater than 100% for highly skewed, multi-modal data. NAP is equal to the empirical AUC (Area Under the Curve) from a ROC test. Strengths of NAP are its simplicity, its reflection of visual nonoverlap, and its statistical power. In many cases it is a better solution than tests of Mean or even Median differences across phases (Parker & Vannest, 2009). Effect sizes for NAP values are reported according to Parker and Vannest's recommendations: 0–.65 = week effects, .66–.92 = moderate effects, .93–1.0 = large or strong effects (Parker & Vannest, 2009).

Results

The AUTO-group ($n = 7$) completed 1.1 ± 0.1 strength training sessions per week, while the SELF-group ($n = 9$) completed 1.0 ± 0.1 strength training sessions per week. On average, the AUTO-group and SELF-group completed 5.8 ± 1.2 and 6.4 ± 1.4 sets in leg extensor exercises (hip, knee, and ankle extensors) per strength training session, respectively.

Mean number of strength training sessions in total across 10 weeks were 10.6 ± 0.8 (Regular 5.0 ± 0.0, Micro 5.6 ± 0.8) for AUTO-group and 10.6 ± 1.0 (Regular 5.3 ± 1.1, Micro 5.2 ± 1.6) for the SELF-group. Mean number of sets in leg extensor (ankle, knee and hip) exercises per session were similar between the groups for both the regular (AUTO: 8.2 ± 1.8, SELF: 8.9 ± 2.0) and micro programme (AUTO: 3.6 ± 0.4, SELF: 3.8 ± 0.4). Mann-Whitney U test confirmed that there were no group differences in training volume (number of strength-training sessions, sessions with the regular and micro programme, or number of sets completed) between the groups. The AUTO-group was regulated based on their HIR distance and an overview of sessions regulated (regular/micro) to high (3/2) moderate (2/2) or low (1/1) volume strength training can be found in Table 2.

A calculation of HIR-distance was additionally performed for the SELF-group to explore if HIR-distance was associated with their subjective regulation of strength training volume. On average, 4.7 ± 1.3 of the SELF-group's strength sessions across the 10-week intervention were self-selected in accordance with the AUTO-group's criteria, while 5.9 ± 1.6 was not.

The pre- and post-test results are presented in Table 3 with percent change in physical performance from pre- to post-test presented in Figure 2. No differences in physical and body composition measures were found between the groups at pre- or post-test. When comparing post- to pre-test measures, no significant differences was evident in the physical performance measures for the respective groups, or when analysing all players as one group. For body

Table 2. Autoregulated strength training sessions for the AUTO-group ($n = 7$).

	High volume training (HIR: <421)		Moderate volume training (HIR: 421–687)		Low volume training (HIR: >687)	
	Total	Mean ± SD	Total	Mean ± SD	Total	Mean ± SD
Strength sessions (n)	27	3.9 ± 1.9	29	4.1 ± 1.2	18	2.5 ± 2.8
Regular (n)	12	1.7 ± 0.8	13	1.9 ± 0.9	10	1.4 ± 1.5
Micro (n)	15	2.1 ± 1.2	16	2.3 ± 1.0	8	1.1 ± 1.4

Number of strength training sessions/programs in total across all AUTO-group participants, and that was regulated to a high, moderate or low training volume.

Table 3. Physical performance and body composition at pre- and post-test.

	Pre-test			Post-test			Change from pre- to post-test		
Test variable	SELF (*n*=9)	AUTO (*n*=7)	Combined (*n*=16)	SELF (*n*=9)	AUTO (*n*=7)	Combined (*n*=16)	SELF (*n*=9)	AUTO (*n*=7)	Combined (*n*=16)
Physical performance tests									
10 m (s)	1.53 ± 0.07	1.52 ± 0.05	1.52 ± 0.06	1.52 ± 0.06	1.49 ± 0.03	1.51 ± 0.05	−0.01 ± 0.04	−0.02 ± 0.05	−0.02 ± 0.04
30 m (s)	3.95 ± 0.17	3.91 ± 0.11	3.93 ± 0.14	3.92 ± 0.16	3.88 ± 0.10	3.90 ± 0.13	−0.03 ± 0.08	−0.03 ± 0.08	−0.03 ± 0.08
30 m max speed (m/s)	8.75 ± 0.43	8.88 ± 0.32	8.81 ± 0.38	8.78 ± 0.42	9.06 ± 0.38	8.89 ± 0.42	−0.03 ± 0.18	0.17 ± 0.18	0.08 ± 0.19
CMJ (cm)	39.3 ± 6.2	42.3 ± 3.6	40.6 ± 5.3	40.9 ± 7.1	43.5 ± 6.1	42.0 ± 6.6	1.7 ± 3.6	1.19 ± 3.94	1.46 ± 3.64
Relative CMJ power (W/kg)	31.8 ± 3.7	32.8 ± 4.1	32.2 ± 3.8	31.6 ± 3.7	32.0 ± 3.9	31.8 ± 3.7	0.2 ± 2.3	−0.8 ± 1.8	−0.5 ± 1.8
Leg press Pmax (W)	1487 ± 309	1667 ± 405	1566 ± 353	1488 ± 362	1650 ± 431	1559 ± 388	1 ± 193	−17 ± 113	−7 ± 158
Relative leg press Pmax (W/kg)	19.2 ± 2.7	21.5 ± 4.2	20.2 ± 3.5	19.3 ± 4.0	21.2 ± 4.5	20.1 ± 4.2	0.2 ± 2.3	−0.3 ± 1.2	0.0 ± 1.9
Leg press Fmax (N)	2794 ± 377	3071 ± 640	2915 ± 509	2898 ± 368	3037 ± 647	2959 ± 494	104 ± 146	−34 ± 302	44 ± 230
Relative leg press Fmax (N/kg)	36.2 ± 3.8	40.0 ± 7.4	37.8 ± 5.8	37.8 ± 3.7	39.3 ± 6.9	38.4 ± 5.2	1.6 ± 2.3	−0.6 ± 4.0	0.6 ± 3.2
Body composition assessment									
Body mass (kg)	77.4 ± 8.4	76.6 ± 7.1	77.0 ± 7.6	76.9 ± 7.9	76.9 ± 6.1	76.9 ± 6.9	−0.5 ± 1.7	0.3 ± 1.8	−0.2 ± 1.7
Total Lean mass (kg)	65.9 ± 5.9	66.5 ± 6.9	66.2 ± 6.1	65.4 ± 5.7	66.9 ± 6.5	66.1 ± 5.9	−0.5 ± 1.6	0.4 ± 1.2	−0.1 ± 1.4
Total Fat mass (kg)	8.6 ± 3.9	7.4 ± 1.7	8.1 ± 3.1	8.5 ± 2.9	7.4 ± 1.7	8.0 ± 2.5	−0.1 ± 1.5	0.0 ± 0.8	−0.1 ± 1.2
Total fat (%)	11 ± 3	10 ± 2	11 ± 4	11 ± 3	10 ± 3	11 ± 3	0.0 ± 0.1	0.0 ± 0.1	0.0 ± 0.1
Legs total mass (kg)	27.3 ± 3.5	27.7 ± 2.4	27.4 ± 3.0	27.4 ± 3.4	28.1 ± 2.4*#	27.7 ± 2.9*	0.1 ± 0.7	0.4 ± 0.4*#	0.3 ± 0.6*
Legs lean mass (kg)	22.4 ± 2.4	23.2 ± 2.3	22.8 ± 2.3	22.6 ± 2.3	23.6 ± 2.2*#	23.0 ± 2.3*	0.1 ± 0.7	0.4 ± 0.3*#	0.2 ± 0.6*
Legs fat mass (kg)	3.3 ± 1.5	2.9 ± 0.7	3.1 ± 1.2	3.3 ± 1.1	2.9 ± 0.9	3.1 ± 1.0	0.0 ± 0.6	0.0 ± 0.3	0.0 ± 0.5
Legs fat (%)	12 ± 4	11 ± 3	12 ± 4	12 ± 3	11 ± 3	12 ± 3	0.0 ± 0.1	0.0 ± 0.1	0.0 ± 0.1

*Different from pre-test ($p = <0.05$). # between group difference from pre- to post-test ($p = <0.05$). CMJ: Countermovement jump, Pmax: maximum power (W and W/kg total body mass) extrapolated from Keiser leg press power profile, Fmax: maximum force (N and N/kg total body mass) extrapolated from Keiser leg press power profile, Body composition assessment from dual-energy X-ray absorptiometry, %: percentage. Note: negative change in 10 and 30 m time indicate improved performance.

composition, a statistically higher leg mass and legs lean mass was shown at post- compared to pre-test, for the AUTO-group ($z = -2.197$, $p = 0.031$ and $z = -2.197$, $p = 0.034$) and when analysing all players as one group ($z = -2.094$, $p = 0.039$ and $z = -2.275$, $p = 0.024$). Comparingly, a between group difference was observed from pre- to post-test in leg mass ($x^2 = 4.000$, $df = 1$, $p = 0.046$) and legs lean mass ($x^2 = 4.000$, $df = 1$, $p = 0.046$).

Match data

With no differences between the AUTO- and SELF-group in physical performance after the intervention period, the influence on match data was assessed by merging the eight players that met the inclusion criteria for external load match data in to one group. Players appeared in 4.1 ± 1.1 matches (33 observations) with 89.2 ± 12.9 min playing time in the baseline period and in 4.5 ± 0.8 matches (36 observations) with 91.9 ± 7.4 min playing time in the follow-up period. External load match performance variables from the respective periods and NAP results are presented in Table 4. Overall, a moderate effect (NAP 0.66–0.92) was found for six of the included variables, while a weak effect (NAP 0–0.65) was found for the remaining five variables.

Discussion

The aim of this study was to assess the difference between objectively regulating strength training volume based on football match external load, compared to a subjective regulation method allowing the players to self-select their training volume. A novelty was to include and explore the change in external load match performance after an intervention period. Contrary to our hypothesis, our main finding was that there were no meaningful group differences in physical performance, or body composition after the intervention period. NAP analysis of external load match performance showed week to moderate effects, however, with the difference from the baseline to the follow-up period being lower than typical match-to-match variabilities suggesting that self-selection of strength training volume may be as effective as objectively regulating professional football players in-season training volume.

We did not observe any difference between the AUTO- and SELF-group in physical performance or body composition after the intervention period. However, compared to pre-test, assessment of body composition showed a 0.2–0.4 kg higher leg mass and legs lean mass for the AUTO-group and when assessing both groups together. This was however, the only significant differences observed, and with a SD of 2–3 kg among participants, the practical effect of this significant change should not be exaggerated. The lack of observed difference between the

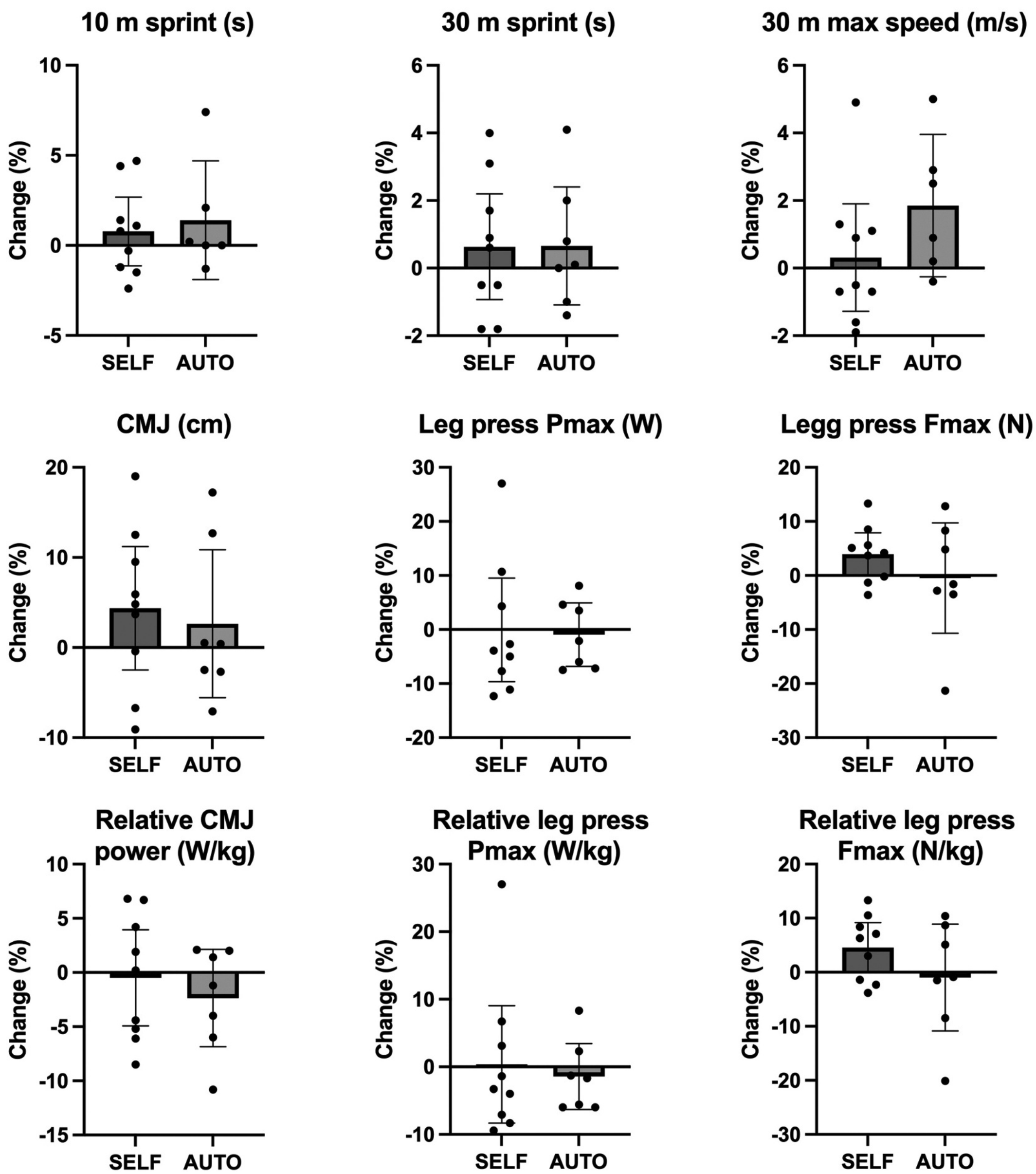

Figure 2. Mean ±95% CI % change in physical performance tests, including individual changes from pre- to post test. 10 and 30 m; Time to 10 m and 30 m during sprint tests, Max Speed: Maximum speed (m/s) during 30-m sprint testing, CMJ: Countermovement jump, Pmax: maximum power (W and W/kg total body mass) extrapolated from Keiser leg press power profile, Fmax: maximum force (N and N/kg total body mass) extrapolated from Keiser leg press power profile.
Note: positive change in 10- and 30-m time indicates improvement from pre- to post test.

Table 4. External load match performance variables during baseline and follow-up period.

Variable	Baseline period	Follow-up period	NAP (90% CI)
Distance per min (m/min)	116.6 ± 12.1	119.3 ± 9.5	.67 (.43–.92)
Peak Speed (m/s)	8.18 ± .47	8.43 ± .46	.65 (.41–.90)
PlayerLoad™ per min (au/min)	11.79 ± 1.59	11.87 ± 1.25	.60 (.35–.85)
HIR distance (19.8–25.2 km/h) (m/min)	6.43 ± 2.58	7.31 ± 1.71	.71(.47–.96)
Sprint distance (>25.2 km/h) (m/min)	1.37 ± .93	1.78 ± .89	.72 (.48–.97)
Efforts HIR (19.8–25.2 km/h) (#/min)	.43 ± .16	.48 ± .12	.67 (.43–.92)
Efforts Sprint (>25.2 km/h) (#/min)	.07 ± .05	.09 ± .05	.76 (.51–1.00)
High intensity events (>2.5 m/s) (#/min)	1.22 ± .26	1.34 ± .24	.65 (.41–.90)
Accelerations (>2.5 m/s) (#/min)	.27 ± .08	.31 ± .24	.74 (.50–.90)
Decelerations (>2.5 m/s) (#/min)	.26 ± .08	.25 ± .09	.41 (.16–.65)
Change of directions (>2.5 m/s) (#/min)	.69 ± .18	.78 ± .17	.64 (.40–.89)

All values except Peak speed are relative to playing time (i.e., per min). Au; arbitrary units, #; number. HIR; High intensity running.

groups is likely explained by the low training volume and similarities in the undertaken strength training. In accordance with general recommendations suggested to improve physical performance, we aimed for two strength training sessions per week (Beato, Maroto-Izquierdo, et al., 2021; McQuilliam et al., 2022; Schoenfeld et al., 2021). However, due to the real-world challenges with timing of in-season strength training previously reported (McQuilliam et al., 2022; Rønnestad et al., 2011; João R.; Silva et al., 2015), the present study ended up with ~ 1 session per week. Therefore, the overall volume of training being regulated is low and such low volumes may be well within the recoverable load for most players. Hence, autoregulating strength training load in-season may not be needed with such low training volumes. A potential reason for the lack of difference in strength training volume between the AUTO- and SELF-group could be that the SELF-group was also utilizing undertaken HIR distance when selecting training volume. However, when comparing the HIR distance and undertaken training volume for the players in the SELF-group, our results show otherwise. We hypothesize that autoregulation methods can be more important with a larger number of sessions or training weeks that also could differentiate the overall volume of undertaken training between the groups. Potential differences following an intervention period with higher strength training volumes should be assessed by future studies.

Although previous studies mainly included in-session objective markers during strength training to regulate training load (Zhang et al., 2021), we applied an objective football-related field measure shown to be associated with fatigue (Hader et al., 2019) and compared this to a subjective regulation method. While the SELF-group was instructed to reflect on subjective feeling and readiness, we did observe tendencies suggesting that some players were more likely to consistently select a high or low strength training volume. Personal preferences, with some players keener of strength training, and other players potentially favouring other aspects of their strength and conditioning training (therefore selecting a low volume), may explain this observation. Contrastingly, the application of HIR distance for the AUTO-group is unaffected by players personal preferences when prescribing training volume. Following this augment, applying a subjective regulation in periods with higher training volume could result in larger individual differences and potential de-training effects due to a low stimulus for some players. On the other hand, the individual aspect is important, and an objective marker might not be sensitive enough to capture every aspect of a player's ability to perform. Therefore, a combination of objective and subjective regulations might be preferable (Greig et al., 2020; Zhang et al., 2021).

Our findings align with the previous findings indicating a maintained physical performance with ~ 1 strength training session per week (Beato, Maroto-Izquierdo, et al., 2021; Rønnestad et al., 2011; Silva et al., 2015). However, "one session" can be imprecise, as the total volume (e.g., number of sets per muscle) of undertaken training differ between studies. For example, the players in the current study performed ~ 6 sets of leg extensor exercises per session, while Rønnestad et al. (2011) performed 3 sets per session. Nonetheless, 3 and 6 sets are lower than the typical recommendations for strength trained athletes of ~ 10–30 sets per muscle group, per week (Beato, Maroto-Izquierdo, et al., 2021; Schoenfeld et al., 2021). While strength and conditioning coaches report that they prescribe of ≥ 2 sessions per week (McQuilliam et al., 2022), adherence is typically lower. For example, professional players were reported to have 1.5 ± 0.9 strength training sessions per micro cycle (time between matches) (Cross et al., 2019). However, they were only asked to report from 7-day turnaround cycles without any substantial travel. In real-world conditions, involving the complexity of congested match schedules, travels, national team appearances, change of coach, training philosophy, match importance/preparations, and so on (Malone et al., 2019; McQuilliam et al., 2022; Rønnestad et al., 2011), up to 10 sets/~1 session per week seems to represent the real-world practice when timing strength training sessions during the competitive period (João R. Silva et al., 2015).

