IN-SEASON VARIATION OF SKATING LOAD AT DIFFERENT PLAYING POSITIONS IN MALE ELITE ICE HOCKEY

A single season longitudinal study

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Aikaisemmat tutkimukset korkean intensiteetin joukkueurheilulajeista osoittavat, että pitkä kilpailukausi vaikuttaa monin tavoin negatiivisesti pelaajien fyysisiin ominaisuuksiin ja sitä kautta myös suorituskykyyn kauden loppua kohden mentäessä. Tämän tutkimuksen tarkoituksena oli havainnoida jääkiekossa pelipaikkakohtaista luistelukuormituksen muuttumista kilpailukauden neljässä eri vaiheessa, ja näin selvittää miten kilpailukausi vaikuttaa lajispesifiin suorituskykyyn. Tässä tutkimuksessa pelaajat ryhmiteltiin pelipaikkakohtaisesti keskushyökkääjiin, laitahyökkääjiin ja puolustajiin, kun aikaisemmissa tutkimuksissa pelaajia on tarkasteltu joko yhtenä joukkona tai pelaajat on jaettu hyökkääjiin sekä puolustajiin. Vastaavaa koko kauden kattavaa luistelumuuttuja-analyysia ei ole aikaisemmin jääkiekon osalta tehty.

Tutkimuksen aineisto käsitti 146 jääkiekkopelaajan vaihtokohtaiset luistelutiedot kaudella 2019-2020 pelatusta 372 runkosarjaottelusta Suomen pääsarjatasolla. Tutkimuksen aineisto kerättiin Bitwise Oy:n toimesta Wisehockey-urheiluanalytiikkajärjestelmän avulla. Tutkimuksessa käytettiin yhteensä 14 Bitwisen tarjoamaa luistelumuuttujaa: yli 0.5 sekuntia kestävien eri kiihtyvyysalueiden ylittävien kiihdytysten ja jarrutusten määrät per vaihto, eri kiihtyvyysalueilla ilman aikarajaa suoritettujen kiihdytysten ja jarrutusten määrät per vaihto, vaihto- ja pelikohtaiset peliajat, absoluuttiset ja suhteelliset peliajat eri luistelunopeusalueilla per vaihto, vaihto- ja pelikohtaiset luistelumatkat, luistelumatkat eri luistelunopeusalueilla, maksimaaliset ja keskimääräiset luistelunopeudet per vaihto, sekä yli 1 sekuntia kestävien yhtäjaksoisten käyntien lukumäärät eri luistelunopeusalueilla per vaihto. Tilastollinen analyysi toteutettiin hyödyntämällä toistomittausanalyysia. Pelipaikkakohtaisen jaon lisäksi pelikausi jaettiin neljään kvartaaliin (Q1-Q4) analyysia varten.

Yli 0.5 sekuntia kestäneiden kiihdytysten sekä jarrutusten määrät laskivat kauden loppua kohden pelipaikasta riippumatta. Vastaavasti ilman aikarajaa suoritettujen kiihdytysten ja jarrutusten määrät eri kiihdytysalueilla kasvoivat Q1 ja Q2 välillä. Yli 1 sekuntia kestäneiden suoritusten määrä per vaihto ≥ 15 km/h nopeusalueella kasvoi välillä Q1 ja Q2, ja vastaavasti käyntien määrä ≥ 20 km/h nopeusalueella pieneni Q3 ja Q4 välillä ilman, että näillä kuitenkaan oli merkitsevää vaikutusta luisteltuun matkaan ja suhteelliseen luisteluaikaan eri nopeusalueilla. Hyökkääjät suorittivat enemmän korkeaintensiteettisiä ja maksimaalisia jarrutuksia, luistelivat enemmän korkeammilla nopeusalueilla, ja heillä oli suurempi keskimääräinen sekä maksimaalimen luistelunopeus verrattuna puolustajiin. Keskushyökkääjät luistelivat enemmän suuremmilla luistelunopeuksilla ja viettävät enemmän aikaa korkeaintensiteettisillä nopeusalueilla verrattuna laitahyökkääjiin. Puolustajat viettivät enemmän aikaa matalaintensiteettisellä luistelunopeusalueilla verrattuna hyökkääjiin. Pelipaikkojen ja kauden eri vaiheiden välillä ei tutkimuksessa havaittu keskinäistä vaikutusta.

Tutkimuksen tuloksista voidaan päätellä, että jääkiekkokausi varsinkin korkeimmalla sarjatasolla kuormittaa pelaajia siten, että se näkyy erityisesti pitkäkestoisten kiihdytysten ja jarrutusten määrässä, mutta ei luisteluintensiteeteissä, peliajassa tai luistelumatkassa. Luistelukuormituksen muutokset kauden eri vaiheissa ei tulosten perusteella vaikuta olevan pelipaikkariippuvaisia. Tulokset antavat olettaa, että keskushyökkääjiä ja laitahyökkääjiä tulisi tarkastella erikseen pelaajatyyppeinä havaittujen luisteluintensiteettierojen vuoksi.