When performing training interventions, there is an underlying assumption that a change in physical performance relates to the players performance in training and matches. However, training intervention studies have typically been isolated to laboratory-testing, and potential performance-enhancing effects are simply assessed by evaluating the pre-post changes, with some studies also including a follow-up test to identify longitudinal effects after the intervention (Iaia et al., 2015; Rønnestad et al., 2011). Therefore, a secondary aim for this study was to address external load match performance at the same timepoints as the physical performance tests. Additionally, we intended to assess the relationship between changes in physical- and external load performance. However, with few players fulfilling the inclusion criteria for match data, and limited changes due to the overall low training volume, we were unable to explore this aim. Nevertheless, we included a baseline and follow-up period and used NAP analysis to assess changes in external load match performance between the periods. While 33 and 36 match observations from baseline and follow-up period were included in NAP analysis, the data is only a representation from 8 of 16 players fulfilling the strength intervention. Nonetheless, and unlike traditional approaches, NAP analysis allows every observation at both periods to be assessed for each individual player before combining all players and display an overall "effect" from the baseline to the follow-up period. While a weak to moderate effect is shown in these external load variables, it is important to notice the actual difference in external load output during each period, and the practical importance. For example, sprint distance has a moderate effect (NAP = 0.72) and increases from 1.37 m/min to 1.78 m/min between the baseline to the follow-up period. With ~90 min playing time, this difference equals ~40 m. This is less than a half football field, and importantly lower than the match-to-match variations for sprint distance (Carling et al., 2016; Gregson et al., 2010). Additionally, this was an in-season study including 1–2 weekly matches and focus on football field training, all contributing to stimuli relevant for external load match performance. Thus, our findings should not be interpreted as an effect per se, but rather be interpreted together with the physical performance results following the intervention period, supporting the evidence for a maintained physical- and external load match performance following a strength intervention period with ~ 1 low volume strength training session per week.

While we highlight the scarcity of in-season intervention studies, we acknowledge that there are several limitations to our design. Performing in-season studies involving professional players limits the experimental control over the design and researchers influence. For example, the number of strength training sessions was influenced by the philosophy of the head coach and match importance, resulting in increased focus on field training with technical and tactical focus in this specific period. Furthermore, the inclusion of a control-group is unrealistic when working with this population. Therefore, the effects of performing 1 vs 2 strength training sessions per week or simply performing football specific field training in our participants are unknown. While we randomly assigned players to the AUTO- or SELF-group, there is a possibility that the selection of such small groups might influence the results as individuals may respond differently to specific autoregulation methods. Furthermore, the AUTO- and SELF-group performed strength training in the same facility and at the same time, which could have influenced the self-selection of training volume in the SELF-group. However, the SELF-group always selected their training volume before either group initiated training sessions to minimize the likelihood of such an interaction between groups. In addition, the players were used to having individualized strength training prescriptions provided by the coaching staff, and therefore did not place focus on what training other players performed. Nevertheless, the SELF-group was dependent on the players being honest with themselves and actively reflecting on their readiness before selecting training volume. Thus, a player could repeatedly select a low volume if they desired. We could have implemented a RPE or wellness scale in an attempt to control this regulation. However, both scale-measurements and the applied regulation of the SELF-group is dependent on factors such as standardizations (e.g., when and how is data collected) and athlete buy-in for the implementation to work as intended (Abbott & Taber, 2021). While we emphasize the possibility for the players to "cheat", these are professional players always competing for a spot among the 11 players starting a match, and are likely aware that an insufficient training volume can lead to detraining. Thus, autoregulating training volume based on self-selection represents a real-world practical example, allowing the players to self-regulate themselves to be optimally prepared for match performance.

The effects of a subjective vs an objective autoregulation method should however also be assessed in periods with higher training volume before concluding. The AUTO-group in the present study was regulated on an objective marker by the application of HIR distance that is previously shown to be closely associated with markers of neuromuscular fatigue across 165 soccer players with different positional demands (Hader et al., 2019). In addition, the chosen thresholds in the present study represents a three-way division of HIR distance from a similar HIR distribution across players as the athletes in Hader et al. (2019). However, we acknowledge that such collective calculation of the thresholds across athletes to regulate training volume has its limitations. Match HIR distance is subject to the influence of positional demands (Buchheit et al., 2020) and thereby variations in HIR distance loads, which, in turn, can affect the optimal prescription of strength training volume. Unfortunately, we were unable to address position-specific differences due to the small sample size. Therefore, we recommend that future research explores individual regulations based on personalized reference points, as opposed to the utilization of absolute values as observed in the present study. Furthermore, HIR distance is only one external load measure as highlighted by Hader et al. (2019). Additionally, external load is only one aspect of player monitoring and further studies should aim to explore other external load measures as well as the inclusion of internal load measures to objectively regulate strength training. In addition, it could be speculated that external on-field load measures such as HIR distance better reflect a combination of the most relevant load and associated fatigue than typical pre-session assessment of neuromuscular fatigue measures (Boullosa et al., 2020). However, typical readiness variables such as CMJ or a combination of such off-field measurements could potentially be better markers of overall fatigue and readiness. Finally, we aimed to explore the relationships between changes in physical and external load performance following an intervention period. This is however challenging during an in-season phase with limited control and a number of contextual factors influencing the variability of match performance. We do however believe that external load measures in addition to traditional physical performance assessments after periods of intensified training (e.g., intervention periods, pre-season, etc.) can provide valuable information. However, it is important to ensure accuracy and standardization of the measurements. As such, standardized small-sided games can serve as a measure in this regard and we encourage future studies to explore the inclusion of external load during such conditions. In summary, our findings with weak to moderate effects in external load match performance is to be expected. Thus, the relationship between a change in physical performance and how this relates to external load performance remains to be determined.

Conclusion

Our findings demonstrated that objective autoregulation of strength training volume based on football match HIR distance did not differentiate from allowing players to self-regulate based on their subjective readiness to train during a 10-week intervention period. This is likely explained by a low, and similar volume in the strength training undertaken. Furthermore, no meaningful change was observed in external load match performance. Future studies are however, needed to assess the difference in these two autoregulation methods during periods with higher strength training volumes. To conclude, this study demonstrates that an in-season strength training regime, applying either an objective or subjective autoregulation method with ~ 6 sets of leg extensor exercises, performed once a week, can maintain professional football players physical- and external load match performance during a competitive period.

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Data availability statement

Data that supports the findings of this study are available from the corresponding author (Byrkjedal, PT.), upon reasonable request.

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Paper IV

Assessing the individual relationship between physical test improvements and external load match performance in male professional football players – a brief report.

Byrkjedal, P. T., Bjørnsen, T., Luteberget, L. S., Ivarsson, A., & Spencer, M.

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frontiers

Assessing the individual relationships between physical test improvements and external load match parameters in male professional football players – A brief report

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Abstract

Purpose: To explore if a meaningful improvement in physical performance following an in-season strength training intervention can be related to external load match parameters at an individual level in professional male football players.

Methods: Eight male professional football players (25.4±3.1 yrs, 184.1±3.4 cm, 79.3±2.2 kg) completed a 10-week strength intervention period, in addition to football specific training and matches. Commonly used physical and external load measures were assessed pre- and post-intervention. Physical performance improvements had to exceed the measurements typical error and the smallest worthwhile difference (SWD) to be considered meaningful. SWD and non-overlap of all pairs (NAP) analysis was performed to assess external load match parameters pre- and post-intervention period. A Bayesian pairwise correlation analysis was performed to assess relationships between changes in physical performance and external load match parameters.

Results: Three players displayed meaningful improvements in 2 to 5 measures of physical performance. However, positive changes greater than SWD, and positive effects in NAP results were shown for all players in external load match parameters. Kendall's Tau correlation analysis showed evidence (base factor >3) for only one correlation (maximum speed – decelerations, τ = -.62), between the changes in physical performance and external load measures, while the remaining comparisons were unrelated.

Conclusions: The findings suggest that improvements in physical performance may not necessarily translate to improvements in external load match parameters. Further research, with larger sample sizes, is needed to understand potential mechanisms between acute and chronic physical performance changes and football external load parameters during training and matches.

1 Introduction

Coaches and practitioners may interpret improvements in physical capacity of fitness tests as coinciding with improvements in physical match performance, based on the assumption of a causal relationship between these variables, with little evidence of the construct validity (e.g., dose-response relationship) (1). Well-developed physical performance is indeed important for football-specific performance. However generic measures of physical performance are influenced by numerous factors, including reliability and validity, which must be considered whenever interpretating changes in physical performance (2, 3). E.g., to minimize the impact of extraneous factors it is imperative to conduct physical testing in controlled environments, with an understanding of the equipment's inherent measurement errors. For example, common physical performance measures, such as 10- and 30-m linear sprint time, maximum speed, countermovement jump (CMJ) and leg press power have demonstrated a raw and relative (%) typical error (TE) of 0.03-0.05 seconds (TE%: ~1.3), 0.18 m/s (TE%: 1.4), 1.7 cm (TE%: 4.6) and 70 W (TE%: 4.4), respectively (2). Besides awareness of reliability, determining the meaningfulness of any observed change is an essential aspect of player monitoring, and can, as an example, be calculated by estimating the smallest worthwhile difference (SWD) (2-4). Thus, utilizing the TE and SWD may be seen as feasible criteria in the process of determining whether performance improvements or declines should be interpreted as meaningful or not.

In addition to tracking changes in physical performance over time, external load data is commonly used to monitor training and match load in football at a group and individual level (5, 6). Previous research has found strong cross-sectional associations between physical performance and match running performance in football (7, 8), and football-specific training has been shown to improve physical performance (9). Thus, recent research suggests that external load measures can be reflective of players physical performance (10). However, physical performance and external load data are known to differ between competitive levels (7) and there is a lack of knowledge on how changes in physical performance is reflected in external load parameters among highly trained players. For example, speed and explosive movements are regarded as important for football-specific performance (5, 11) and minor performance enhancements in these players may potentially influence the likelyhood of success in match-decisive actions (12, 13). Contrastingly, external load is typically assessed cross-sectionally and it is currently unknown how changes in physical performance measures impact external load in match-play. In addition, when evaluating highly trained players, subtle differences and unique variation within and between players is of upmost importance (12). Consequently, the assessment of players in elite sports necessitates a personalized approach, highlighting the significance of tailoring evaluations to individual needs (11, 14). Contrastingly, research has traditionally focused on group assessments when presenting their findings (6, 14).

With the importance of assessing individual responses in both physical test performance and external match load data, this brief report aims to explore if a meaningful improvement in players physical test performance is related to external load match performance by assessing the individual player response. This brief report is based on data from a strength intervention study by Byrkjedal et al (2023) including a team of male professional football players (15).

2 Methods

This case study originates from a 15-week study where professional footballers underwent a 10-week strength training intervention (15). Physical performance (30-m sprint, CMJ, and leg press power) was measured pre- and post-intervention, and external load match parameters were monitored in five matches at the start ("baseline") and at the end ("follow-up") of the intervention period. An overview of the study period is presented in Figure 1. This report aims to identify meaningful improvements in player's physical test performance and to explore the relationship with changes in external load match parameters. See Byrkjedal et al., 2023 (15) for more details on the original study design and data processing.

"Insert Figure 1 here"

2.1 Subjects

16 outfield players representing a Norwegian 2nd tier club completed the strength intervention period and were eligible for inclusion in this brief report. However, players had to participate in a minimum of two matches (with ≥60 min playing time per match) in both the baseline- and follow-up period to be included in this brief report. Eight male players (baseline n=6, follow-up n=2) were excluded due to lack of match participation and/or sufficient playing time. Thus, a total of eight players (25.4 ± 3.1 yrs, 184.1 ± 3.4 cm, 79.3 ± 2.2 kg) are included for further analysis. Written informed consent was obtained before the study commenced. The study was performed according to the Helsinki declaration of 1975, approved by the local ethical committee at the University of Agder, Kristiansand, Norway, and Norwegian Center for Research Data (approval reference: 464080).

Briefly, physical performance testing pre- and post-intervention was completed in one day using a test-battery of 30-m sprint, CMJ, and Keiser leg press. The 30-m sprint test involved 2-4 maximal sprints with 4 min passive rest, where the best attempt was analyzed. CMJs were completed with 2-3 sets of 3 jumps performed 30 s apart, separated by 2-3 min passive rest. The mean jump height of the two best attempts was analyzed. Lower limb strength and power were assessed using a horizontal pneumatic leg press device with a 10-RM protocol (15). To be considered a meaningful improvement, performance enhancements had to exceed raw and relative (%) TE and SWD (2-4). The same test equipment and protocols as Lindberg et al (2022) (2), were used, and pre-test results were used to calculate SWD (3, 4).

Match performance was assessed with a tracking system from Catapult Sports (Vector S7, Firmware 8.10, Catapult Sports, Melbourne, Australia). Ten matches, five in the baseline and in the follow-up period were included to investigate the effect in external load match parameters after the intervention period. External load parameters, relative to playing time, included distance per min, PlayerLoad™, high-speed running (19.8-25.2 km/h; HSR) and sprint running (>25.2 km/h) distance, accelerations, decelerations and change of directions (summary of movements in the respective direction's with an intensity >2.5 m/s). The sum of these were displayed as high-intensity events (16).

2.2 Statistics

Descriptive results were calculated using Microsoft Excel (version 16.67, 255 Microsoft Corp. Redmond, WA, USA) and are reported as Mean ± SD (standard deviation). Differences in external load parameters are reported as mean with 95% upper and lower confidence limits. A nonparametric Bayesian correlation analysis was performed in JASP (Jeffreys's Amazing Statistics Program; version 0.16.1) to investigate the relationship between the physical test performance and external load parameters. The Kendall Tau correlations in combination with Bayes Factors (BF) were calculated for each comparison. The BF is one method to quantify the likelihood of an alternative hypothesis (H1) compared with the null hypothesis (H0) and is expressed as BF_{10}. A BF_{10} >3 was interpreted as evidence supporting the association. For a more comprehensive description and full interpretation of BF_{10}, see Byrkjedal et al (2023) (16).

Differences in external load match parameters between the baseline- and follow-up period were analyzed using SWD, calculated as 0.2 of the between players SD at pre-test/baseline (3), and non-overlap of all pairs (NAP). NAP is a nonparametric technique for measuring non-overlap or "dominance" for two phases, and a feasible way to interpret individual effects between two periods. Advantages with the NAP are, for example, that it can be applied in distributions that lack normality and all data points collected is included into the analyses. Disadvantages are that it cannot be used to evaluate trends or serial dependency. For a more thorough explanation of NAP and its application, see Parker and Vannest, 2009 (17). Effect sizes for NAP values were interpreted according to previous recommendations: 0–.65 = week effects, .66–.92 = moderate effects, .93–1.0 = large or strong effects (17).

3 Results

Results from pre- and post-intervention period and changes in physical test performance and external load match parameters are presented in Table 1. Kendall's Tau correlations between changes in physical test performance and external load are presented in Table 2. Three players showed physical test improvements greater than the SWD, TE and TE%, and their individual NAP effects in the three most common external load match parameters (total-, high-intensity running- and sprint running distance) (5) are presented in Figure 2. Individual figures and NAP effects across all variables for all eight players are available in supplementary materials.

"Insert Table 1 and 2 here"

"Insert Figure 2 here"

4 Discussion

This study explored the effects in external load match parameters following a meaningful change in physical test performance post an in-season strength intervention including a small sample of professional football players. Our results suggest that a meaningful change in physical test performance does not directly impact external load match parameters, and we do not observe changes in physical test performance to be associated with changes in external load match parameters.

When looking at the results (Table 1), three players (a, e, and h) showed meaningful physical test improvements. Contrastingly several other players showing strong NAP-effects and changes >SWD, suggesting that meaningful improvements in physical test performance were not consistently reflected in external load match parameters. Indeed, this study was conducted in-season, with a high football-specific focus likely explaining the uniform improvements in external load match parameters.

External load has been explored as a simple tool to monitor players physical fitness in a previous study, and although some parameters were correlated, it was highlighted that the measures may not be sensitive enough to detect small but meaningful alternations in players fitness (10). This observation is coherent with our findings. Furthermore, a small range of physical performance improvements complicates the identification of a relationship, nevertheless, such minor improvements may still be important for football-specific performance. Despite cross-sectional assessments demonstrating a relationship between physical performance and external load data across subjects (7, 11), our finding suggests that small but meaningful within-subject improvements in physical performance might not affect external load parameters.

Current research emphasize the large variations within external load match data, therefore the lacking sensitivity that is a huge challenge when attempting to assess associations in changes of potentially associated data such as physical fitness test results (18). It is possible that larger physical performance improvements typically seen after years of practice, for example from youth academy to senior elite level players (7, 8, 11), would be necessary to reflect changes in external load data.

Sport-specific performance such as match-play is a highly complex task, difficult to decipher by fixed moving patterns such as generic physical performance tests or external load parameters (1, 7, 16). The inherent challenge of identifying small but meaningful performance changes is evident even in simple physical performance assessments (1, 2), and with the variation in external load parameters (11, 15), the lack of an association in the current study is not unexpected. However, the importance of physical performance testing or external load monitoring per se, should not be neglected. While we emphasize the challenges of assuming a causal relationship between them without supportive data (1), both physical performance results and external load data in themselves can be of high value for practitioners in optimizing player performance and development, minimizing risk of injuries and preparing for competitive performance (5, 7, 11).

Previously (9, 10) and in the current study, external load match data has been included to explore the relationships with physical performance, despite the known challenges with match-to-match variabilities (19) and influence of contextual factors (20). However, drills, such as small sides games, have been thoroughly utilized as a way of standardizing game-play (21). Such drills may represent a feasible measure of players performance and should be further explored as a method to standardize the external load demands when exploring the relationships between physical fitness and external load parameters in future studies (6).

5 Practical application

Although this data set has a small sample size, we believe our findings can serve as a foundation for future studies. In general, we highlight the need to increase the knowledge on how strength training adaptations can impact a variety of football match external load parameters and performance. With no direct link between improvements in physical performance tests and changes in external load match parameters, coaches and practitioners should evaluate the importance of physical and external load monitoring separately and avoid postulating an effect between two measures without supportive data. We emphasize the need for researchers and practitioners to work closely together to better understand and explore how physical performance changes can potentially affect different measures of football specific parameters.

6 Conclusions

Improvements in physical test performance may not necessarily translate to changes in external load match parameters. More research is needed to address and understand the mechanisms between changes in physical performance and how this affects measures of match related external load performance. Future studies should include larger samples of trained players and include a non-strength training control group to further investigate the relationship between changes in physical test performance and measures of external load from both training and match situations.

7 Nomenclature

CMJ: Countermovement jump
TE: Typical error

SWD: Smallest worthwhile difference
NAP: Non-overlap of all pairs
HSR: High-speed running
Bayes Factors: BF

8 Conflict of Interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

9 Acknowledgments

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Table 1: Individual results and change from pre-test/baseline to post-test/follow-up in physical test performance and external load match parameters.

	Physical performance					External load								
	10-m s	**30-m** s	**Max speed** m/s	**CMJ** cm	**Pmax** W	**TD** m/min	**Peak speed** m/s	**Player-Load** au/min	**HIR** m/min	**SPR** m/min	**HIE** nr/min	**Acc** (>2.5) nr/min	**Dec** (>2.5) nr/min	**CoD** (>2.5) nr/min
Pre-test/baseline period														
Player a (n=4)	1.60	4.04	8.64	41.5	1534	106.6 ± 5.5	7.96 ± 0.58	10.6 ± 0.8	3.31 ± 0.92	0.55 ± 0.44	1.03 ± 0.06	0.21 ± 0.04	0.21 ± 0.03	0.61 ± 0.02
Player b (n=5)	1.65	4.27	7.97	27.4	1165	132.4 ± 7.0	7.56 ± 0.20	13.7 ± 1.2	7.92 ±1.77	0.66 ± 0.39	1.01 ± 0.14	0.25 ± 0.06	0.19 ± 0.04	0.58 ± 0.09
Player c (n=5)	1.44	3.71	9.42	46.9	1164	112.2 ± 4.1	8.74 ± 0.39	12.0 ± 0.3	6.62 ± 1.48	1.90 ± 0.79	0.93 ± 0.13	0.21 ± 0.03	0.24 ± 0.03	0.47 ± 0.08
Player d (n=4)	1.49	3.85	9.06	44.0	1902	100.4 ± 4.1	8.01 ± 0.39	9.7 ± 0.5	2.28 ± 0.84	0.51 ± 0.35	1.44 ± 0.07	0.41 ± 0.10	0.22 ± 0.04	0.81 ± 0.09
Player e (n=5)	1.49	3.80	9.36	47.5	2098	121.0 ± 2.4	8.29 ± 0.24	12.9 ± 0.3	7.19 ± 1.12	1.60 ± 0.66	1.21 ± 0.13	0.28 ± 0.05	0.27 ± 0.08	0.66 ± 0.07
Player f (n=3)	1.54	3.93	8.77	42.7	1597	128.6 ± 6.1	8.25 ± 0.49	13.3 ± 0.8	7.94 ± 1.55	1.98 ± 1.24	1.26 ± 0.04	0.23 ±0.03	0.35 ± 0.05	0.68 ± 0.08
Player g (n=2)	1.46	3.79	9.09	38.7	1719	127.0 ± 8.1	8.33 ± 0.21	11.3 ± 1.3	7.61 ± 1.33	1.01 ± 0.19	1.59 ± 0.39	0.36 ± 0.09	0.33 ± 0.11	0.90 ± 0.19
Player h (n=5)	1.52	3.92	8.87	39.0	1673	110.3 ± 7.3	8.32 ± 0.34	10.4 ± 0.9	8.40 ± 2.43	2.47 ± 0.57	1.51 ± 0.19	0.24 ± 0.02	0.31 ± 0.09	0.96 ± 0.11
Post-test/follow-up period														
Player a (n=5)	1.53	3.88	9.06	49.4	1599	111.8 ± 4.2	8.58 ± 0.55	11.2 ± 0.6	5.08 ± 0.95	1.16 ± 0.63	1.17 ± 0.07	0.30 ± 0.05	0.18 ± 0.02	0.70 ± 0.10
Player b (n=3)	1.67	4.29	7.94	28.7	1035	130.4 ± 3.0	7.70 ± 0.40	12.5 ± 0.6	8.72 ± 0.79	0.90 ± 0.47	1.04 ± 0.15	0.20 ± 0.06	0.22 ± 0.04	0.61 ± 0.20
Player c (n=5)	1.47	3.78	9.35	43.8	1105	115.3 ± 3.5	8.59 ± 0.47	12.1 ± 0.4	8.30 ± 1.00	2.50 ± 0.49	1.19 ± 0.20	0.27# ± 0.03	0.26 ± 0.06	0.65 ± 0.18
Player d (n=5)	1.51	3.89	9.14	42.8	1764	107.8# ± 3.6	8.31 ± 0.26	10.4 ± 0.4	4.93# ± 1.01	0.93 ± 0.44	1.30 ± 0.16	0.39 ± 0.08	0.21 ± 0.05	0.69 ± 0.13
Player e (n=5)	1.46	3.72	9.60	55.7	2267	126.5 ± 4.6	8.57 ± 0.56	13.3 ± 0.4	7.45 ± 0.61	1.77 ± 0.43	1.42 ± 0.11	0.33 ± 0.07	0.25 ± 0.06	0.84# ± 0.10

Player f (n=5)	n/a	3.99	n/a	39.6	1478	130.3 ± 3.2	8.26 ± 0.37	13.4 ± 0.3	7.93 ± 1.22	1.67 ± 0.55	1.77# ± 0.12	0.34# ± 0.04	0.42 ± 0.06	1.00# ± 0.15
Player g (n=4)	1.46	3.79	9.06	38.9	1683	126.6 ± 3.8	8.81# ± 0.24	11.7 ± 0.8	8.73 ± 0.92	2.08# ± 0.51	1.39 ± 0.13	0.32 ± 0.07	0.20 ± 0.04	0.86 ± 0.13
Player h (n=4)	1.52	3.88	9.31	43.9	1573	110.0 ± 1.6	8.45 ± 0.20	10.2 ± 0.3	8.38 ± 0.35	3.25 ± 0.72	1.30 ± 0.06	0.27 ± 0.01	0.23 ± 0.02	0.81 ± 0.04
Change pre/baseline period – post/follow-up period														
Player a	**0.08***	**0.16***	**0.42***	**7.9***	65	5.3† -2.4, 12.9	0.62† -0.28, 1.51	0.7† -0.4, 1.8	1.77† 0.28, 3.26	0.61† -0.28, 1.49	0.14† 0.03, 0.25	0.08† 0.01, 0.15	-0.03 -0.07, 0.01	0.09† -0.03, 0.22
Player b	-0.02	-0.02	-0.04	1.3	-130	-2.0 -12.1, 8,6	0.14† -0.36, 0.64	-1.3 -3.1, 0.6	0.80† -1.90, 3.50	0.24† -0.51, 0.99	0.02 -0.23, 0.28	-0.05 -0.15, 0.06	0.04† -0.03, 0.11	0.03 -0.21, 0.28
Player c	-0.03	-0.07	-0.07	-3.1	-59	3.1† -3.1, 11.5	-0.14 -0.72, 0.44	0.1 -0.4, 0.6	1.68† -0.17, 3.52	0.60† -0.42, 1.62	0.26† 0.02, 0.50	0.06† 0.01, 0.11	0.02† -0.05, 0.10	0.18† -0.02, 0.38
Player d	-0.02	-0.04	0.08	-1.2	-138	7.4† 1.4, 13.7	0.30† -0.21, 0.82	0.7† 0.1, 1.3	2.65† 1.15, 4.14	0.42† -0.23, 1.06	-0.14 -0.35, 0.06	-0.02 -0.16, 0.13	-0.01 -0.08, 0.07	-0.12 -0.30, 0.06
Player e	**0.03***	**0.08***	**0.23***	**8.2***	**169***	5.5† 0.1, 10.9	0.28† -0.35, 0.90	0.4† -0.1, 1.0	0.25 -1.06, 1.60	0.17† -0.65, 0.99	0.22† 0.05, 0.38	0.05† -0.04, 0.14	-0.03 -0.13, 0.07	0.19† 0.06, 0.31
Player f	n/a	-0.05	n/a	-3.0	-119	1.7 -6.9, 10.3	0.00 -0.74, 0.75	0.0 -1.0, 1.0	-0.01 -2.40, 2.39	-0.32 -1.82, 1.19	0.51† 0.33, 0.68	0.11† 0.05, 0.18	0.07† -0.03, 0.17	0.32† 0.09, 0.56
Player g	0.00	0.00	-0.03	0.2	-36	-0.4 13.0, 12.2	0.48† -0.08, 1.04	0.4† -1.9, 2.7	1.12† -1.39, 3.63	1.06† -0.03, 2.17	-0.20 -0.75, 0.35	-0.04 -0.21, 0.14	-0.13 -0.29, 0.03	-0.03 -0.39, 0.32
Player h	0.00	0.03	**0.45***	**5.0***	-100	-0.3 -9.3, 8.6	0.13† -0.33, 0.59	-0.3 -1.3, 0.81	-0.03 -2.97, 2.91	0.78† -0.23, 1.79	-0.20 -0.44, 0.03	0.03† 0.01, 0.05	-0.08 -0.19, 0.03	-0.15 -0.29, -0.01

Note: Positive change in 10- and 30-m sprint times indicate improved performance from pre to post. Physical performance results are reported with raw data points and raw difference. External load parameters are reported with mean ± SD in the baseline and follow-up period, while changes are reported as mean difference including 95% lower and upper confidence limits. N/a; missing data. *Bold text indicates that physical test performance changes were >SWD, raw and relative (%) TE. #Strong effects in Non overlap of all pair analysis (in follow-up period compared to baseline period). † >SWD calculated from baseline-period results. n: number of included matches in the respective periods, CMJ: Countermovement jump, Pmax: Max power (W), TD: total distance, AU: Arbitrary units, HSR: high speed running distance, SPR: sprint running distance, HIE: high intensity events, Acc: accelerations, Dec: decelerations, CoD: change of directions.

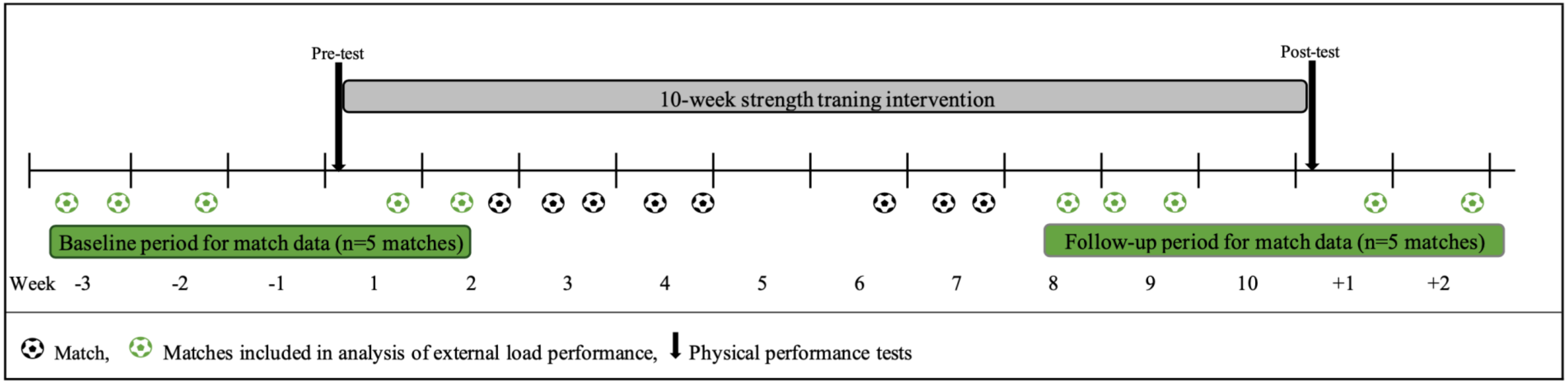
Table 2: Kendall's Tau correlations between changes in physical performance and external load match parameters from pre-test/baseline period to post-test/follow-up period.

	10-m	**30-m**	**Max speed**	**CMJ**	**Pmax**
TD	0.07 (-0.38, 0.48)	0.07 (-0.38, 0.48)	0.14 (-0.33, 0.53)	0.07 (-0.38, 0.48)	0.21 (-0.28, 0.57)
Peak speed	0.22 (-0.27, 0.58)	0.57 (-0.03, 0.78)	0.36 (-0.18, 0.66)	0.43 (-0.13, 0.70)	0.14 (-0.33, 0.53)
PlayerLoad™	0.15 (-0.33, 0.53)	0.21 (-0.28, 0.57)	0.29 (-0.23, 0.62)	0.07 (-0.38, 0.48)	0.36 (-0.18, 0.62)
HSR	-0.30 (-0.63, 0.22)	-0.07 (-0.49, 0.38)	0.00 (-0.43, 0.43)	-0.21 (-0.57, 0.28)	-0.07 (-0.48, 0.38)
SPR	-0.22 (-0.58, 0.27)	0.14 (-0.33, 0.53)	0.36 (-0.18, 0.66)	0.00 (-0.43, 0.43)	0.14 (-0.33, 0.53)
HIE	0.15 (-0.32, 0.53)	-0.26 (-0.60, 0.25)	-0.47 (-0.73, 0.10)	-0.11 (-0.50, 0.35)	0.11 (-0.35, 0.50)
Acc	0.52 (-0.07, 0.75)	0.07 (-0.38, 0.48)	0.00 (-0.43, 0.43)	-0.07 (-0.48, 0.38)	0.21 (-0.28, 0.57)
Dec	-0.04 (-0.46, 0.40)	-0.40 (-0.69, 0.15)	-0.62* (-0.80, -0.01)	-0.33 (-0.65, 0.20)	-0.33 (-0.65, 0.20)
CoD	0.30 (-0.21, 0.63)	-0.14 (-0.53, 0.33)	-0.50 (-0.74, 0.08)	0.00 (-0.43, 0.43)	0.29 (-0.23, 0.62)

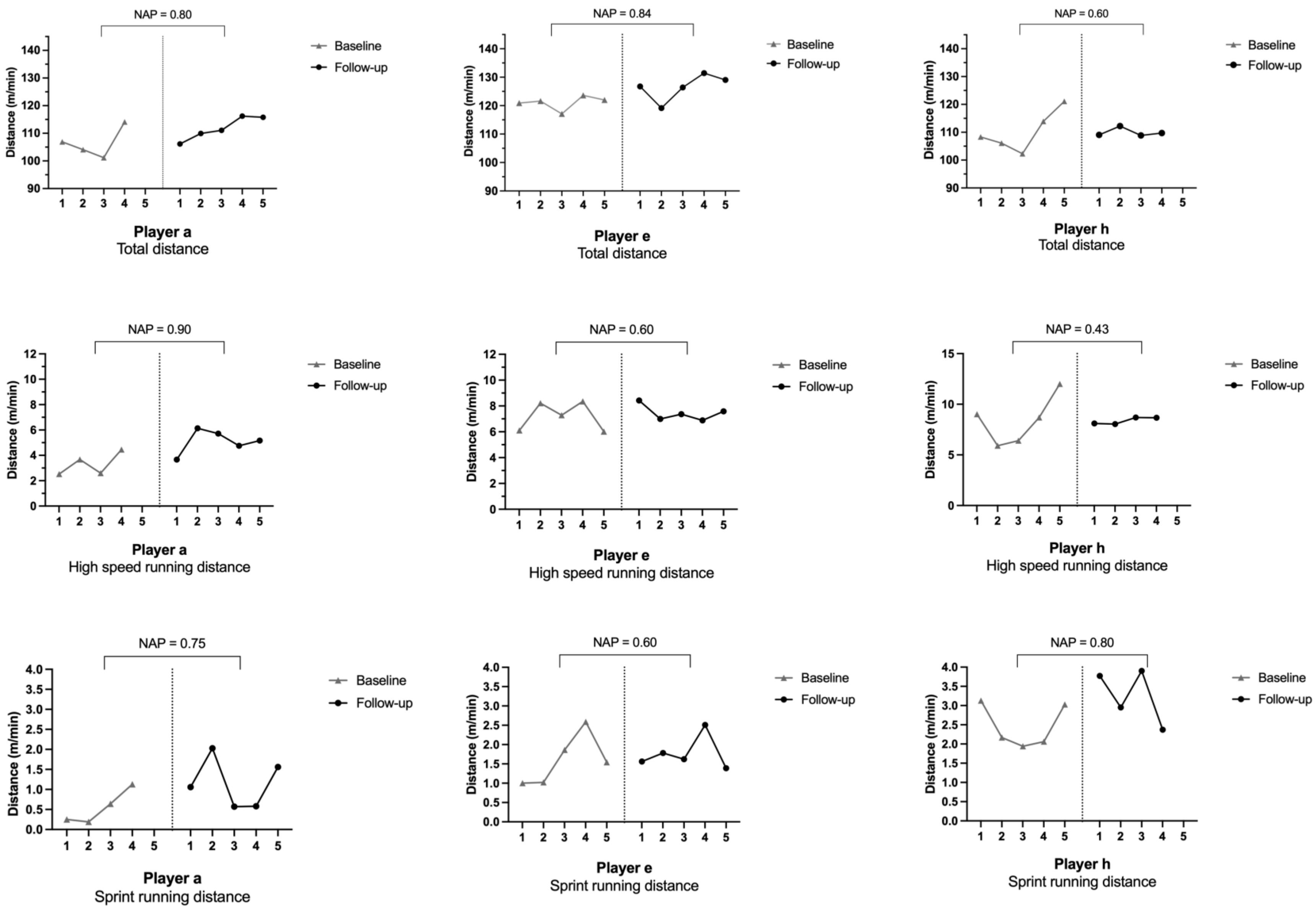
* Indicates BF_{10} >3. Values in brackets indicate 95% lower and upper credible intervals. TD: total distance, HSR: high speed running distance, SPR: sprint running distance, HIE: high intensity events, Acc: accelerations, Dec: decelerations, CoD: change of directions, CMJ: countermovement jump, Pmax: maximum power (W).

Figure 1: Schematic overview of the study, including specific test points, strength intervention period and matches played.

Figure 2: Non-overlap of all pairs analysis results for total distance, high-speed running distance and sprint running distance for players with a meaningful improvement in physical performance post-strength intervention period.



Pre-test
Post-test
10-week strength traning intervention
Baseline period for match data (n=5 matches)
Follow-up period for match data (n=5 matches)
Week -3 -2 -1 1 2 3 4 5 6 7 8 9 10 +1 +2
Match,
Matches included in analysis of external load performance,
Physical performance tests


NAP = 0.80
Player a
Total distance
NAP = 0.84
Player e
Total distance
NAP = 0.60
Player h
Total distance
NAP = 0.90
Player a
High speed running distance
NAP = 0.60
Player e
High speed running distance
NAP = 0.43
Player h
High speed running distance
NAP = 0.75
Player a
Sprint running distance
NAP = 0.60
Player e
Sprint running distance
NAP = 0.80
Player h
Sprint running distance
Distance (m/min)
Baseline
Follow-up

Appendix 1-12

Appendix 1

Original PhD project plan and the consequences of covid-19

The consequences of Covid-19

The aim of the current thesis was to provide more insights to the external load match demands and explore how physical test performance can be related to measures of external training and match load data. Thorough planning and talks with potential partners were conducted Q4 2019 – Q1 2020. However, the project was affected by the global Covid-19 pandemic. The following appendix provides a description of the original plan, how this was affected by Covid-19, and the following adjustments that were made to the project during this period.