Asiasanat: jääkiekko, joukkueurheilu, harjoittelukuormitus, sisäinen kuormitus, ulkoinen kuormitus, lähipaikannusjärjestelmä, luistelu, pelipaikka

ABSTRACT

Reinikainen, M. 2021. In-season variation of skating load at different playing positions in male elite ice hockey: A single season longitudinal study. Faculty of Sport and Health Sciences, University of Jyväskylä, Master´s thesis in exercise physiology, 99 pp, 1 appendix.

Balance between recovery and the load in high-intensity sport such as ice hockey is the key to best possible performance. Previous studies in ice hockey as well as studies from other high-intensity team sports suggest that players´ performance decreases toward the end of the season. The aim of this study was to examine if the sport specific external load would change towards the end of competitive season in ice hockey. In addition, the purpose of this study was to compare skating loads during the in-season between three different playing positions: centers, wingers, and defensemen. Previous studies have not examined the effect of playing position so extensively.

The study subjects were total of 146 male Finnish elite league ice hockey players from total of 9 teams. This study contained players skating data from total of 372 matches which were played during the regular season of 2019-2020. The study was done with repeated measures for three player subgroups based on playing position (centers, wingers, defensemen). Season was divided into four different quarters (Q1-Q4). Skating load measurements were performed via Local Positioning System based Wisehockey analytics platform provided by Bitwise corporation. The skating variables used were the following: accelerations and decelerations over 0.5 second threshold limits per shift, accelerations and decelerations in different threshold ranges per shift, time on ice per shift and per match, relative and absolute time spent in different velocity ranges per shift, skating distance per shift and per match, skating distance in different velocity ranges per shift, maximum and mean velocities per shift, and number of over 1 second visits over different velocity limits per shift.

Numbers of both, prolonged (> 0.5 sec) high-intensity and maximal accelerations and decelerations decreased towards the end of the season. Correspondingly, accelerations and decelerations in different threshold ranges increased from Q1 to Q2 without subsequent decline when measured without time limit. The number of over 1 second visits per shift at the limit of $\geq$ 15 km/h increased from Q1 to Q2 and over 1 second visits at the limit of $\geq$ 20 km/h decreased from Q3 to Q4, without any reflection in skating distance or the time spent in related skating velocity ranges over the same periods of time. No interaction was found between playing positions and season phases regarding to any of the measured skating metrics. Centers and wingers performed more high-intensity and maximal decelerations, skated higher intensities overall, and had higher maximal and mean skating speed per shift compared to defensemen. Centers skate slightly higher skating speeds and spend more time in very high skating intensities during the shift compared to wingers. Defensemen skated more distance per match and spent more time on ice during the match and spent more time in lower skating intensities than forwards.

As a conclusion, full competitive season of ice hockey seems to impair the players´ ability to perform prolonged accelerations and decelerations. However, the decrease of performance towards the end of the season is not visible in any other skating variables. Different season phases did not affect skating load playing position specifically. This study clearly indicates that forwards cannot be grouped as a one playing position, since centers skate with higher intensities, both in time and in distance, than wingers.

Key words: ice hockey, team sport, training load, internal load, external load, local positioning system, skating, playing position

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ABSTRACT

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1 INTRODUCTION

Ice hockey as a sport has changed vastly throughout the years. Today the game is seen faster, more intense, and more physical than ever before. As the game itself has become more demanding, the skills required from the players at the highest competitive level have increased and become more wholesome. Players are already bigger than ever, but they also have to be fast, strong and possess a high endurance capacity. Acknowledging and developing these skills will take the professionalism in the competitive level to the next stage.

As in many other team sports, in ice hockey the athlete must remain in top condition throughout the long competitive season. This is conversely to many of the individual sports where the goal of the season is usually set to a certain competition each year. In team sports each match counts. Therefore, the highest fitness level of the athlete needs to extend through the whole season. This sets demands on the athletes´ physical condition, especially when the length of the professional competitive season in ice hockey is longer than the off-season where the actual condition base is built. Hence, in a high-intensity sport like ice hockey, the correlation between recovery time and the physical load from the matches and practices is a balancing act. Recovery is essential for the player development, but the features of the sport set certain challenges to it.

The purpose of this study is to examine how the prolonged season affect to the players´ skating load, and the affect it has on different playing positions at the highest competitive level. Few studies have investigated the skating load during in-season matches, but there is a lack of prior research regarding to a full-season of training. Instead, previous research in ice hockey has largely focused on seasonal changes in physiological responses and body composition during an ice hockey season. The aim is to link the individual matches and findings from physiological responses to a whole season from the perspective of skating load and its variables. In addition, there is almost no scientific research done in ice hockey regarding to centers and wingers, as prior research has focused almost exclusively on ice hockey players in general or the players have been seen as forwards and defensemen. Thus, this study provides much-needed information on playing position specific level of performance in more depth by separating players between centers, wingers and defensemen.

2 ICE HOCKEY AS A SPORT

Ice hockey, combining high level of technical skills with high-intensity intermittent exercise, is physically demanding team sport. Ice hockey match consists total of three 20-minute periods with 15-minute rest after 1st and 2nd period, plus a possible “sudden-death” overtime period (5, 10 or 20 minutes) after 3rd period to settle a tie match. In regular season if no goal is scored during the overtime period a penalty-shot shootout will be used to determine a winner. Maximum of six players (one goalkeeper plus five skaters, or no goalkeeper plus six skaters) can be on the ice at the same time during the on-going match from one team with unlimited free substitutions from players registered in a match lineup. (IIHF 2019, 31, 48)

International Ice Hockey Federation (IIHF) have set the maximum of 22 (20 skaters, 2 goalkeepers) players limit for a match (IIHF 2019, 30), that also applies to the Liiga (national top league in Finland). In the National Hockey League (NHL), team size is limited to 20 players (18 skaters, 2 goalkeepers) (NHL Rulebook, 6). Team can also be short-handed due to a virtue of having fewer skaters (e.g. 3 vs 5, 4 vs 5) on the ice than opponent due to a result of one or more penalties. This situation is also known as penalty kill. The opposite situation, when at least one opposing player is serving a penalty, is called a power play (e.g. 5 vs 4 or 5 vs 3). (IIHF 2019, 75)

Majority of current research have separated ice hockey players based on their playing positions as goalkeepers, defensemen and forwards. Three forward players form an offensive lineup, typically including two wingers and one center forward, while defense players also work in pair during a match. High generalization of different forward player roles is that centers have important role as offensive playmakers with devoting defensive responsibilities as well, while wingers seek the route to the offensive end to fight for the puck. (NHL 2021) These positional roles can be split even further based on which side of the rink they are playing, such as left defenseman, right wing etc. Kutáč and Sigmund (2015) have made a more specific categorization for forward players as playmakers, snipers, two-way forwards, power forwards, grinders and enforcers based on gaming position and possible relationship during sports performance. In this study, the forwards are being differentiated as centers and wingers for the clarity of categorization.

What differs ice hockey from other major team sports is the surface (ice) the game is played and the size of the field. IIHF´s standard dimensions of ice rink are maximum of 61 meters long by 30 meters wide and minimum of 56 meters long and 26 meters wide. The corners of the ice rink must be rounded in the arc of circle with a radius of 7.0 to 8.5 meters. (IIHF 2016, 77) Besides the size, the surface of the field is likely to play a significant role of the high-intensity nature of the game compared to other team sports (Lignell et al. 2018).

The length of ice hockey season varies between the countries and leagues. For example, in the NHL, "the world´s premier ice hockey league" (Marsh 2012), season consists of 82 matches per team in addition to possible playoff series. In the Liiga, each team have total of 60 matches on top of possible playoff series, which is then played as best-of-seven principle from quarterfinals stage (Liiga 2020a). This means, that in order to win the championship, a team may have to play up to more than 20 matches in the playoff-series in addition to regular season matches. Ice hockey season lasts approximately 7 to 8 months at professional level depending on the league. At the highest level, teams usually play more than two matches a week, in addition to which players also trains on a daily basis (Allard et al. 2020).

Prior studies show that ice hockey players have evolved physically and with sport specific capacity during the evolution of the game and due to the greater physical demands of the game in professional level (Montgomery 2006; Quinney et al. 2008). Cox et al. (1995) suggest that these changes are result of changes in training methods and therefore higher fitness levels in professional ice hockey. Other and perhaps parallel explanation could be the fact that at high level the teams prefer physically bigger players, and therefore the scouting system is assessing players with physical size and/or strength, aggressiveness and/or toughness. Today teams are also more professional with fitness and strength coaches as well as improved in-house training facilities. (Montgomery 2006) To succeed at top level, players need to be fast, strong, skillful and durable athletes.

2.1 Energetic demand of ice hockey

As the total duration of 60-minute match, which typically is extended close to 2.5-3 hours (Cox et al. 1995; Montgomery 1988), and due to the high-intensity, intermittent and multi-directional nature of the sport, ice hockey sets a greater energy demand on athletes´ metabolic system when compared to the sports which cover the same distance by straight ahead running (Lignell et al. 2018; Reilly, 1997). Montgomery (1988) is citing the characterization of energy system usage by Seliger et al. (1972) that in ice hockey match approximately one-third of the energy demand is aerobic based, and two-thirds is more of an anaerobic, high-intensity activity. This can be seen as a statement that has not been really questioned in a sport specific research since then.