Original plan and the consequences of Covid-19

This PhD project was planned to commence late Q4 2019 / early Q1 2020, with the objective of exploring the relationships between physical test performance and external training and match load data, and how changes in one was reflected in the other. The original project was intended to be conducted across three sub-projects, sub-1, -2 and -3:

- **Sub-1:** This sub-project would focus on the quantification of external training and match load and the relation to physical test performance. **Sub-1** aimed to include external load data from team sport players during training, standardized drills, and matches in addition to assessments of physical test performance.
- **Sub-2**: This sub-project aimed to improve physical test performance and explore if a change would be reflected in external training and match load data. **Sub-2** intended to include an experimental strength intervention utilizing velocity-based strength training. The intervention would involve dividing the participants into two groups, one trained with low velocity loss and the other with high velocity loss. The physical test performance and external training and match load data would be assessed before and after the intervention period.
- **Sub-3:** This sub-project aimed to explore the longitudinal effects of changes in physical test performance and external training and match load data. **Sub-3** overlaps with the aims of **Sub-1** and intent to include regular assessments of physical test performance and external training and match load until approximately one year after the completion of **Sub-2**.

Two team sport clubs, one from ice-hockey and one from football, both with senior professional and junior/academy teams, were invited and agreed to participate in the project. The inclusion of two different sports facilitated the execution of the sub-projects across different competitive periods and allowed for comparison between sports. Furthermore, while external training and match load measures have mainly been utilized in outdoor field sports, the project aimed to provide novel insights into the external load demands within ice-hockey.

The original project period and data collection (**Sub-1** and **Sub-2**) were expected to be completed in 2020, with longitudinal follow-up (**Sub-3**) conducted in 2021, with the possibility of an extension in to 2022. In addition to match play, the project intended to include standardized match play replication drills, such as small-sided games, as an additional measure to address the changes in external training and match load data over time.

3.1.1 Covid-19 and re-planning the project

The pandemic induced a lock-down and postponement of training and match activities at the end of Q1 2020. The initial lock-down period was characterized by uncertainty and intermittent information. For instance, it was uncertain how and when players could restart their activities, consequently affecting the re-commencement of the project. During this period, several contingency plans were discussed within the project group, depending on numerous factors and potential outcomes. For example, are players allowed to resume sport activities? Will there be differences in government regulations between being indoors/outdoors or in sport participation for age groups (e.g., senior vs junior)? What are the consequences of new lockdowns? Focus was placed on the following aims when discussing and taking decisions regarding recommencement of the project:

- Include external training and match load data from indoor conditions.
- Assess players physical test performance.
- Compare physical performance to external training and match load data.
- Identify changes in physical test performance and explore if such changes could be reflected in external training and match load data.

Accordingly, the project was continually under re-planning and decisions were to a large degree made ad-hoc, depending on the current circumstances (e.g., new lockdowns, re-openings, etc.). Consequently, the project was completed as follows:

Ice-hockey matches including highly trained junior team players were tracked during Q3-Q4 2020. Due to a regional lockdown elsewhere, match activity was postponed mid-November 2020. Pending the re-start of official matches, tracking of a standardized match format, (i.e., scrimmage) was performed in Q4 2020. During the same period, assessment of physical test performance was performed over two test days. Regular match activity was never resumed for the current season and the LPS system was removed in Q2 2021. An intervention study, exploring two different methods of regulating the undertaken strength training volume, was completed during Q2-Q4 2021 in a team of highly trained professional football-players. During this period, physical performance and body composition was assessed pre- and post-intervention, in addition to monitoring of external match load.

An overview of the original plan, including specific aims and intended research periods for the sub-projects, and adjustments made as a consequence of Covid-19, can be found in Table 1.1. Additionally, an overview of the revised and completed project is presented in Table 1.2. Despite the methodological changes, the overall purposes of **sub-1** and **sub-2** were achieved, however without a regular assessment of external training load during small-sided games. While physical performance tests were completed 2-3 and 11-12 months after the intervention period, the lack of controlled training drills to explore standardized external training load data, and replacement of players made it unfeasible to fulfill the aims of **sub-3**. This subproject is therefore not included in the revised and completed project. Overall, the main aims discussed among the project group, and presented across the four bullet points, were fulfilled in the revised project and findings are presented across four papers included in the present thesis. A thorough presentation of the methods and included data can be found in the thesis methods chapter.

Table 1.1: Original project plan and Covid-19 consequences.

	Original plan					**Covid-19 consequences and adjustments**
Sub-project	*Year*	*Period*	*Sub-project aim*	*Sport*	*Level*	
1	2020	Q1-2	Install LPS systems and perform familiarization. Track ice hockey matches (regular and play-offs).	Ice hockey	Professional	• No tracking of professional team players (only familiarization pre-covid).
1, 2		Q2-3	Perform intervention period, including physical performance pre- and post-tests and external load tracking from small-sided games.	Ice hockey	Junior	• No intervention period. • Track regular matches Q3-4 2020. • Perform scrimmages Q4 2020. • Perform physical performance tests Q4 2020.
1, 2		Q3-4	Perform intervention period, including physical performance pre- and post-tests and external load tracking from small-sided games.	Football	Junior	• No tracking of junior team players (matches and small sided games).
1, 3		Q3-4	Longitudinal follow-up physical test performance and external load data.	Ice hockey	Junior	• No follow-up of junior team players.
1, 2		Q2-4	Perform intervention period, including physical performance pre- and post-tests and small-sided games.	Football	Professional	• In-season intervention performed Q 2-4 2021. • Pre- and post-tests completed Q 3-4. • No inclusion of small-sided games.
3	2021	Q1-2	Follow up physical test performance and external load.	Ice hockey	Professional and junior	• No longitudinal follow-up.
3		Q1-4	Follow up physical test performance and external load.	Football	Professional and junior	• No longitudinal follow-up.

Table 1.2: Revised and completed project plan after Covid-19 adjustments.

Sub-project	Period	Sub-project aim	Sport	Level	Included in papers
	2020				
1	Q1-2	Install LPS systems and perform familiarization.	Ice hockey		n/a
1	Q2-4	Track external load match performance.	Football	Professional	No
1	Q3	Perform physical test performance assessment.	Football	Professional and junior	No
1	Q3-4	Track external load during official and simulated matches.	Ice hockey	Junior	**Paper I** and **II**
1	Q4	Perform physical test performance assessments.	Ice hockey	Junior	**Paper II**
	2021				
1	Q1	Perform physical test performance assessment.	Football	Professional and junior	No
1	Q2-4	Track external load during training and matches.	Football	Professional	**Paper III** and **IV**
2	Q3-4	Perform strength intervention period, with inclusion of physical test performance and external load assessments pre- and post-intervention.	Football	Professional	**Paper III** and **IV**
	2022				
1, 3	Q1	Perform physical test performance assessment.	Football	Professional and junior	No
1, 3	Q3	Perform physical test performance assessment.	Football	Professional and junior	No

A summary of completed sub-projects during the project period. Note that the table includes a complete overview of the project periods, and that some of the described sub-projects / -aims, are not included in the remaining part of the thesis.

Appendix 2

Decision regarding application to *NSD*

NSD NORSK SENTER FOR FORSKNINGSDATA

NSD sin vurdering

Prosjekttittel

Hurtighetsbasert styrketrening og en longitudinell oppfølging av belastning i trening og kamp

Referansenummer

464080

Registrert

28.01.2020 av Per Thomas Byrkjedal - per.byrkjedal@uia.no

Behandlingsansvarlig institusjon

Universitetet i Agder / Fakultet for helse- og idrettsvitenskap / Institutt for folkehelse, idrett og ernæring

Prosjektansvarlig (vitenskapelig ansatt/veileder eller stipendiat)

Thomas Bjørnsen, thomas.bjornsen@uia.no, tlf: 4798619299

Type prosjekt

Forskerprosjekt

Prosjektperiode

15.02.2020 - 31.12.2021

Status

17.02.2020 - Vurdert

Vurdering (1)

17.02.2020 - Vurdert

Det er vår vurdering at behandlingen av personopplysninger i prosjektet vil være i samsvar med personvernlovgivningen så fremt den gjennomføres i tråd med det som er dokumentert i meldeskjemaet den 17.02.2020 med vedlegg, samt i meldingsdialogen mellom innmelder og NSD. Behandlingen kan starte.

MELD VESENTLIGE ENDRINGER
Dersom det skjer vesentlige endringer i behandlingen av personopplysninger, kan det være nødvendig å melde dette til NSD ved å oppdatere meldeskjemaet. Før du melder inn en endring, oppfordrer vi deg til å lese om hvilke type endringer det er nødvendig å melde:
https://nsd.no/personvernombud/meld_prosjekt/meld_endringer.html
Du må vente på svar fra NSD før endringen gjennomføres.

TYPE OPPLYSNINGER OG VARIGHET
Prosjektet vil behandle særlige kategorier av personopplysninger om helseopplysninger og alminnelige kategorier av personopplysninger frem til 31.12.2021. Data med personopplysninger oppbevares deretter

internt ved behandlingsansvarlig institusjon frem til 31.12.2026, dette til forskningsformål.

LOVLIG GRUNNLAG
Prosjektet vil innhente samtykke fra de registrerte til behandlingen av personopplysninger. Vår vurdering er at prosjektet legger opp til et samtykke i samsvar med kravene i art. 4 nr. 11 og art. 7, ved at det er en frivillig, spesifikk, informert og utvetydig bekreftelse, som kan dokumenteres, og som den registrerte kan trekke tilbake.

Lovlig grunnlag for behandlingen vil dermed være den registrertes uttrykkelige samtykke, jf. personvernforordningen art. 6 nr. 1 bokstav a, jf. art. 9 nr. 2 bokstav a, jf. personopplysningsloven § 10, jf. § 9 (2).

PERSONVERNPRINSIPPER
NSD vurderer at den planlagte behandlingen av personopplysninger vil følge prinsippene i personvernforordningen om:

- lovlighet, rettferdighet og åpenhet (art. 5.1 a), ved at de registrerte får tilfredsstillende informasjon om og samtykker til behandlingen
- formålsbegrensning (art. 5.1 b), ved at personopplysninger samles inn for spesifikke, uttrykkelig angitte og berettigede formål, og ikke viderebehandles til nye uforenlige formål
- dataminimering (art. 5.1 c), ved at det kun behandles opplysninger som er adekvate, relevante og nødvendige for formålet med prosjektet
- lagringsbegrensning (art. 5.1 e), ved at personopplysningene ikke lagres lengre enn nødvendig for å oppfylle formålet

DE REGISTRERTES RETTIGHETER
Så lenge de registrerte kan identifiseres i datamaterialet vil de ha følgende rettigheter: åpenhet (art. 12), informasjon (art. 13), innsyn (art. 15), retting (art. 16), sletting (art. 17), begrensning (art. 18), underretning (art. 19), dataportabilitet (art. 20).

NSD vurderer at informasjonen som de registrerte vil motta oppfyller lovens krav til form og innhold, jf. art. 12.1 og art. 13.

Vi minner om at hvis en registrert tar kontakt om sine rettigheter, har behandlingsansvarlig institusjon plikt til å svare innen en måned.

FØLG DIN INSTITUSJONS RETNINGSLINJER
NSD legger til grunn at behandlingen oppfyller kravene i personvernforordningen om riktighet (art. 5.1 d), integritet og konfidensialitet (art. 5.1. f) og sikkerhet (art. 32).

Catapult Sports er databehandler i prosjektet. NSD legger til grunn at behandlingen oppfyller kravene til bruk av databehandler, jf. art 28 og 29.

For å forsikre dere om at kravene oppfylles, må dere følge interne retningslinjer og eventuelt rådføre dere med behandlingsansvarlig institusjon.

OPPFØLGING AV PROSJEKTET
NSD vil følge opp underveis (hvert annet år) og ved planlagt avslutning for å avklare om behandlingen av personopplysningene er avsluttet/pågår i tråd med den behandlingen som er dokumentert.

Lykke til med prosjektet!

Kontaktperson hos NSD: Mathilde Hansen
Tlf. Personverntjenester: 55 58 21 17 (tast 1)

Appendix 3

Decision regarding application to *FEK*

Per Thomas
Byrkjedal

Besøksadresse:
Universitetsveien 25
Kristiansand

Ref: [object Object]

Tidspunkt for godkjenning: : 28/02/2020

Søknad om etisk godkjenning av forskningsprosjekt - Hurtighetsbasert styrketrening og en longitudinell oppfølging av belastning i trening og kamp

Vi informerer om at din søknad er ferdig behandlet og godkjent.

Kommentar fra godkjenner:
FEK godkjenner søknaden under forutsetning av at prosjektet gjennomføres som beskrevet i søknaden.

Hilsen
Forskningsetisk komite
Fakultet for helse - og idrettsvitenskap
Universitetet i Agder

UNIVERSITETET I AGDER

POSTBOKS 422 4604 KRISTIANSAND

TELEFON 38 14 10 00

ORG. NR 970 546 200 MVA - post@uia.no -

www.uia.no

FAKTURAADRESSE:

UNIVERSITETET I AGDER,

FAKTURAMOTTAK

POSTBOKS 383 ALNABRU 0614 OSLO

Appendix 4

Decision from *NSD* regarding timeline extension for data acquisition

NSD NORSK SENTER FOR FORSKNINGSDATA

NSD sin vurdering

Prosjekttittel

Hurtighetsbasert styrketrening og en longitudinell oppfølging av belastning i trening og kamp

Referansenummer

464080

Registrert

28.01.2020 av Per Thomas Byrkjedal - per.byrkjedal@uia.no

Behandlingsansvarlig institusjon

Universitetet i Agder / Fakultet for helse- og idrettsvitenskap / Institutt for folkehelse, idrett og ernæring

Prosjektansvarlig (vitenskapelig ansatt/veileder eller stipendiat)

Thomas Bjørnsen, thomas.bjornsen@uia.no, tlf: 4798619299

Type prosjekt

Forskerprosjekt

Prosjektperiode

15.02.2020 - 31.12.2023

Status

31.05.2021 - Vurdert

Vurdering (2)

31.05.2021 - Vurdert

NSD har vurdert endringen registrert 21.05.2021. Dato for prosjektslutt er endret til 31.12.2023. Data med personopplysninger oppbevares da også lengre, nemlig til 31.12.2028 grunnet dokumentasjonshensyn. De registrerte informeres om endringene.

Det er vår vurdering at behandlingen av personopplysninger i prosjektet vil være i samsvar med personvernlovgivningen så fremt den gjennomføres i tråd med det som er dokumentert i meldeskjemaet med vedlegg den 31.05.2021. Behandlingen kan fortsette.

OPPFØLGING AV PROSJEKTET

NSD vil følge opp ved planlagt avslutning for å avklare om behandlingen av personopplysningene er avsluttet.

Lykke til med prosjektet!

Tlf. Personverntjenester: 55 58 21 17 (tast 1)

17.02.2020 - Vurdert

Det er vår vurdering at behandlingen av personopplysninger i prosjektet vil være i samsvar med personvernlovgivningen så fremt den gjennomføres i tråd med det som er dokumentert i meldeskjemaet den 17.02.2020 med vedlegg, samt i meldingsdialogen mellom innmelder og NSD. Behandlingen kan starte.

MELD VESENTLIGE ENDRINGER
Dersom det skjer vesentlige endringer i behandlingen av personopplysninger, kan det være nødvendig å melde dette til NSD ved å oppdatere meldeskjemaet. Før du melder inn en endring, oppfordrer vi deg til å lese om hvilke type endringer det er nødvendig å melde:
https://nsd.no/personvernombud/meld_prosjekt/meld_endringer.html
Du må vente på svar fra NSD før endringen gjennomføres.

TYPE OPPLYSNINGER OG VARIGHET
Prosjektet vil behandle særlige kategorier av personopplysninger om helseopplysninger og alminnelige kategorier av personopplysninger frem til 31.12.2021. Data med personopplysninger oppbevares deretter internt ved behandlingsansvarlig institusjon frem til 31.12.2026, dette til forskningsformål.

LOVLIG GRUNNLAG
Prosjektet vil innhente samtykke fra de registrerte til behandlingen av personopplysninger. Vår vurdering er at prosjektet legger opp til et samtykke i samsvar med kravene i art. 4 nr. 11 og art. 7, ved at det er en frivillig, spesifikk, informert og utvetydig bekreftelse, som kan dokumenteres, og som den registrerte kan trekke tilbake.

Lovlig grunnlag for behandlingen vil dermed være den registrertes uttrykkelige samtykke, jf. personvernforordningen art. 6 nr. 1 bokstav a, jf. art. 9 nr. 2 bokstav a, jf. personopplysningsloven § 10, jf. § 9 (2).

PERSONVERNPRINSIPPER
NSD vurderer at den planlagte behandlingen av personopplysninger vil følge prinsippene i personvernforordningen om:

- lovlighet, rettferdighet og åpenhet (art. 5.1 a), ved at de registrerte får tilfredsstillende informasjon om og samtykker til behandlingen
- formålsbegrensning (art. 5.1 b), ved at personopplysninger samles inn for spesifikke, uttrykkelig angitte og berettigede formål, og ikke viderebehandles til nye uforenlige formål
- dataminimering (art. 5.1 c), ved at det kun behandles opplysninger som er adekvate, relevante og nødvendige for formålet med prosjektet
- lagringsbegrensning (art. 5.1 e), ved at personopplysningene ikke lagres lengre enn nødvendig for å oppfylle formålet

DE REGISTRERTES RETTIGHETER
Så lenge de registrerte kan identifiseres i datamaterialet vil de ha følgende rettigheter: åpenhet (art. 12), informasjon (art. 13), innsyn (art. 15), retting (art. 16), sletting (art. 17), begrensning (art. 18), underretning (art. 19), dataportabilitet (art. 20).

NSD vurderer at informasjonen som de registrerte vil motta oppfyller lovens krav til form og innhold, jf. art. 12.1 og art. 13.

Vi minner om at hvis en registrert tar kontakt om sine rettigheter, har behandlingsansvarlig institusjon plikt til å svare innen en måned.

FØLG DIN INSTITUSJONS RETNINGSLINJER
NSD legger til grunn at behandlingen oppfyller kravene i personvernforordningen om riktighet (art. 5.1 d), integritet og konfidensialitet (art. 5.1. f) og sikkerhet (art. 32).

Catapult Sports er databehandler i prosjektet. NSD legger til grunn at behandlingen oppfyller kravene til bruk av databehandler, jf. art 28 og 29.

For å forsikre dere om at kravene oppfylles, må dere følge interne retningslinjer og eventuelt rådføre dere med behandlingsansvarlig institusjon.

OPPFØLGING AV PROSJEKTET
NSD vil følge opp underveis (hvert annet år) og ved planlagt avslutning for å avklare om behandlingen av personopplysningene er avsluttet/pågår i tråd med den behandlingen som er dokumentert.

Lykke til med prosjektet!

Kontaktperson hos NSD: Mathilde Hansen
Tlf. Personverntjenester: 55 58 21 17 (tast 1)

Appendix 5

Informed consent form - study one

Vil du delta i forskningsprosjektet: «Hastighetsstyrt styrketrening med oppføling av belastning i trening og kamp»?

Dette er en forespørsel til deg om å delta i et forskningsprosjekt hvor formålet er å undersøke hvordan prestasjonen endres i trening og kamp over en hel sesong. I dette skrivet gir vi deg informasjon om hensikten med prosjektet og hva deltakelse som forsøksperson vil innebære for deg.