A classic model of energy systems prescribes that sustained bursts of muscle contractions lasting up to 10 seconds are largely powered by intramuscular phosphagen (adenosine triphosphate = ATP, creatine phosphate = PCr) stores, and from there the glycolytic system takes over, even though there is overlapping between the energy production processes. After the exercise is being extended from seconds to minutes and beyond, oxidative phosphorylation is the major pathway for the ATP generation in high intensities, intramuscular glycogen being the dominant fuel source, while oxidation of fatty acids is being preferred in low intensities. (Gastin 2001; Hargreaves & Spriet 2020) The evidence suggests that this classic way of dividing energy systems to oxidative (aerobic) and oxidation independent (anaerobic) metabolic pathways in different exercise intensities or time domains is highly dualistic, and do not reflect the energy systems during actual exercise in the way it can be measured today.

Different methods have been used to study anaerobic system contribution during exercise from freeze-clamping technique via muscle biopsies (e.g. Bogdanis et al. 1996; Dawson et al. 1997; Vigh-Larsen et al. 2020a) to calculations via indirect mathematical estimations (Duffield et al. 2004). Similarly, oxygen deficit measurements have been more or less estimations based on oxygen demand and oxygen uptake accumulation calculations (Medbø & Tabata 1989). As Gastin (2001) has covered in his review of energy systems contribution during maximal exercise the challenges of different methods used to evaluate especially anaerobic energy, that so far, the accurate determination of anaerobic energy release during an exercise has been challenging. Not to mention that different energy system contributions are almost impossible to accurately measure during the competitive ice hockey match due to the lack of suitable technology.

However, it has been demonstrated with rats that PCr consumption in working muscle during a muscle contraction cycle is much higher than it has been believed, and that the PCr has already recovered multiple times before muscle biopsy has been taken, in fact in milliseconds time scale (Chung et al. 1998). This indicates that the time between muscle contraction and muscle biopsy sample gives erroneous results and, consequently, leads to false conclusions in reference to the efficiency of the energy systems used in given exercise. Addition to Chung et al. (1998) findings, McCully et al. (1994) demonstrated with non-invasive technology that the decrease of muscle oxygen saturation is tightly in line with the decrease of muscle PCr in a working muscle and, vice versa, PCr recovery is coupled with oxygen recovery (figure 1). As Schulman and Rothman (2001) have pointed out, oxygen is highly involved during the release of energy that is needed to support rapid muscle contractions within milliseconds time scales. This contradicts with the classic energy system model where phosphagen, glycolytic and oxidative systems work almost like an isolation from each other at least in terms of how fast different energetic processes occur during exercise (Hargreaves & Spriet 2018). The role of immediate oxygen usage is also supported by the findings from applied physiology where intermittently done high-intensity training has been shown to drive skeletal muscles to upregulate oxidative capacity due to increased oxygen demand (Burgomaster et al. 2005; Gillen et al. 2014).

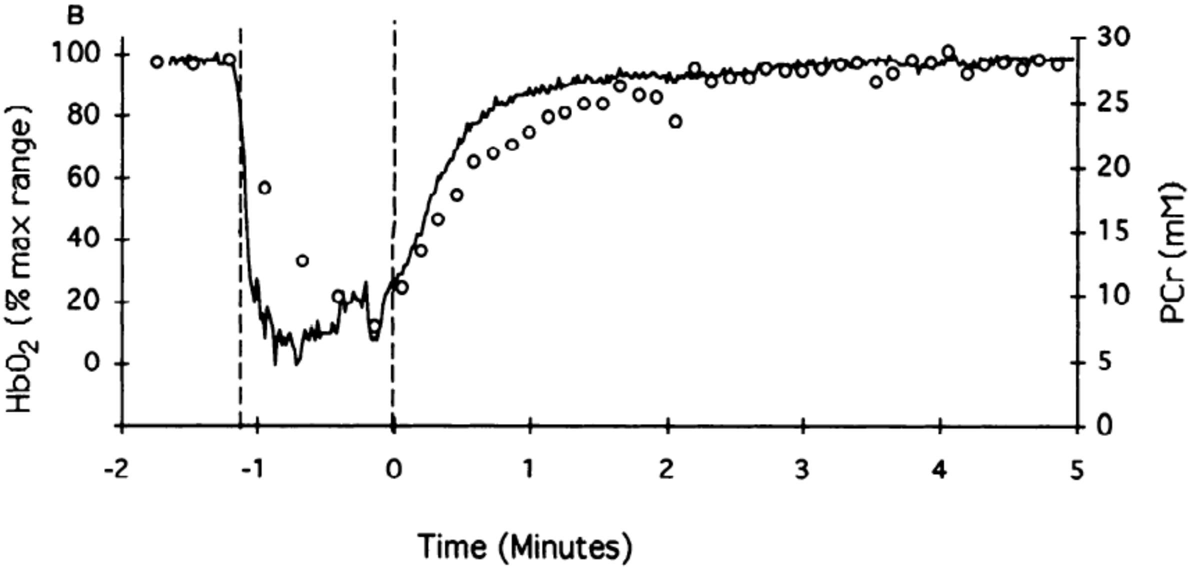


FIGURE 1 Measured relationship between oxygenated haemoglobin (solid line) and PCr saturation (circles) during maximal exercise (McCully et al. 1994).