FORMÅL

Man har lenge antatt at en endring i styrke vil kunne påvirke prestasjon i trening og kamp, men få har undersøkt dette. I nyere tid har det blitt mer og mer vanlig å ta i bruk digitale hjelpemidler i analyser og oppfølging av utøvere som kan brukes til å undersøke en slik endring i prestasjon på trening eller i kamp. Disse enhetene har innebygde sensorer som blant annet kan måle små hurtige bevegelser (eksempelvis: akselerasjoner, stopp, oppbremsing, fall, hopp osv) og kan i tillegg koble seg opp mot GPS utendørs. Vi ønsker å se om det finnes sammenhenger mellom fysisk kapasitet (fra fysiske tester) og prestasjon i trening og kamp (målt gjennom GPS-enheter), samt hvordan dette utvikler seg over tid.

HVA INNEBÆRER DELTAKELSE I STUDIEN?

Ved å delta i studien samtykker du til å gjennomføre testing av din fysiske kapasitet i følgende øvelser;

- 30m Sprint på is
- 30m sprint (løping)
- Hopp
- 1 RM m/trap-bar
- In-Body kroppsskanning

De nevnte testene vil bli en del av en testprotokoll som kan gjennomføres på flere tidspunkter før, under og etter sesong. Laget testes fortrinnsvis samlet og testingen er beregnet til å vare ca en halv dag. De første planlagte testtidspunktene er Desember 2020 og januar/februar 2021.

I tillegg til de fysiske testene vil du i trening og kamp benytte en mikroelektronisk enhet. Denne bæres i en spesialsydd vest tett på kroppen. I tillegg til å fange opp posisjon og hastighet via et innendørs GPS-system (LPS) kan den blant annet også små intensive bevegelser som normalt ikke fanges opp av «GPS»-signalene. Eksempler på denne type bevegelser er oppbremsinger/stopp, retningsforandringer, hopp, taklinger og akselerasjoner. Informasjonen fra disse enhetene vil bli innsamlet av masterstudenter. Under innsamlingen av disse dataene vil kun fysisk trener og prosjektleder ha oversikt over hvilken brikke som brukes av hvilken spiller. Alle data/navn vil bli anonymisert til ID-nr før de overleveres

Universitetet i Agder. Kun prosjektleder vil ha tilgang til dekodingsnøkkelen (oversikt over navn og ID-nr). Informasjonen vil kunne bli samlet inn til ca April 2021.

FORDELER OG ULEMPER MED DELTAGELSE SOM FORSØKSPERSON

Du vil som deltaker i denne studien kunne få resultater fra idrettsvitenskapelige tester i et kontrollert miljø og gi deg tilbakemelding på din fysiske kapasitet. Du vil også kunne oppleve noen ulemper ved å delta i studien;

- Du må sette av tid til testing, tid du kanskje vil brukt annerledes.
- Testing og trening kan føre til stølhet og oppfattes som smertefullt/ubehagelig.
- Det er alltid en risiko for skader ved både trening og testing, men disse anses ikke som større enn den treningen du er vant til fra før.

HVA SKJER MED INFORMASJONEN OM DEG?

Vi vil bare bruke opplysningene om deg til formålene vi har fortalt om i dette skrivet. Vi behandler opplysningene konfidensielt og i samsvar med personvernregelverket. Alle personopplysninger vil bli avidentifisert. Det betyr at resultatene blir ikke lagret under navn, men med en kode fra første dag i prosjektet. Navnet ditt blir derfor koblet til en kode som oppbevares i en safe ved Institutt for idrettsvitenskap og kroppsøving, Universitetet i Agder. Det er kun prosjektansvarlig som har tilgang til denne. Dine personopplysninger vil ikke kunne identifiseres i publikasjoner.

Prosjektet skal etter planen avsluttes 31.04.2021 og alle dine data vil da bli anonymisert. Dine anonymiserte data vil bli oppbevart i 5 år ettersom vi er pliktet til å oppbevare data og separat navneliste i 5 år etter sluttdato for etterprøvbarhet og kontroll av resultatene. Etter dette, altså 31.04.2026, vil all data i prosjektet slettes.

Dine rettigheter: Så lenge du kan identifiseres i datamaterialet, har du rett til:
- innsyn i hvilke personopplysninger som er registrert om deg,
- å få rettet personopplysninger om deg,
- få slettet personopplysninger om deg,
- få utlevert en kopi av dine personopplysninger (dataportabilitet), og
- å sende klage til personvernombudet eller Datatilsynet om behandlingen av dine personopplysninger.

Hva gir oss rett til å behandle personopplysninger om deg?
Vi behandler opplysninger om deg basert på ditt samtykke.

På oppdrag fra Universitetet i Agder har NSD – Norsk senter for forskningsdata AS vurdert at behandlingen av personopplysninger i dette prosjektet er i samsvar med personvernregelverket.

FRIVILLIG DELTAKELSE

Der er frivillig å delta i studien og du kan når som helst trekke deg fra studien uten å oppgi noen grunn. Alle opplysninger om deg vil da bli anonymisert. Det vil ikke ha noen negative konsekvenser for deg hvis du ikke vil delta eller senere velger å trekke deg.

Dersom du har spørsmål til studien, eller ønsker å benytte deg av dine rettigheter, ta kontakt med prosjektansvarlige Per Thomas Byrkjedal (Doktorgradsstipendiat: per.byrkjedal@uia.no / 93498951) eller Thomas Bjørnsen (thomas.bjornsen@uia.no / 986 19 299), vårt personvernombud Ina Danielsen, Universitetet i Agder, ina.danielsen@uia.no, telefon +47 452 54 401, eller NSD – norsk senter for forskningsdata AS (personverntjenester@nsd.no / 55 58 21 17). Prosjektansvarlig institusjon er Universitetet i Agder.

Med vennlig hilsen

Thomas Bjørnsen (Prosjektansvarlig) & Per Thomas Byrkjedal (PhD-stipendiat).

SAMTYKKEERKLÆRING

Jeg har mottatt og forstått informasjon om prosjektet *Hastighetsstyrt styrketrening med oppføling av belastning i trening og kamp* og har fått anledning til å stille spørsmål. Jeg samtykker til:

- ☐ å delta i studien
- ☐ at mine opplysninger behandles anonymisert frem til all data i prosjektet slettes senest 31.04.2026.

---------------------- ---

(Dato) (Signatur deltaker)

Appendix 6

Informed consent form - study two

Do you wish to participate in the research project "velocity-based strength training and a follow-up of training- and match load"?

The goal of this research-project is to explore how team players performance can change throughout a season. As a team sport player, we invite you to participate in this study. The following information is provided to inform you on the risks, benefits and rights if you should choose to participate in this project.

AIM

A change in strength has for a period of time been perceived to have an influence on match and training performance. However, few have actually explored this potential influence. As time has evolved, the use of micro electronical measurement units (MEMS) (equipped with GPS and accelerometers), has been quite common across several elite and sub-elite team sports. These devises provide information on speed and distances, as well as short, high-intensity moves such as jumps, change of directions, decelerations and accelerations. Our aim is to explore the association between physical performance (assessed through testes) and training and match performance, measured through MEMS. In additions, we wish to assess how this develops over time (season).

WHAT DOES PARTICIPATION IN THIS STUDY MEAN FOR YOU?

By participating in this study, you consent to assess your physical performance in the following tests;

- Body composition (iDXA-scan)
- Sprint
- Jump
- Leg press

The tests mentioned, will be included as standard-tests and can be used to assess performance at additional test-points (e.g. before, during and after a season). Completion of these tests are estimated to take 1,5 hours. Test-points are typically during pre-season (jan-apr) and during the autumn (sept-nov), depending on the fixtures.

In addition to the physical performance tests, your training- and match load data will be sampled by wearing a MEMS unit. This is a small device and it's worn inside a tight fitted west on your upper trunk. Your physical coach/a team representative will gather the data from these devices and the information will be anonymized to ID-numbers before its shared with the University of Agder. Only the project leader will have access to the decryption code (link to Name and ID). Information will be gathered until end of December 2023.

PRO's AND CON's ASSOCIATED WITH PARTICIPATION IN THIS PROJECT

As a participant in this project, you will be provided and given insight to scientific test-results of your physical performance. However, there are some potetial disadvantages if you choose to participate in this project:

- You have to make time (ca 1,5 hours) for each test day. Time you may wished to spend at your own choosing.
- Testing and training may be associated with muscle soreness and a discomfort.
- There always a risk of injuries during training and testing, but the risks are not expected to proceed the risks experienced during your daily training regime.
- A body composition scan (iDXA) is performed by X-ray and includes a small dose of radiation. This radiation dose is equivalent to the dose you experience during an intercontinental flight.

WHAT WILL HAPPEN TO YOUR PERSONAL INFORMATION?

We will only use the information as described in this letter. Your information will be treated confidentially and in accordance with the guidelines for personal data protection. All personal information will be anonymized. No information will be saved under your name, but under an ID-code, only decryptable by a decryption-key stored locally in a safe at the Institute of Sport Science and Physical Education offices at the University of Agder, Kristiansand. Only the project leader will have access to this safe. Your personal information will not be identifiable in research publications.

The project is scheduled to be terminated 31.12.23 an all data will thereby be anonymized. Your anonymized data will be stored for 5 years as we are obligated to store this and a decrypted name-lists for 5 years after termination of the project. This is for verification and control of the results. After these 5 years, all data from the project will be deleted.

Your rights; as long as you can be identified in the data-material, you have a right to;

- Have insight in personal material registered on you.
- Have your information corrected
- Have personal information deleted
- Have access to a copy of your personal information
- Make a complaint to a data protection official or the Norwegian data protection Authority regarding the processing of your personal information

Who gives us (the University of Agder) a right to process your personal information?

- We process your personal information by your written consent.

The Norwegian center for research data has on request by the University of Agder concluded that the processing of your personal information is in accordance with the personal information privacy policy.

VOLUNTARY PARTICIPATION

Your participation in this project is voluntary and you can at any point and for any reason withdraw yourself from the study without giving any reason for this. All your information will then be anonymized. There is no negative consequence for you if you choose not to participate or withdraw yourself from the project.

If you have any questions to the study, or wish to use your rights, please contact the project-leaders Per Thomas Byrkjedal (Doktorgradsstipendiat: per.byrkjedal@uia.no / 93498951) or Thomas Bjørnsen (thomas.bjornsen@uia.no / 986 19 299), our data protection official Ina Danielsen, Universitetet i Agder, ina.danielsen@uia.no, phone +47 452 54 401 or Norwegian center for research data (NSD) (personverntjenester@nsd.no / 55 58 21 17). The institution responsible for the project is the University of Agder.

Best regards

Thomas Bjørnsen & Per Thomas Byrkjedal

CONSENT-FORM

I have received and understood the information related to participation in the project *velocitybased strength training and a follow-up of training- and match load* and I've been given the chance to ask questions. I hereby consent to

- ☐ participate in the study
- ☐ that my personal information can be procced in an anonymized form until all data related to the project is deleted 31.12.28

--------------------- --

(Date) (Signature participant)

Appendix 7

Collaboration agreement between *UiA/Department of sport science and physical education* and *IK Start*

UiA Institutt for idrettsvitenskap og kroppsøving

START

SAMARBEIDSAVTALE

MELLOM

Idrettsklubben Start og Universitetet i Agder, Fakultet for helse- og idrettsvitenskap

1. PARTER

Denne samarbeidsavtalen er inngått mellom IK Start AS (organisasjonsnummer 945.523.433) og Universitetet i Agder (UiA), Fakultet for Helse- og Idrettsvitenskap (organisasjonsnummer 970.546.200.), heretter kollektivt omtalt som «partene».

2. BAKGRUNN OG FORMÅL

Bakgrunnen for denne avtalen er at partene ønsker å bidra til å forsterke spillerutvikling i norsk fotball, i det øyemed at norske fotballklubber skal kunne konkurrere på lik linje med internasjonale klubber og kvalifisere seg til mesterskap.

Avtalen har som formål å kunne realisere synergieffekter mellom de to partene gjennom gjensidig samarbeid innen følgende områder.

- Samarbeid om forskning på prestasjonsutvikling for spillere, trenere, ledere og lag.
- Samarbeid om utveksling av personell i den hensikt å videreutvikle kompetanse.
- Samarbeid om felles utviklingstiltak gjennom å utnytte og videreutvikle hverandres kompetanse.

3. SAMARBEIDSFORUM

Partene har i fellesskap opprettet et samarbeidsforum, bestående av følgende partsrepresentanter:

Fra IK Start: Adm. direktør/Sportslig leder

Fra UiA: Instituttleder Sveinung Berntsen Stølevik og Professor Bjørn Tore Johansen

I samarbeidsforumet skal partene arbeide for å oppnå avtalens formål og drive samarbeidet fremover. Samarbeidsforumet skal arbeide for å etablere både tiltak som kan iverksettes relativt raskt og med enkle grep, samt tiltak som spenner over 10 til 20 år. Samarbeidsforumet skal også arbeide for en kontinuerlig forankrings prosess i Teknisk Hjerte (IK Start).

Partenes representanter i samarbeidsforumet er også ansvarlige for å forankre samarbeidsavtalen i egen organisasjon.

4. PARTENES RETTIGHETER OG FORPLIKTELSER

4.1 IK Start

IK Start forplikter seg ved inngåelse av denne avtalen til følgende:

- Gi UiA, herunder både vitenskapelige ansatte og studenter, tilgang på tallmateriale, eksempelvis testbatteri lagret i sideline, IK Starts testresultater, data fra nye verktøy som går på kunstig video intelligens eller andre trackingsystemer.
- Gi vitenskapelige ansatte og studenter tilknyttet UiA tilgang til IK Starts virksomhet til bruk i forsknings- og utviklingsprosjekter (FoU-prosjekter).
- Stille eget personell og utstyr til rådighet for FoU-prosjekter i UiAs regi.

4.2 Universitetet i Agder

UiA forplikter seg ved inngåelse av denne avtalen til følgende:

- Oppfordre vitenskapelig ansatte og studenter ved UiA til å utvikle og gjennomføre FoU-prosjekter i samarbeid med IK Start, herunder videreformidle IK Start sine ønsker og behov for FoU-arbeid. UiA velger like fullt selv hvilke FoU-prosjekter som skal iverksettes, og er følgelig ikke pliktige til å iverksette FoU-prosjekter etter IK Starts ønske.

UiA har rett til å benytte innhentet data fra IK Start til bruk i forskning. Det kan ikke legges restriksjoner på offentliggjøring og publisering av forskningsresultatene.

5. TRENERSTUDIUM

Begge parter ønsker at det etableres et nasjonalt trenerstudium i Agder, og vil gjennom denne samarbeidsavtalen undersøke mulighetene for dette.

Ingen av partene har ved denne samarbeidsavtalen forpliktet seg til å bidra til et slikt trenerstudium, og eventuell etablering av et slikt studium forutsetter at det inngås egen avtale om dette.

6. GENERELLE BESTEMMELSER OG PRESISERINGER

6.1 Samarbeidsavtalen er ikke til hinder for at partene kan inngå tilsvarende eller andre former for samarbeidsavtaler med andre organisasjoner og institusjoner.

6.2 Bruk av motpartens navn og/eller logo i markedsføring o.l., forutsetter skriftlig samtykke fra motparten i forkant av slik markedsføring.

6.3 Partene skal holde hverandre skadesløse mot alle tap eller enhver skade på egen eiendom, skade for eget personell, krav fra partenes respektive tredjeparter og enhver følgeskade som måtte oppstå ved gjennomføring av ulik aktivitet som utføres i samsvar med denne samarbeidsavtalen.

7. AVTALENS VARIGHET

7.1 Avtalen gjelder i 3 – tre- år, fra 01.01.21 til 31.12.2023. Avtalen skal evalueres etter ett år.
7.2 Avtalen skal reforhandles dersom en eller flere av følgende situasjoner inntreffer før den 31.12.2020:

- Partene er enige om å reforhandle
- Reforhandling er nødvendig som følge av offentlige pålegg, endring i lov osv.
- Dersom vesentlige forutsetninger for avtalen endres eller faller bort

7.3 Hver av partene kan til enhver tid komme med forslag om endringer i avtalen. Endringer kan ikke tre i kraft før de er vedtatt av begge parter.
7.4 Ved uforutsette endringer hos en av partene, skal den andre part varsles umiddelbart.
7.5 Ved vesentlig mislighold fra en av partene kan hver av partene si opp avtalen ved skriftlig varsel. Mislighold anses ikke som vesentlig dersom den misligholdende part har klart å utbedre misligholdet eller når partene er blitt enig om en løsning for å utbedre misligholdet innen 30 dager etter slikt varsel.

8. TVISTER

8.1 I tilfelle uenighet om forståelsen av denne avtalen skal partene ved forhandlinger søke å løse saken i minnelighet.
8.2 Dersom enighet ikke oppnås, skal saken søkes løst ved mekling etter Den Norske Advokatforenings regler for mekling. Dersom partene ikke er kommet til enighet innen 60 dager etter at en av partene skriftlig begjærte mekling, og partene ikke er enige om å forlenge fristen, kan tvisten løses ved ordinær domstolsbehandling ved Kristiansand tingrett.

9. SIGNATUR

Intensjonsavtalen underskrives i 2 eksemplarer, hvorav partene beholder 1 eksemplar hver.

Kristiansand, 12/4-21

Sportslig leder

Atle Roar Håland

IK Start

Kristiansand, 15/3-21

Instituttleder

Sveinung Berntsen Stølevik

Institutt for idrettsvitenskap og kroppsøving, Fakultet for helse- og idrettsvitenskap, Universitetet i Agder

Appendix 8

Research collaboration agreement between *UiA/Department of sport science and physical education* and *IK Start*

UiA Institutt for idrettsvitenskap og kroppsøving

START

Avtale om
FORSKNINGSPROSJEKT

mellom

Idrettsklubben Start og Institutt for idrettsvitenskap og kroppsøving ved Fakultet for helse- og idrettsvitenskap, Universitetet i Agder

1. PARTER

Denne avtalen er inngått mellom IK Start AS og Universitetet i Agder (UiA), institutt for Idrettsvitenskap og kroppsøving, heretter kollektivt omtalt som «partene».
Avtalen er et utfyllende tillegg til samarbeidsavtalen som er inngått mellom partene xx.xx.21.
Avtalen (denne) blir heretter omtalt som «tilleggsavtalen».

2. BAKGRUNN OG FORMÅL

Bakgrunnen for tilleggsavtalen er det siste årets samarbeid mellom partene, samt et pågående doktorgradsprosjekt. I denne tilleggsavtalen ønsker partene å konkretisere og spesifisere enkelte av punktene i samarbeidsavtalens paragraf 4. Partenes rettigheter og forpliktelser.

Tilleggsavtalens formål er å forankre og videreføre det siste årets velfungerende samarbeid. IK Start har ytret et ønske om å i større grad la seg forske på og samtid øke klubbens kunnskap og konkurransedyktighet i forbindelse med dette. For UiA er forutsigbarhet og tilgang til toppidrettsmiljøene vesentlig for forskning og utviklingsaktivitet (FoU).