What this means is that even though some of the energy system processes are oxygen independent, this does not mean that anaerobic processes can be differentiated from aerobic processes when it comes to exercise, because the time frame between these processes is so short

(Shulman & Rothman 2001). Based on this, in ice hockey when player is skating, performing high-intensity efforts like accelerating or sprinting, shooting a puck etc., player´s muscles utilize oxygen at the same rate as the PCr is being utilized. Hence, the definition of ice hockey being as a predominantly anaerobic sport does not correspond with the actual research of physiology underlying the sport. Therefore, the suggestion is that the original conclusions of Seliger et al. (1972) on ice hockey being an anaerobically dominant sport are outdated and should for that reason be re-examined. A better understanding of energy systems will help to optimize the training of athletes with the demands of sport in mind.

2.2 Ice hockey players anthropometric profiles

Players´ body mass and height have increased through the years, while at the same time relative body fat has remained constant or slightly decreased, players being around 10 cm taller and 17 kg heavier today compared to early days of the game (Cox et al., 1995; Montgomery 2006; Quinney et al., 2008). Based on IIHF ranking system, the average height of the elite ice hockey player is 184.3 (± 5.8) cm with average body weight of 88.1 (± 7.7) kg, whereas in the NHL, players are slightly bigger with average height being 186 (± 5.3) cm with body weight of 91.7 (± 6.9) kg (Sigmund et al. 2016). Previous studies have shown that there seem to be specific anthropometric profiles for different playing positions. A general principle has been that defensemen are taller, and they have higher body mass than forwards and goalkeepers (Montgomery 1988; Quinney et al. 2008; Vescovi et al. 2006). Sigmund et al. (2016) also reported that wingers are slightly taller and heavier than centers among the forward players.

The proportion of mean body fat mass is reported to be between 10% and 16% depending largely on the measurement methods (Chiarlitti et al. 2018; Kutac & Sigmund 2015; Montgomery 2006; Peterson et al. 2015b; Roczniok et al. 2016; Vescovi et al. 2006; Vigh-Larsen et al. 2020b). The body mass index (BMI) has increased by 2.3 kg/m^2 during the years indicating higher volume of muscle mass. (Montgomery 2006). Body fat percent also varies between playing position. Overall, goaltenders tend to have higher body fat percent than defenders or forwards. Montgomery (1988) states that fat mass does offer some protection during the collision with boards and opponents and is beneficial when body checking opponents, because of added inertial mass. However, according to Chiarlitti et al. (2018) lean tissue mass is strongly correlated with producing strength and power output, and high muscle mass with lower fat mass levels are associated with faster skating speed (Gilenstam 2011; Peyer et al. 2011; Potteiger et al. 2010) and with success in ice hockey (Burr et al 2008). It should be noted that, playing position is not necessarily modifying players physical appearance and capabilities, but rather differences between players in different playing positions could reflect training and conditioning specifically designed to meet the metabolic requirements of each position (Cox et al. 1995; Quinney et al. 2008).

2.3 Ice hockey players physical qualities

As a stop-start sport with repetitive sprinting, contact with opponents and the constant need to react quickly to different match situations, players need to have overall body strength and power. At the same time players need to have a good aerobic capacity to maintain sufficient power production during shifts, recover fast from the high-intensity bursts between the shifts, periods and even matches and trainings. Requirements for fast power production repeatedly and endurance are a tradeoff for ice hockey players. This is reflected in fiber type distribution profile of hockey players and also in the intramuscular glycogen depletion patterns, which is discussed in more detail in chapter 3.2.2. Ice hockey players´ muscle architecture appears to be evenly distributed between slow twitch (ST) (type I) and fast twitch (FT) (type II/IIA) muscle fibers, or slightly predominance of ST fibers, with only very small percentage of fast glycolytic (type IIX) and hybrid fibers. (Green et al. 1978; Green et al. 2010; Montgomery 1988; Åkermark et al. 1996) In contrast, elite basketball players (Ostojic et al. 2006) and soccer players, depending on level of play (elite vs non-elite) (Ostojic 2004), reportedly have slightly predominance of FT fibers. In general, ST fibers have high oxidative and low glycolytic capacity, relatively high resistance to fatigue as well as low activation threshold – in other words, these muscle fibers activated more easily. In contrary, FT fibers have lower oxidative and higher glycolytic capacity than ST fibers, they fatigue more rapidly and have higher activation threshold, being recruited when high levels of force or power are needed. (Herbison et al. 1982)

The strength of lower extremities is needed for skating, acceleration, agility and body checking, while the upper body strength is needed for body checking, shooting and controlling the puck. The speed component of the game comes from the players´ ability to react fast to different situations when on-ice, while the power is necessity for quickly achieving top speed, e.g. for loose puck situations, shooting the puck with greater force etc. (Bežák & Přidal, 2017; Twist &

Rhodes, 1993) In terms of sport specific performance, and specifically on-ice skating speed, players need to have enough lower extremity strength to produce both horizontal and vertical power in acceleration phase of high-intensity skating (Colyer et al. 2018; Kawamori et al. 2013; Renaud et al. 2017). Together with lower extremity strength qualities, well-balanced energy systems with sufficient aerobic capacity (Glaister 2005; Peterson et al. 2016) is a must in order to perform consecutive sprints during each shift.