3. PARTENES RETTIGHETER OG FORPLIKTELSER

I tillegg til samarbeidsavtalen gjelder følgende:

3.1 IK Start

IK Start forplikter seg ved inngåelse av denne tilleggsavtalen til følgende:

- Stille sine fullverdige spillerstaller tilgjengelig for fysiske tester i regi av UiA minst to ganger pr år.
  - Herunder både A-lag, B-lag og UA-avdeling
  - Start kan ikke tilbakeholde spillere fra å la seg teste med mindre det foreligger særskilt grunn.
- Gi tilgang til fullverdige datasett fra tracking-systemer.
- Gi UiAs personell (forskere, stipendiater, masterstudenter eller andre vitenskapelige tilsatte) tilgang til å drive forskningsaktivitet på Sparebanken Sør Arena.
  - Med dette menes det at noe treningsaktivitet på gressmatta på Sparebanken Sør Arena tilpasses slik at det kan drives FoU arbeid. Dette skal gjøres i samråd med IK Start og kan ikke kreves styrt av UiA.

3.2 Universitetet i Agder

UiA forplikter seg ved inngåelse av denne tilleggsavtalen til følgende:

- Legge til rette for fysiske tester i testlaboratorier *minst 2 ganger pr år*, fortrinnsvis i januar/februar og september/oktober
  - Det legges til rette for flere testperioder der det er praktisk mulig.

- Forsøke å legge til rette for ytterlige testing ved forespørsel.
- Informere og forsøke å legge til rette for testing av IK Starts spillere i prosjekter partene finner relevante.
- Bidra til analyser og utvikling basert på data fra tracking-systemer og fysiske tester
- Sørge for at alle tester og prosedyrer følger gjeldende regelverk for FoU.

4. GENERELLE BESTEMMELSER OG PRESISERINGER

4.1 Generelle bestemmelser og presiseringer omtalt i punkt 6. i samarbeidsavtalen gjelder også her.

4.2 Avtalen forutsetter at det ved UiA foreligger et doktorgradsprosjekt med tilhørende masteroppgaver som kan bidra med arbeidskraft inn i samarbeidet. Terminering av det pågående doktorgradsprosjektet vil medføre annullering av tilleggsavtalen.

4.3 Avtalen forutsetter samarbeid med fysisk trener, eller tilsvarende ansatt hos IK Start. Dersom vedkommende går ut av klubben og ikke erstattes med likeverdig personell, kan partene bli enige om å avslutte tilleggsavtalen.

4.4 Det presiseres at all aktivitet og testing i regi av UiA må være i relasjon til eksisterende eller ny-etablerte master-, Ph.d.- eller FoU prosjekter. IK Start gis ikke anledning til å benytte UiAs test-lokaler, ressurser og personell til egen aktivitet. Med dette menes det at IK Start ikke kan kreve tester (eksempelvis DXA) gjennomført hvis dette ikke ligger innunder pågående FoU aktivitet.

5. AVTALENS VARIGHET

5.1 Punktene fra samarbeidsavtalens punkt 7. gjelder også her, med unntak av bestemmelsene om varighet, jfr. punkt 5.2 nedenfor.

5.2 Tilleggsavtalen har en varighet på 2 år, fra 01.01.2021 til 31.12.2022.

6. SIGNATUR

Avtalen underskrives i 2 eksemplarer, hvorav partene beholder 1 eksemplar hver.

Kristiansand, 12/4-21

[signature]

Sportslig leder
Atle Roar Håland
IK Start

Kristiansand, 15/3-21

[signature]

Instituttleder
Sveinung Berntsen Stølevik
Institutt for idrettsvitenskap og kroppsøving, Fakultet for helse- og idrettsvitenskap, Universitetet i Agder

Appendix 9

Individual Coefficient of variation in external load variables (**study one** and **two**)

Table 9.1: CV in external load variables from official matches during **study one**.

Official	TD (m/min^{-1})	Peak speed (m/s^{-1})	SlowSS (m/min^{-1})	ModSS (m/min^{-1})	HighSS (m/min^{-1})	SprSS (m/min^{-1})	PlayerLoad (au/min^{-1})	HIEs (nr/min^{-1})	Acc (nr/min^{-1})	Dec (nr/min^{-1})	CoD (nr/min^{-1})
FP07	4 %	3 %	7 %	6 %	15 %	28 %	6 %	14 %	30 %	15 %	16 %
FP11	6 %	4 %	9 %	12 %	12 %	22 %	5 %	12 %	25 %	15 %	15 %
FP19	15 %	5 %	26 %	30 %	32 %	45 %	16 %	33 %	28 %	38 %	36 %
FP23	4 %	1 %	1 %	13 %	7 %	26 %	8 %	5 %	35 %	32 %	5 %
FP25	9 %	4 %	8 %	11 %	15 %	21 %	8 %	15 %	60 %	34 %	20 %
FP26	7 %	6 %	2 %	5 %	20 %	88 %	10 %	16 %	37 %	8 %	18 %
FP31	10 %	5 %	11 %	15 %	30 %	50 %	12 %	22 %	24 %	9 %	24 %
FP37	6 %	6 %	9 %	7 %	10 %	26 %	7 %	8 %	30 %	20 %	8 %
FP41	5 %	3 %	9 %	12 %	11 %	25 %	7 %	6 %	46 %	14 %	6 %
FP42	9 %	4 %	12 %	16 %	20 %	48 %	11 %	14 %	104 %	25 %	13 %
FP43	6 %	3 %	2 %	5 %	10 %	46 %	9 %	9 %	32 %	18 %	7 %
FP45	7 %	3 %	9 %	11 %	17 %	27 %	6 %	15 %	26 %	19 %	14 %
FP47	8 %	5 %	14 %	11 %	30 %	50 %	21 %	50 %	76 %	61 %	55 %
FP50	7 %	2 %	11 %	6 %	14 %	23 %	4 %	9 %	86 %	68 %	12 %
FP52	6 %	4 %	10 %	11 %	15 %	15 %	7 %	9 %	19 %	26 %	11 %
FP54	7 %	4 %	11 %	12 %	13 %	45 %	6 %	14 %	25 %	25 %	14 %

TD: Total distance, SS: Speed skating, Mod: moderate, PL: PlayerLoad^{TM} (au), HIEs: High intensity events, Acc: Accelerations, Dec: Decelerations, CoD, Change of directions

Table 9.2: CV in external load variables from scrimmages during **study one**.

Scrimmage	**TD** (m/min^{-1})	**Peak speed** (m/s^{-1})	**SlowSS** (m/min^{-1})	**ModSS** (m/min^{-1})	**HighSS** (m/min^{-1})	**SprSS** (m/min^{-1})	**PlayerLoad** (au/min^{-1})	**HIEs** (nr/min^{-1})	**Acc** (nr/min^{-1})	**Dec** (nr/min^{-1})	**CoD** (nr/min^{-1})
FP04	3 %	2 %	10 %	12 %	5 %	13 %	5 %	10 %	28 %	24 %	11 %
FP07	3 %	4 %	6 %	7 %	8 %	15 %	4 %	7 %	59 %	8 %	8 %
FP11	5 %	4 %	20 %	10 %	13 %	23 %	3 %	14 %	62 %	21 %	17 %
FP15	1 %	5 %	5 %	4 %	1 %	62 %	4 %	8 %	11 %	17 %	8 %
FP19	3 %	3 %	5 %	5 %	8 %	23 %	1 %	11 %	48 %	26 %	10 %
FP21	4 %	4 %	12 %	4 %	18 %	42 %	7 %	16 %	64 %	8 %	18 %
FP27	2 %	2 %	7 %	11 %	6 %	25 %	3 %	6 %	52 %	1 %	6 %
FP28	3 %	2 %	10 %	3 %	5 %	21 %	1 %	1 %	53 %	16 %	5 %
FP29	6 %	4 %	10 %	6 %	12 %	42 %	3 %	7 %	18 %	22 %	5 %
FP31	3 %	4 %	13 %	6 %	4 %	17 %	7 %	13 %	30 %	25 %	13 %
FP32	5 %	4 %	17 %	8 %	12 %	43 %	8 %	8 %	55 %	8 %	8 %
FP36	3 %	4 %	12 %	5 %	6 %	16 %	4 %	7 %	47 %	18 %	8 %
FP37	3 %	2 %	8 %	13 %	9 %	8 %	5 %	4 %	38 %	27 %	5 %
FP38	3 %	5 %	12 %	6 %	18 %	35 %	8 %	18 %	32 %	43 %	15 %
FP42	4 %	6 %	12 %	6 %	11 %	42 %	2 %	9 %	41 %	21 %	9 %

TD: Total distance, SS: Speed skating, Mod: moderate, PL: PlayerLoad^{TM} (au), HIEs: High intensity events, Acc: Accelerations, Dec: Decelerations, CoD, Change of directions.

Table 9.3: CV in external load variables from matches included in baseline and follow-up period during **study two**.

	Spilletid (min)	**TD** (m/min^{-1})	**Peak speed** (m/s^{-1})	**PlayerLoad** (au/min^{-1})	**HSR** (m/min^{-1})	**SPR** (m/min^{-1})	**#HIR** (nr/min^{-1})	**#SPR** (nr/min^{-1})	**HIEs** (nr/min^{-1})	**Acc** (nr/min^{-1})	**Dec** (nr/min^{-1})	**CoD** (nr/min^{-1})
Baseline period												
Player a	22 %	5 %	7 %	7 %	28 %	79 %	46 %	73 %	6 %	20 %	13 %	4 %
Player b	2 %	5 %	3 %	8 %	22 %	60 %	25 %	66 %	14 %	24 %	20 %	16 %
Player c	16 %	6 %	3 %	2 %	22 %	42 %	20 %	53 %	14 %	14 %	14 %	17 %
Player d	2 %	4 %	5 %	5 %	37 %	68 %	30 %	54 %	5 %	24 %	19 %	11 %
Player e	2 %	2 %	3 %	2 %	16 %	41 %	13 %	40 %	10 %	18 %	29 %	11 %
Player f	21 %	5 %	6 %	6 %	20 %	62 %	10 %	45 %	3 %	12 %	15 %	12 %
Player g	26 %	6 %	3 %	12 %	17 %	19 %	16 %	33 %	25 %	24 %	34 %	21 %
Player h	16 %	7 %	4 %	8 %	29 %	23 %	27 %	23 %	13 %	7 %	29 %	12 %
Follow-up period												
Player a	1 %	4 %	6 %	5 %	19 %	55 %	17 %	57 %	6 %	16 %	11 %	15 %
Player b	5 %	2 %	5 %	5 %	9 %	53 %	9 %	58 %	14 %	27 %	18 %	32 %
Player c	2 %	3 %	6 %	3 %	12 %	24 %	10 %	24 %	17 %	13 %	24 %	28 %
Player d	15 %	3 %	3 %	4 %	21 %	47 %	19 %	43 %	12 %	21 %	24 %	19 %
Player e	1 %	4 %	6 %	3 %	8 %	24 %	12 %	19 %	7 %	21 %	22 %	12 %
Player f	8 %	2 %	5 %	2 %	15 %	33 %	16 %	32 %	7 %	12 %	14 %	15 %
Player g	10 %	3 %	3 %	7 %	11 %	25 %	14 %	23 %	10 %	21 %	21 %	15 %
Player h	5 %	1 %	2 %	3 %	4 %	22 %	7 %	25 %	4 %	5 %	9 %	4 %

Total distance, au: arbitrary units, HIR: High speed running, SPR: Sprint running, #: efforts, nr: number, HIE: High intensity events, Acc: accelerations, Dec: decelerations, CoD: Change of directions.

Appendix 10

Calculation and application of high intensity running (HIR: >19.8 km/h) distance as an objective marker to regulate strength training volume

HIR as an external load marker to regulate strength training

The selection of HIR distance as measure to regulate strength training volume was selected based on the findings by Hader et al. (2019), where an increase in HIR distance was associated with increased creatin kinase and lower CMJ power output.

To calculate the specific threshold applied during **study two** (presented in **paper III)**, a tree-way split of the players was warranted. Therefore, repository HIR match data from the ongoing 2021 season were utilized to calculate the specific thresholds. Specifically, 243 match data points from repository match data were included and the use of IQR and SD was explored, with an overview of the different calculations shown in Table 10.1, with the mean ± 0.5 SD of the repository HIR distance data provide a close to equal split of observations. Therefore, a HIR distance of <421 m, 421-687 m, and >687 m, regulating players from the AUTO-group to a high, moderate, or low strength training volume, was applied.

When including the actual HIR distance observations from the matches during the intervention is a similar three-way split observed, with some more observations in the low threshold category. For the AUTO-group specifically, the same trend is observed with fewer (10) observations in the highest distance (>687m) category compared to the low (27) and moderate (29) HIE distance categories, respectively). Specific number for the SELF-group is not included. A comparison of the HIR match observations from the repository data and during the intervention period is shown in Figure 10.1.

Table 10.1: Distribution of match HIR distance and thresholds.

	Low		**Moderate**		**Hard**	
	m	Matches	m	Matches	m	Matches
IQR	<334	63	334-756	120	>756	60
1 SD	<287	46	287-820	152	>820	45
0.5 SD	<421	80	421-687	79	>687	84
Actual	<421	66	421-687	55	>687	58

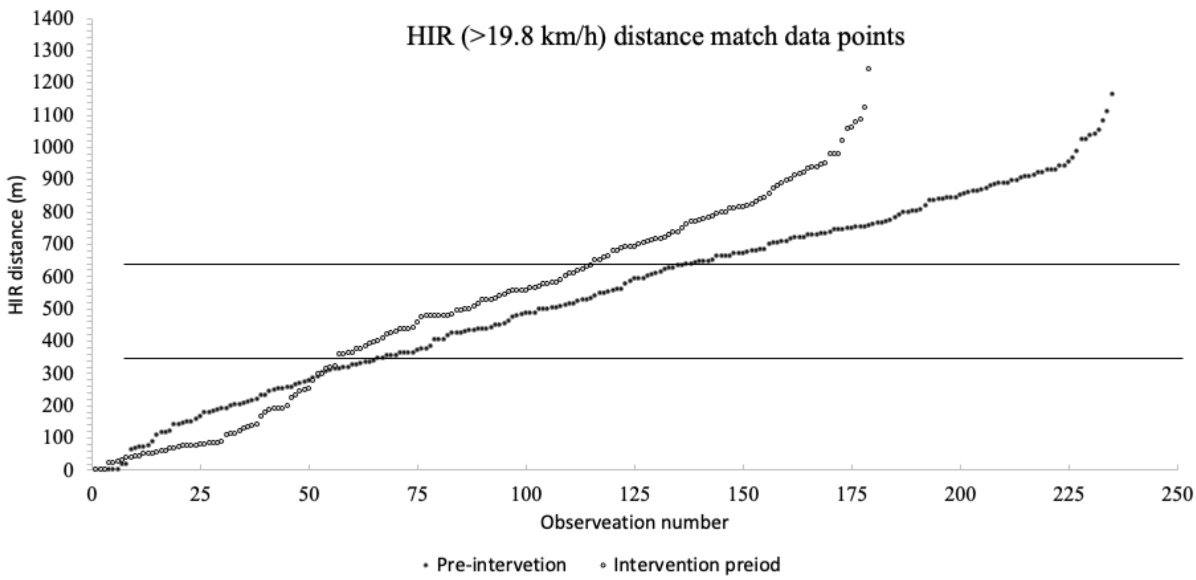


Figure 10.1*: HIR distance match data points distribution during 2021 season. Black dots represent match-points before intervention periods (applied to set thresholds) and open dots represents match-points during the intervention period. Solid lines represent thresholds cutoffs at 421 and 687m, respectively, applied in* ***study III****.*

Hader, K., Rumpf, M. C., Hertzog, M., Kilduff, L. P., Girard, O., & Silva, J. R. (2019). Monitoring the athlete match response: Can external load variables predict post-match acute and residual fatigue in soccer? A systematic review with meta-analysis. *Sports medicine-open*, *5*(1), 1-19.