Players´ power and strength attributes have typically been tested via off-ice tests including standing long jump, vertical jump and 30-second-long maximal intensity cycle ergometer test, a.k.a Wingate-test among other assessments. Typically, defensemen have achieved better results in tests for maximum power production compared to forwards, while similar playing positional differences have not been found in tests measuring the ability to withstand fatigue. (Burr et al. 2008) These lower body assessments are being widely used in team sports predicting individual sprint related attributes like acceleration and velocity (e.g. Farlinger et al. 2007; Henriksson et al. 2016; Mascaro et al. 1992; Peterson et al. 2016; Runner et al. 2016). However, at least in ice hockey, these tests do not seem to correlate with actual match events with multiple repeated high-intensity bouts (= short skating burst) from shift to another and with other match related performances like skating distance, skating velocity and playing time, even though on- and off-ice tests appear to correlate with each other (Korte 2020; Peterson et al. 2016). Bench press, as an upper-body strength and power assessment movement have been shown to correlate in both wrist-shot and slap-shot (Bežák & Přidal 2017), with defenseman performing slightly better on average than forwards (Burr et al. 2008). Bežák and Přidal (2017) highlighted that muscle power may be more important parameter than maximal strength because of higher correlation, concluding that stronger and more powerful players will most likely shoot the puck harder.

Maximal oxygen uptake (VO_{2max}), a.k.a. “aerobic power”, is widely reported and a gold standard measure of aerobic fitness, which according to Poole et al. (2008) “represents the integrated capacity of the pulmonary, cardiovascular and muscle systems to uptake, transport and utilize O_2 (oxygen), respectively”. Peak oxygen uptake (VO_{2peak}) value has also been used to describe maximum aerobic power, because it describes the highest observed value of VO_2 attained during the incremental exercise (Whipp & Ward 1990). It has been suggested that high aerobic fitness level through an enhanced recovery ability and resistance to fatigue is important for ice hockey players to sustain high-intensity, intermittent exercise bouts that occur during training and matches (Montgomery 1988; Montgomery 2006; Quinney et al 2008; Stanula et al. 2014), and especially during the later phases in the actual match situations (Peterson et al. 2015a).

Longitudinal studies from North American professional ice hockey leagues show that the player´s aerobic capacity have remained almost the same through the years of modern ice hockey (55.4 – 57.0 ml/kg/min between the years 2001-2017) (Ferland et al. 2021) or increased slightly (from 54.6 ml/kg/min to 59.2 ml/kg/min between the years 1992 – 2003) (Montgomery 2006). The differences between the studies have been explained by the measurement methods used (on-ice vs. off-ice) as well as the changes in the rules that have made the sport even faster, which however have not been found to affect the relative VO_{2max} results (Ferland et al. 2021). According to Montgomery (2006) the higher value of relative aerobic power may be due to increased body mass. Or the increase of ice hockey players maximal aerobic capacity is a result of increased intensity demands of the game, which occurs in changes of playing time and skating distance per shift, respectively, which will be discussed in more detail in the chapter 3.1.2. Looking at modern ice hockey, there has been less research done on the VO_{2max} of players in European professional leagues compared to ice hockey leagues in North America.

Recently, Ferland et al. (2021) did not find a difference between centers (~ 56 ml/kg/min), wingers (~57 ml/kg/min) and defensemen (~55 ml/kg/min) at the professional level in North America in terms of VO_{2max} when the assessment was performed on-ice with portable metabolic analyzer. Korte (2020) reported in his master´s thesis, that in Liiga forwards had an average of 51.9 (± 3.7) ml/kg/min and defensemen average of 51.0 (± 3.2) ml/kg/min VO_{2max} -value, respectively, when the tests were conducted as indirect incremental cycle ergometer test. Compared to other high-intensity team sports there seem to be no significant differences regarding to athlete´s VO_{2max} -value (Gabbett et al. 2008; Slimani et al. 2019; Ziv & Lidor 2009). Ferland et al. (2021) have concluded that in the modern ice hockey, approximately 56ml/kg/min is the minimal relative VO_{2max} required from the elite players.

It has been stated that aerobic capacity has no direct relation to success in elite level ice hockey (Burr et al. 2008). However, it seems to be universal attribute at the highest level of the sport, but not necessarily the limiting factor like more sport-specific power and speed factors (Ferland et al. 2021), or the effect of efficiency on movement (Alisse et al. 2020). As a conclusion, ice hockey players´ physiology is always more or less a compromise rather than fine-tuned towards one quality. At elite level players need to possess combination of different physiological characters including sufficient aerobic capacity.