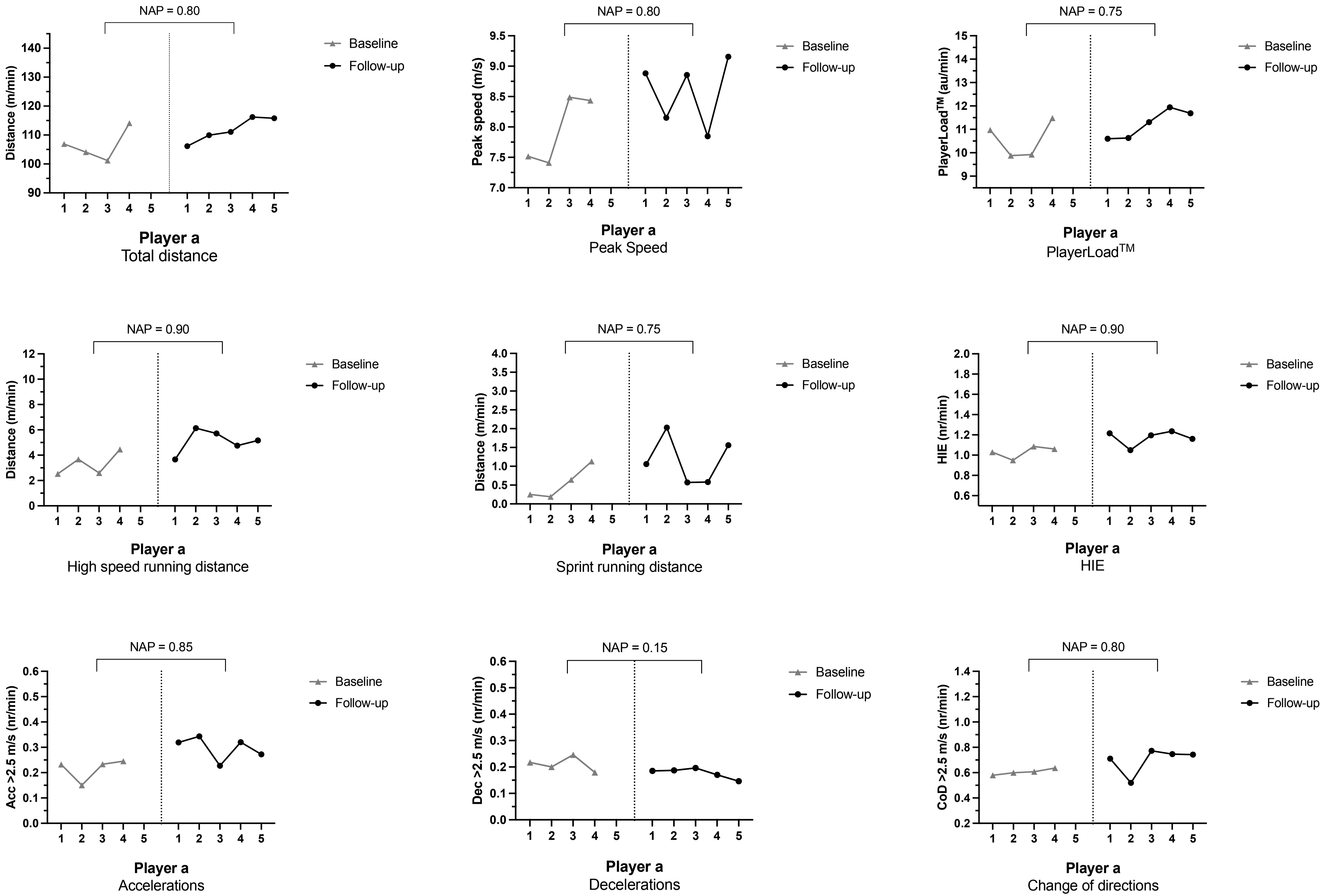
Appendix 11

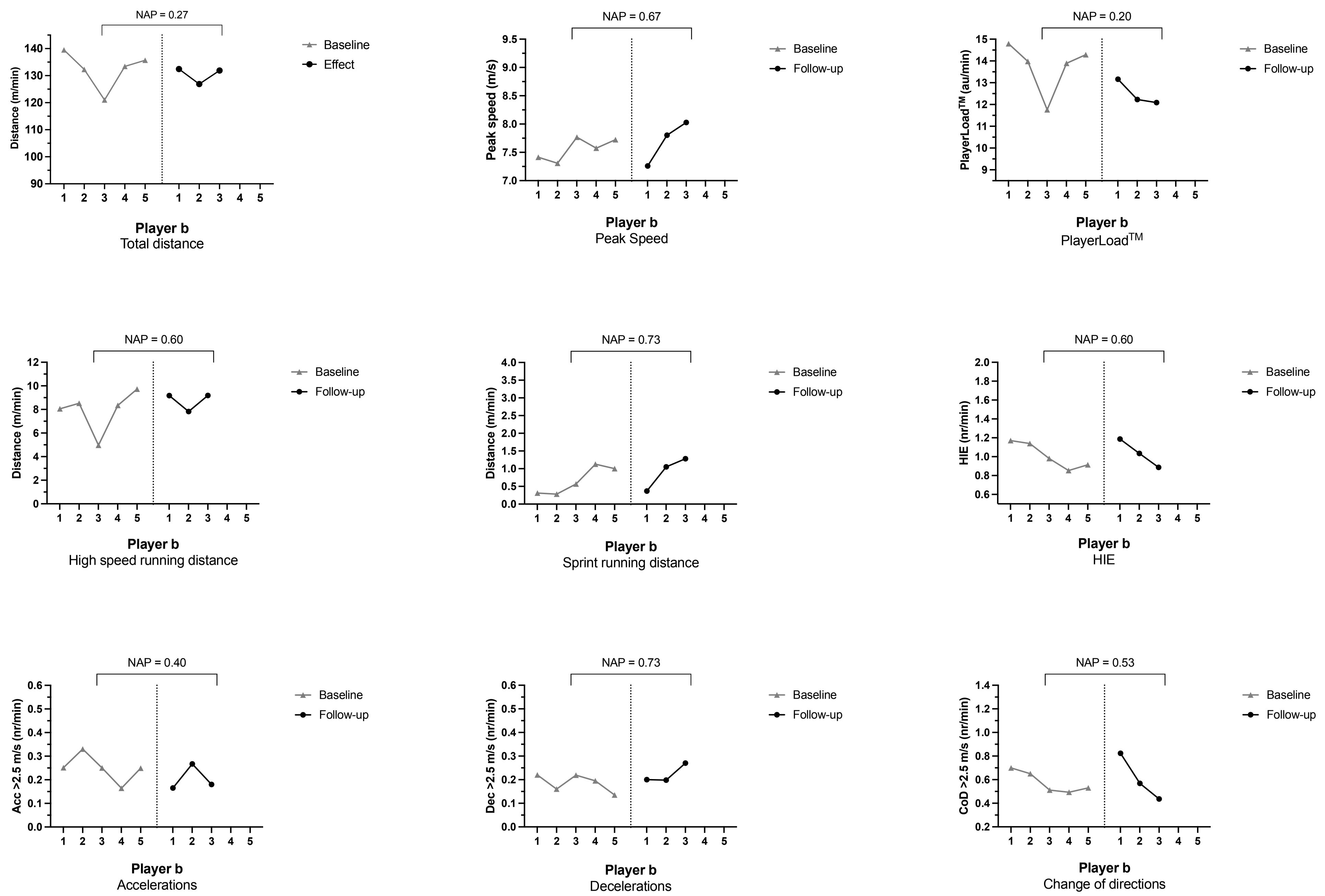
Individual player NAP figures from paper IV

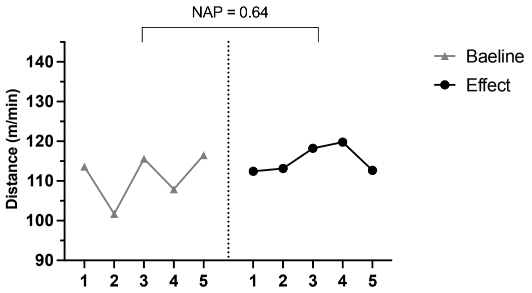
Individual player NAP figures

Eight players (Player a-h) fulfilled the inclusion criteria for external match load data in **paper IV**. The following appendix presents individual NAP-figures for each player in the variables; Total distance, peak speed, PlayerLoad^{TM}, high speed running distance, sprint running distance, high intensity events, accelerations, decelerations and change of directions. Variable descriptions and thresholds can be found in the thesis methods chapter.

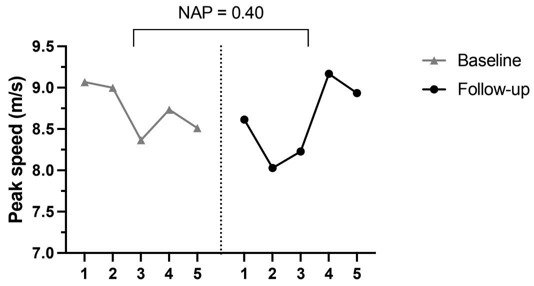
NAP effect sizes in external match loads between the two periods (baseline and follow-up) should be interpreted as; 0–.65 = week effects, .66–.92 = moderate effects, .93–1.0 = large or strong effects.


NAP = 0.80
Distance (m/min)
Baseline
Follow-up
Player a
Total distance
NAP = 0.80
Peak speed (m/s)
Baseline
Follow-up
Player a
Peak Speed
NAP = 0.75
PlayerLoadTM (au/min)
Baseline
Follow-up
Player a
PlayerLoadTM
NAP = 0.90
Distance (m/min)
Baseline
Follow-up
Player a
High speed running distance
NAP = 0.75
Distance (m/min)
Baseline
Follow-up
Player a
Sprint running distance
NAP = 0.90
HIE (nr/min)
Baseline
Follow-up
Player a
HIE
NAP = 0.85
Acc >2.5 m/s (nr/min)
Baseline
Follow-up
Player a
Accelerations
NAP = 0.15
Dec >2.5 m/s (nr/min)
Baseline
Follow-up
Player a
Decelerations
NAP = 0.80
CoD >2.5 m/s (nr/min)
Baseline
Follow-up
Player a
Change of directions

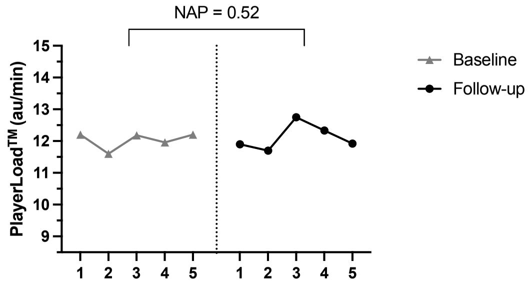

NAP = 0.27
Distance (m/min)
Baseline
Effect
Player b
Total distance
NAP = 0.67
Peak speed (m/s)
Baseline
Follow-up
Player b
Peak Speed
NAP = 0.20
PlayerLoad™ (au/min)
Baseline
Follow-up
Player b
PlayerLoad™
NAP = 0.60
Distance (m/min)
Baseline
Follow-up
Player b
High speed running distance
NAP = 0.73
Distance (m/min)
Baseline
Follow-up
Player b
Sprint running distance
NAP = 0.60
HIE (nr/min)
Baseline
Follow-up
Player b
HIE
NAP = 0.40
Acc >2.5 m/s (nr/min)
Baseline
Follow-up
Player b
Accelerations
NAP = 0.73
Dec >2.5 m/s (nr/min)
Baseline
Follow-up
Player b
Decelerations
NAP = 0.53
CoD >2.5 m/s (nr/min)
Baseline
Follow-up
Player b
Change of directions



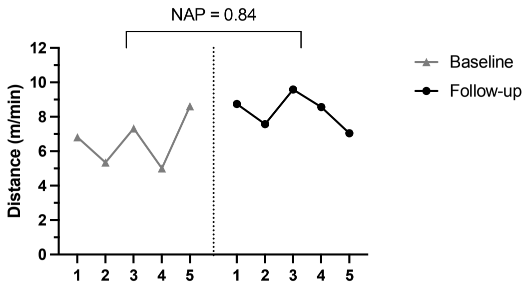
Player c
Total distance



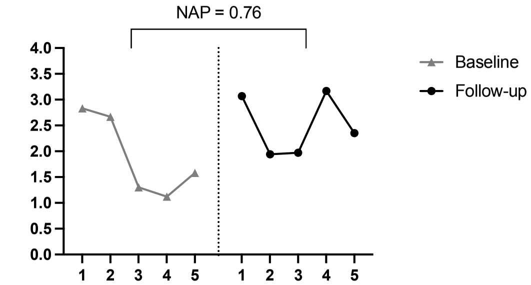
Player c
Peak Speed



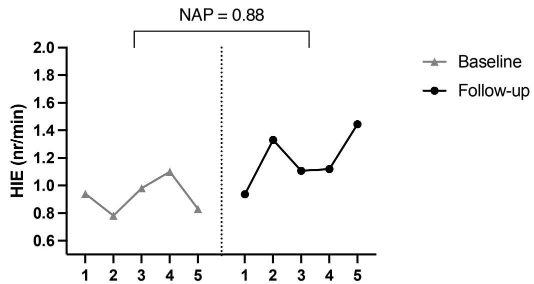
Player c
PlayerLoad^{TM}



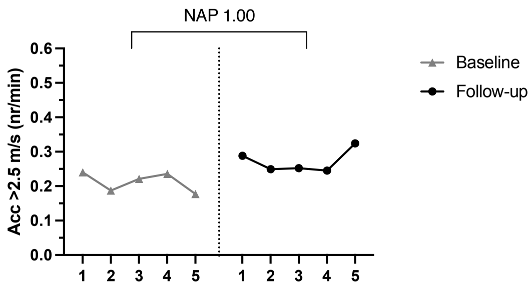
Player c
High speed running distance



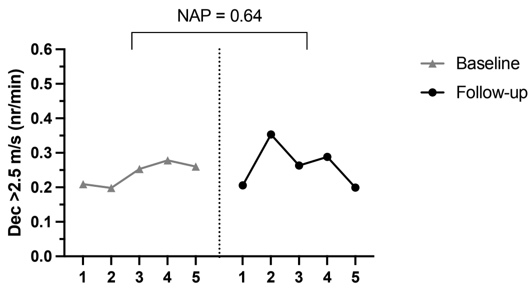
Player c
Sprint running distance



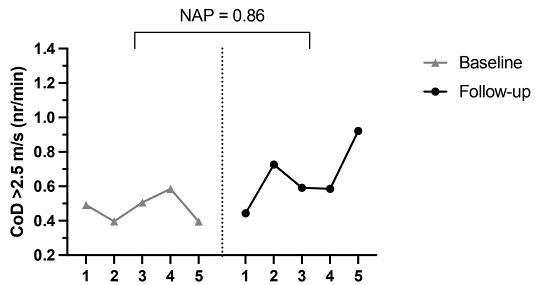
Player c
HIE



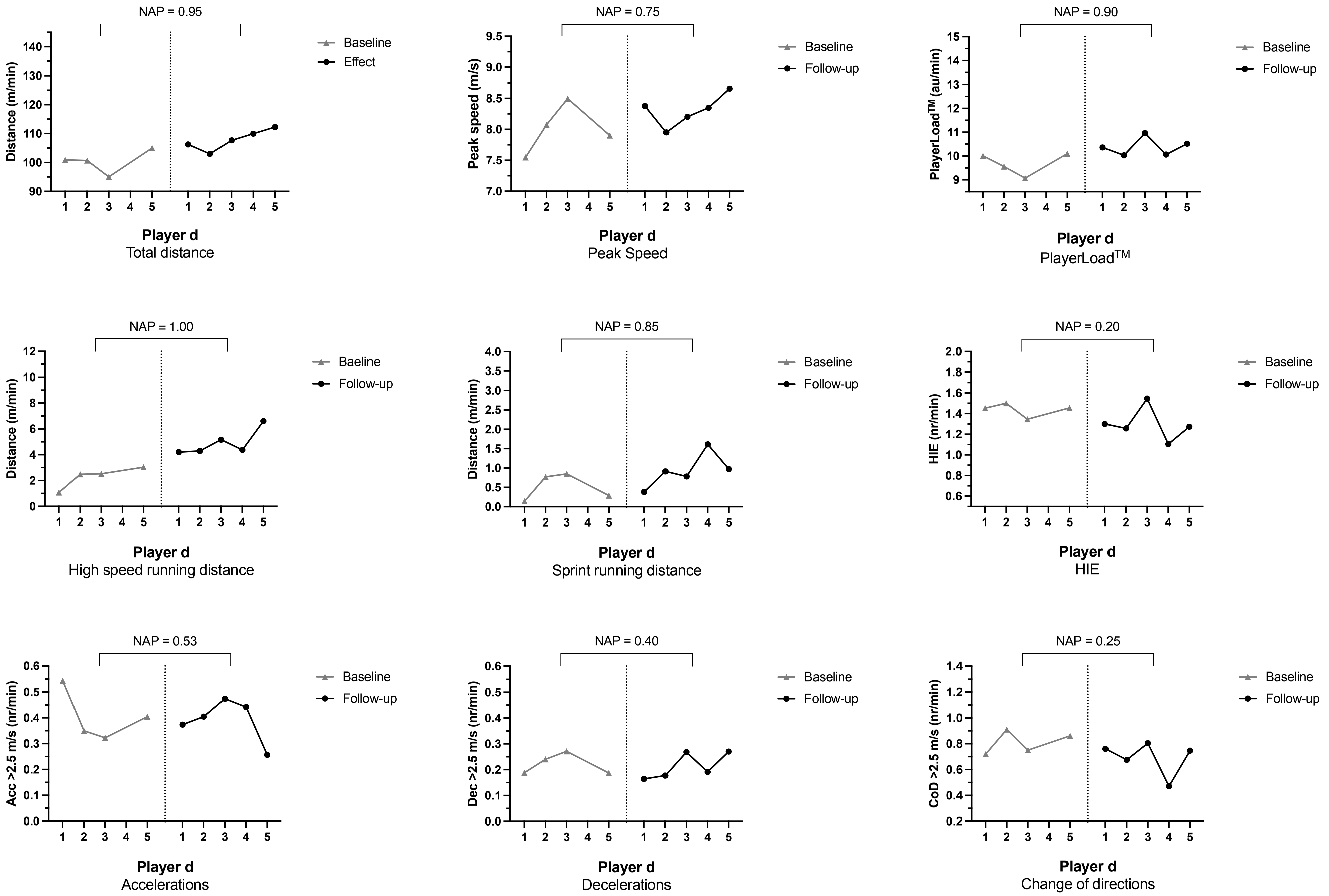
Player c
Accelerations

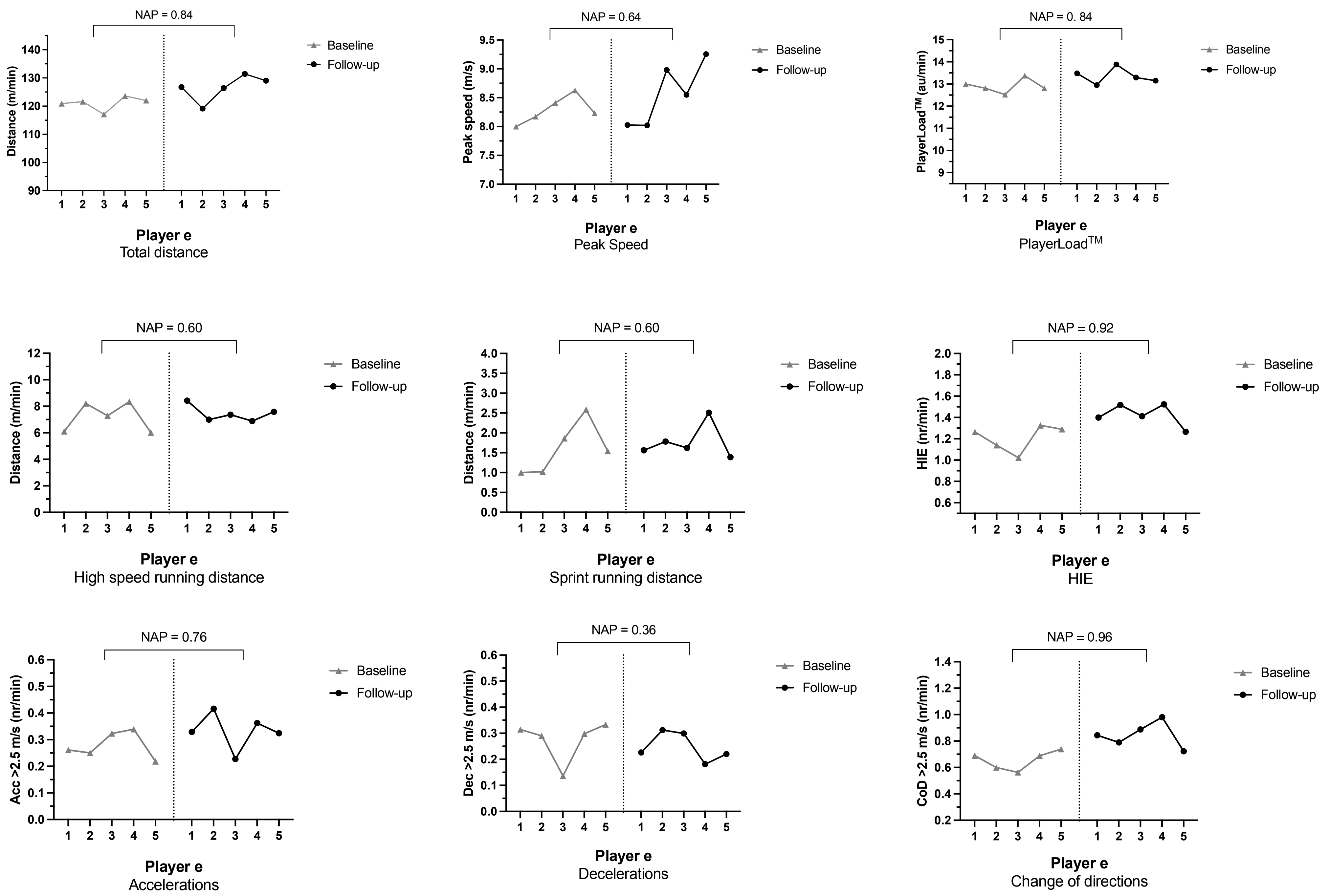


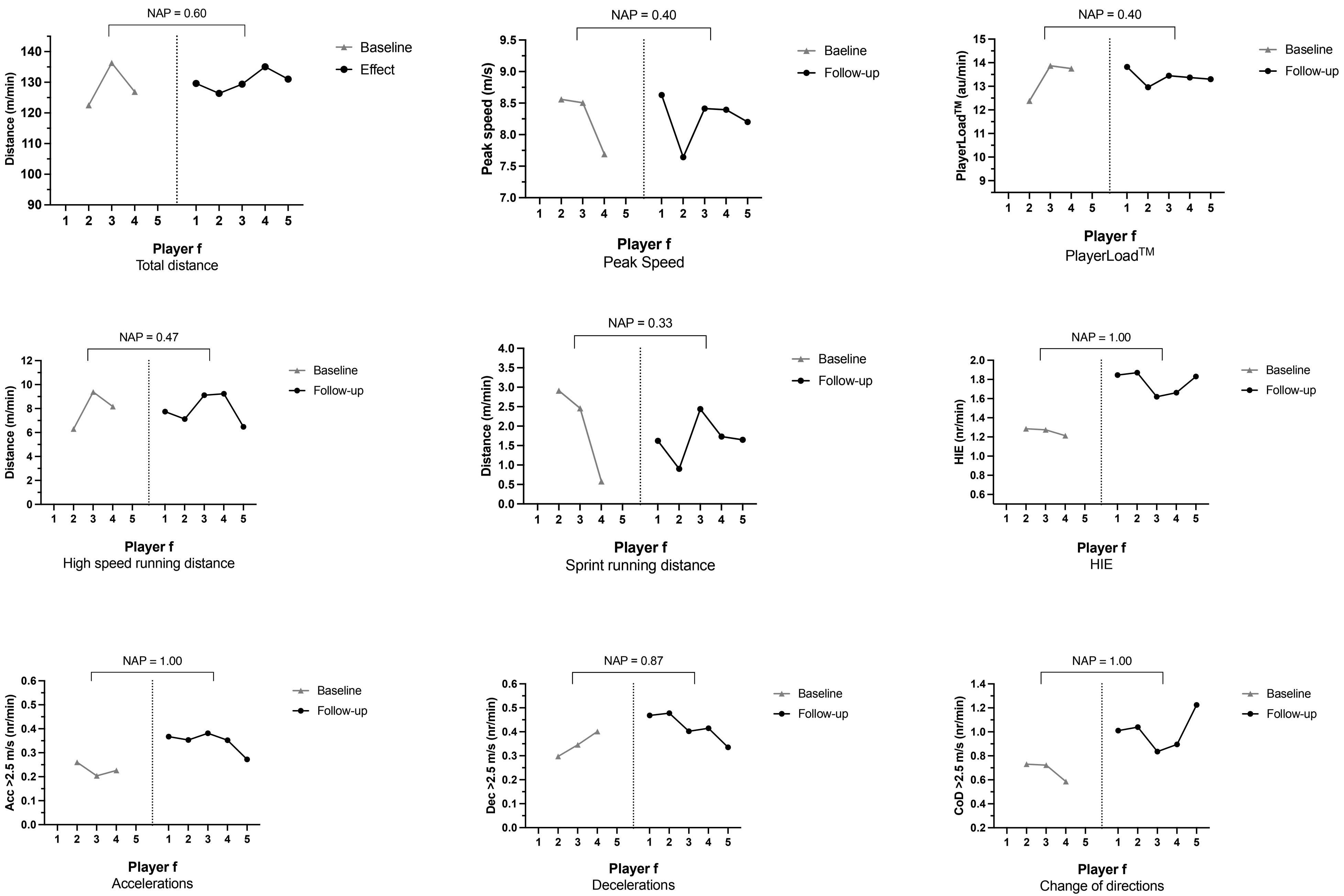
Player c
Decelerations

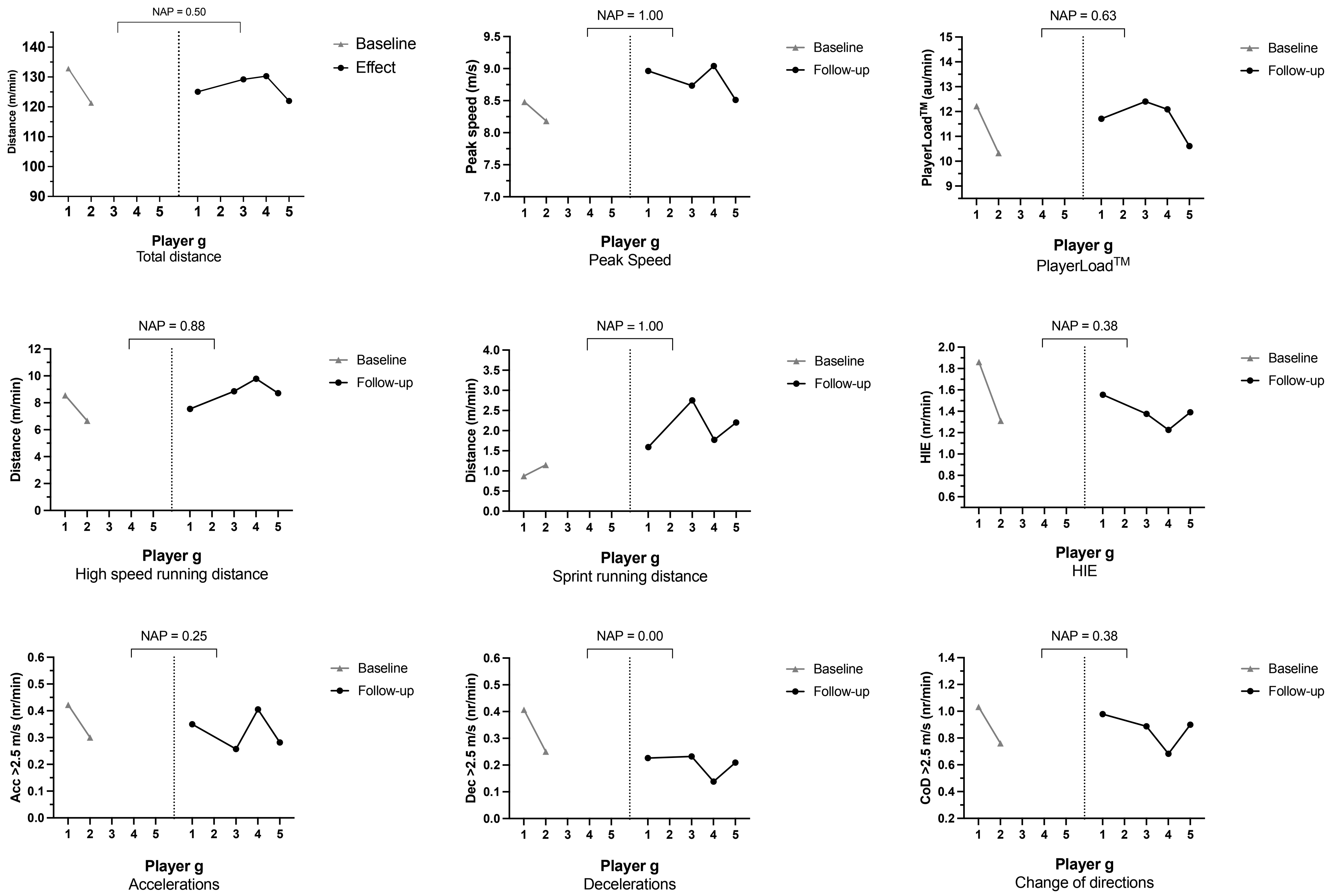


Player c
Change of directions

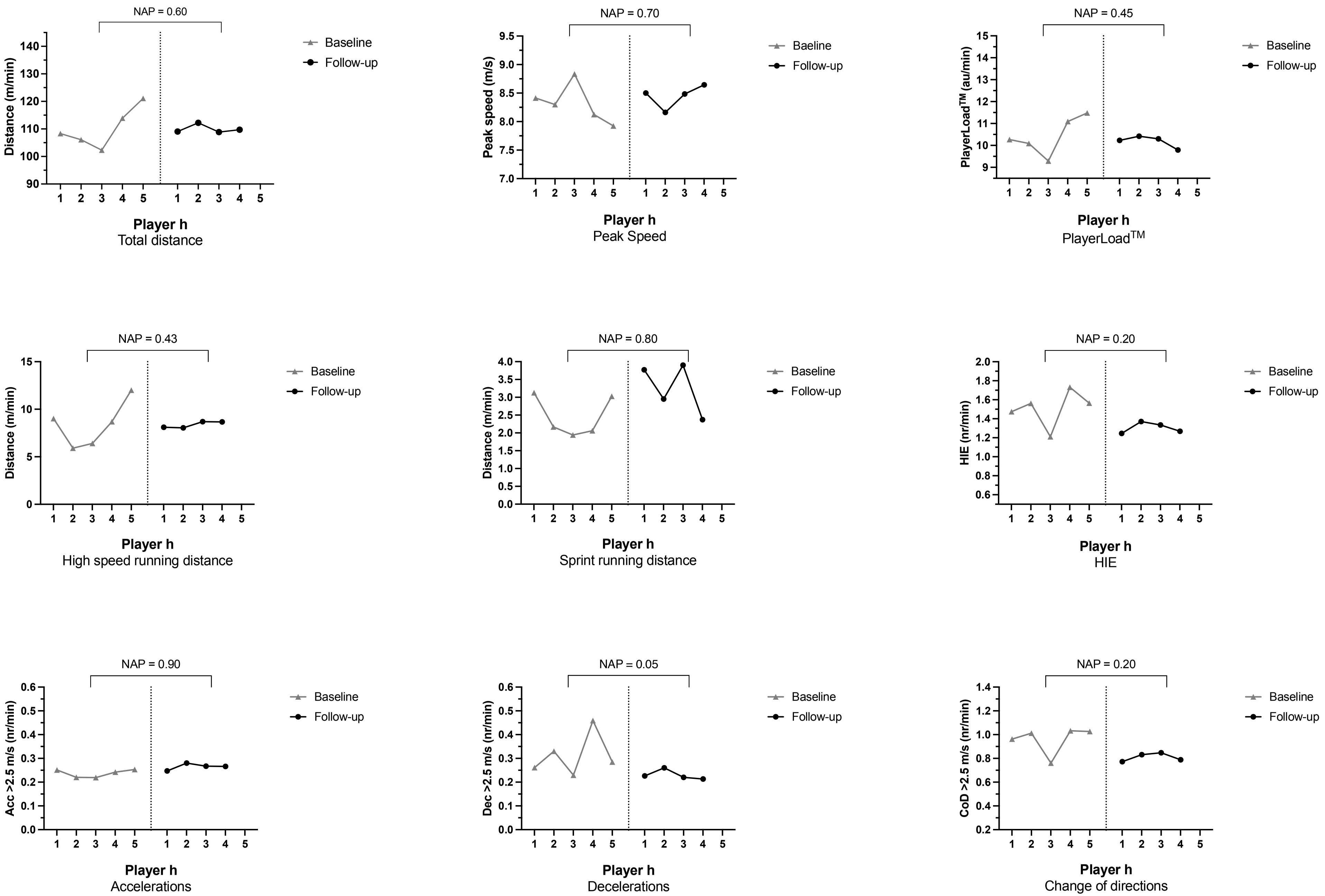

NAP = 0.95
Distance (m/min)
Baseline
Effect
Player d
Total distance
NAP = 0.75
Peak speed (m/s)
Baseline
Follow-up
Player d
Peak Speed
NAP = 0.90
PlayerLoadTM (au/min)
Baseline
Follow-up
Player d
PlayerLoadTM
NAP = 1.00
Distance (m/min)
Baeline
Follow-up
Player d
High speed running distance
NAP = 0.85
Distance (m/min)
Baseline
Follow-up
Player d
Sprint running distance
NAP = 0.20
HIE (nr/min)
Baseline
Follow-up
Player d
HIE
NAP = 0.53
Acc >2.5 m/s (nr/min)
Baseline
Follow-up
Player d
Accelerations
NAP = 0.40
Dec >2.5 m/s (nr/min)
Baseline
Follow-up
Player d
Decelerations
NAP = 0.25
CoD >2.5 m/s (nr/min)
Baseline
Follow-up
Player d
Change of directions


NAP = 0.84
Distance (m/min)
Baseline
Follow-up
Player e
Total distance
NAP = 0.64
Peak speed (m/s)
Player e
Peak Speed
NAP = 0. 84
PlayerLoad^TM (au/min)
Player e
PlayerLoad^TM
NAP = 0.60
Distance (m/min)
Player e
High speed running distance
NAP = 0.60
Distance (m/min)
Player e
Sprint running distance
NAP = 0.92
HIE (nr/min)
Player e
HIE
NAP = 0.76
Acc >2.5 m/s (nr/min)
Player e
Accelerations
NAP = 0.36
Dec >2.5 m/s (nr/min)
Player e
Decelerations
NAP = 0.96
CoD >2.5 m/s (nr/min)
Player e
Change of directions


NAP = 0.60
Distance (m/min)
Baseline
Effect
Player f
Total distance
NAP = 0.40
Peak speed (m/s)
Baseline
Follow-up
Player f
Peak Speed
NAP = 0.40
PlayerLoadTM (au/min)
Baseline
Follow-up
Player f
PlayerLoadTM
NAP = 0.47
Distance (m/min)
Baseline
Follow-up
Player f
High speed running distance
NAP = 0.33
Distance (m/min)
Baseline
Follow-up
Player f
Sprint running distance
NAP = 1.00
HIE (nr/min)
Baseline
Follow-up
Player f
HIE
NAP = 1.00
Acc >2.5 m/s (nr/min)
Baseline
Follow-up
Player f
Accelerations
NAP = 0.87
Dec >2.5 m/s (nr/min)
Baseline
Follow-up
Player f
Decelerations
NAP = 1.00
CoD >2.5 m/s (nr/min)
Baseline
Follow-up
Player f
Change of directions



NAP = 0.50
Distance (m/min)
Baseline
Effect
Player g
Total distance
NAP = 1.00
Peak speed (m/s)
Baseline
Follow-up
Player g
Peak Speed
NAP = 0.63
PlayerLoadTM (au/min)
Baseline
Follow-up
Player g
PlayerLoadTM
NAP = 0.88
Distance (m/min)
Baseline
Follow-up
Player g
High speed running distance
NAP = 1.00
Distance (m/min)
Baseline
Follow-up
Player g
Sprint running distance
NAP = 0.38
HIE (nr/min)
Baseline
Follow-up
Player g
HIE
NAP = 0.25
Acc >2.5 m/s (nr/min)
Baseline
Follow-up
Player g
Accelerations
NAP = 0.00
Dec >2.5 m/s (nr/min)
Baseline
Follow-up
Player g
Decelerations
NAP = 0.38
CoD >2.5 m/s (nr/min)
Baseline
Follow-up
Player g
Change of directions


NAP = 0.60
Distance (m/min)
Baseline
Follow-up
Player h
Total distance
NAP = 0.70
Peak speed (m/s)
Player h
Peak Speed
NAP = 0.45
PlayerLoad™ (au/min)
Player h
PlayerLoad™
NAP = 0.43
Distance (m/min)
Player h
High speed running distance
NAP = 0.80
Distance (m/min)
Player h
Sprint running distance
NAP = 0.20
HIE (nr/min)
Player h
HIE
NAP = 0.90
Acc >2.5 m/s (nr/min)
Player h
Accelerations
NAP = 0.05
Dec >2.5 m/s (nr/min)
Player h
Decelerations
NAP = 0.20
CoD >2.5 m/s (nr/min)
Player h
Change of directions

Appendix 12

Correlation scatterplots between physical sprint performance testing and peak speed from scrimmages and football matches

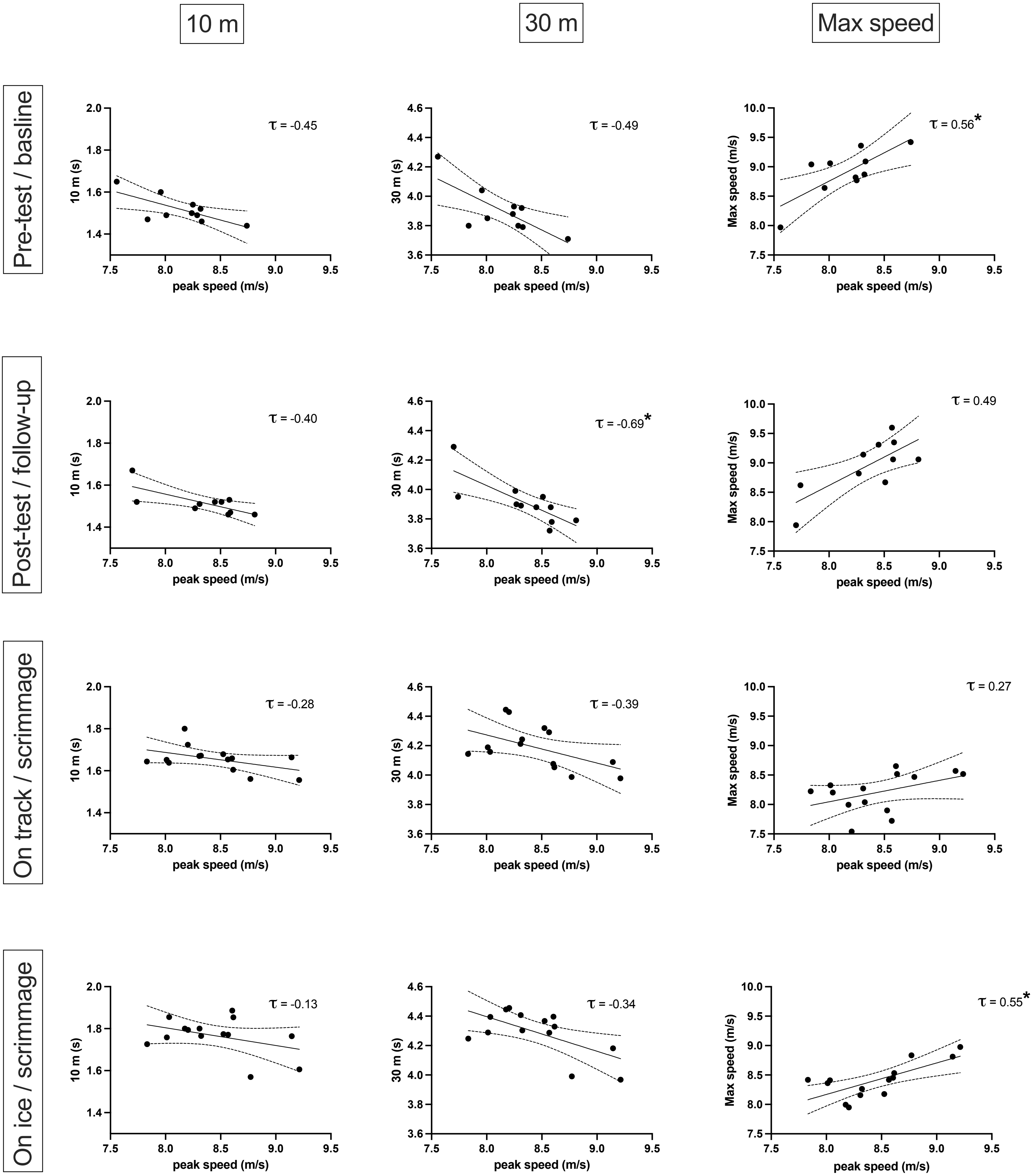


Figure 12.1. Correlation scatterplots and 95% confidence intervals for 10 m and 30 m times and max speed from sprint testing and peak speed from external load data during scrimmages (**paper II**) and pre-test/baseline-period and post-test/follow-up period during **study two**. On track; running sprint from **paper II**. On ice; skating sprints from paper II. ***τ***; Kendall's Tau correlation coefficient. *Indicate credible correlations with Bayes Factor (BF_{10}) >3.