3 TRAINING LOAD

Training load, which can be defined as a product of intensity, duration, and frequency, can be categorized as either external or internal load (Halson 2014). Specific to the nature of the exercise, external loads are objective measures of the work done during the exercise (e.g. speed, number of accelerations, distance travelled etc.) measured with suitable method (e.g. speed radar, time-motion analysis a.k.a TMA, global positioning system a.k.a GPS etc.) and assessed independently of internal workload (Bourdon et al. 2017; Douglas & Kennedy 2019; Impellizzeri et al. 2019). For example, in team sports external load can be measured by the total distance athlete has covered during the match with certain speed (e.g. Castellano et al. 2011; Lignell et al. 2018). Internal load, on the other hand, is how body reacts physiologically to a given workload (e.g. elevated heart rate, increased blood lactate, decreased oxygen saturation in muscle tissue) (Bourdon et al. 2017). This chapter discusses the external and internal loads related to ice hockey and team sports in general and seeks to find explanatory factors for the phenomena in the connections between them.

3.1 External load in ice hockey

Skating can be seen as a sport specific external load in ice hockey. It is as fundamental element in ice hockey as running is a part of soccer or rugby, with high-intensity efforts and frequent change of directions. Skating is, above all, a technique-intensive skill in which economy correlates with total fatigue (Lamoureux et al. 2018), and it can be seen as a differentiating factor between ice hockey players regarding to e.g. skating speed (Renaudet al. 2017) and coordination (Mazurek et al. 2020).When analyzing NHL forwards, Bracko et al. (1998) found total of 27 different game related skating characteristics, including cruising, gliding, skating with different speed intensities, skating backwards, struggling for puck or position etc. These skating characteristics can be categorized into different activity intensities from low and moderate skating intensities all the way to the other end of the intensity spectrum including high-intensity skating and sprinting (Brocherie et al. 2018; Douglas & Kennedy 2019; Lignell et al. 2018). When the skating speed increases, the technique of skating also changes: an initial phase of skating with increasing speed (acceleration) the propulsive demand is relatively high and contact time is much shorter (0.31 seconds) compared to steady-state strides gliding motion (0.38 seconds) (Buckeridge et al. 2015; Stidwell et al. 2010).

In ice hockey, TMA and local positioning system (LPS) have been used for monitoring external load (e.g. movement tracking and analysis). In TMA video record analysis, the most common movement types of the sport are being established with defined velocity ranges, after which the match is recorded and analyzed (Cánovas López et al. 2014). Arbitrary velocity thresholds are commonly used with TMA monitoring (e.g. Brocherie et al. 2018). In order to use TMA and select appropriate sport-specific movements, an adequate knowledge of the sport is a must (Dobson & Keogh 2007), which however is criticized by the record accuracy in sports where movements are explosive and short in duration (Nightingale & Douglas 2018, 157-177; cited by Douglas et al. 2019a). LPS is based on similar locating principles as GPS, but in this case the antennas, which captures the movement signal sent by signaling device placed in athletes´ gear, are placed around the sports arena (Rico-González et al. 2020). The advantage of LPS (and GPS) compared to TMA is that these positioning systems enable to collect, analyze, and interpret the data during the match or afterwards, without requirements for specific movement coding (Dobson & Keogh 2007).

3.1.1 Playing duration

The majority of previous studies regarding to ice hockey player´s external load has mainly focused on the results of direct skating metrics (e.g. skating speed, skating distance) obtained from individual matches. Early studies from decades ago have reported the mean playing time being somewhere between 15–28 minutes at professional level (Green et al. 1976; Montgomery 1988). More recent studies have reported lower mean playing time, when Brocherie et al. (2018) reported average of 16.1 (± 3.6) minutes in male national team match, and Lignell et al. (2018) average of 17.3 (± 1.1) minutes for all players in one NHL match.

Montgomery (1988) cited Thoden and Jette´s (1975) observations that ice hockey players averaged 5 to 6 shifts of 70 to 80 second duration per period with 3 to 4 minutes recovery time between shifts. According to latest findings, players mean number of shifts have increased slightly, when Peterson et al. (2015a) have reported average of 6.8 (± 1.1) shifts per period, based on their observations on NHL database statistics, and Brocherie et al. (2018) reporting 7.4 (± 1.8) shifts per period in their study. There is also change of shift duration reported in recent studies with some variation between 40 - 45 seconds (Brocherie et al. 2018; Peterson et al. 2015; Douglas & Kennedy 2019). The lowest effective on ice playing time was reported by

Lignell et al. (2018) with average of 22.3 (± 1.6) seconds for defensemen and 15.2 (± 0.9) seconds for forwards in the NHL (Lignell et al. 2018). Mean recovery time has remained approximately the same over the years, being 4.5 (± 1.6) minutes according to Brocherie et al. (2018).

3.1.2 Skating distance

Similarly, to playing time, players seem to skate less distance per shift, per match and per playing minute than before based on the results in recent studies. Montgomery (1988) reported players skating approximately between 5000 and 7000 meters during a match, while in the modern game average skating distance per match is reportedly around 4500 meters (Lignell et al. 2018; Brocherie et al. 2018). Playing position specifically, Lignell et al. (2018) have reported average of 5445 (± 337) meters for defensemen and 4237 (± 248) meters for forwards in the NHL, whereas Douglas and Kennedy (2019) have reported similarly 4002 (± 768) meters per match for defensemen and 3681 (± 1058) meters for forwards as an average of five U20-tournament matches. According to Douglas and Kennedy (2019) findings, defensemen skate average of 142 (± 80) meters and forwards 161 (± 90) meters per shift. When studying skating distance per time unit, Lignell et al. (2018) have reported that in the NHL forwards skate 283 (± 7) m/min and defensemen little less with 247 (± 8 m/min), whereas Montgomery (1988) have reported an average of 227 m/min for ice hockey players in university level.

Soccer and rugby offer examples and comparability of high-intensity team sports especially in cases where studies from ice hockey are limited or lacking completely. When comparing the distance covered during the match play, for example in top level soccer, players cover over 11 km distance on average (Andrzejewski et al. 2015) when using computerized tracking system for a measurement method. Correspondingly, mean distance covered in professional soccer match across the season was around 10 km when using GPS measurement (Smpokos et al. 2018). In professional rugby matches, players cover between ~ 4200 – 6400 m during a match (Austin et al. 2011) when the tracking was performed by using TMA. When using GPS as a measurement method, it has been discovered that rugby players cover average of ~ 5000 – 5600 m during matches (McLellan et al. 2011). It should be noted that in addition to the used measurement methods, tactics of an individual team as well as the level of competitive league may affect the results. Nevertheless, these results provide some idea of what kind of external loads are being issued when looking at different team sports. As a generalization, it can be said that ice hockey players cover less distance during match play compared to other high-intensity team sports. The reason for this is probably the relatively lower playing time per athlete, shorter overall match time compared to other team sports, as well as smaller size of the field the game is played.

3.1.3 Skating intensity

According to Davis (1985), high-intensity movement can be determined as an activity that cannot be sustained for prolonged periods of time without swift fatigue. From different skating characteristics high-intensity efforts are crucial for player´s success in the sport, as Renaud et al. (2017) have stated, that players with faster starts are more likely to win puck possession, outmaneuver opponents and achieve tactical separation from defensive players. Few recent studies have focused on skating intensity profiles during an elite ice hockey match. Of these studies, Lignell et al. (2018) and Douglas and Kennedy (2019) have made a more in-depth analysis of players´ positional skating differences within the match, while Brocherie et al. (2018) focused more on changes in time-motion patterns of skating and the development of fatigue during the match.

Lignell et al. (2018) reported that players performed on average 113 (± 7) high-intensity bouts in total, corresponding to 7 (± 0) bouts/min and 19 (± 1) sprints during the match with an average distance of 26 (± 1) meters, peak and average skating speeds being respectively 28.6 (± 0.1) km/h and 25.5 (± 0.1) km/h, respectively. In comparison, Douglas and Kennedy (2019) reported mean maximum speed of 26.9 ± 5.0 km/h with mean skating speed being 14.5 ± 3.5 km/h for forwards on even strength, while defensemen had maximum speed of 24.9 ± 5.0 km/h with average skating speed being 12.6 ± 3.2 km/h, respectively. In the highest level in ice hockey, peak skating speeds are significantly higher, up to over 40 km/h (The Hockey News 2017), than mean values reported in the prior studies. Allard et al. (2020) reported in their study that centers and wingers have higher absolute external load (determined as on-ice acceleration movement above threshold of 0.3 m/s^2) and intensity (determined as external load divided by training session duration), whereas the average external load have been shown to be similar between the playing positions.

Lignell et al. (2018) reported, that players at the highest level, cover almost half (~ 45%) of total distance by skating high-intensity speed (> 17 km/h), of which one-fourth is performed by sprinting (> 24 km/h), while Douglas and Kennedy (2019) stated that forwards cover 56% of their in-shift distance at high-intensity speed (> 17 km/h). These findings are supported by much earlier research (Dillman et al. 1984; Montgomery 1998) stating that players spend almost half of their on-ice time in high-intensity activity. In contrast to other studies Bracko et al. (1998) and Jackson et al. (2017) reported that players spend most of their on-ice time by gliding or skating forward with slow or moderate intensity, suggesting that less than 5% of on-ice time is high-intensity movement. However, it should be noted that especially Bracko et al. (1998) observations were restricted to specific playing position (forwards) and to one period (2^{nd} period) of the match. In addition, regarding high- and low-intensity skating, prior studies have used different skating velocity thresholds and measurement methods, which makes comparison between studies challenging. The differences between various measurement methods in prior studies are discussed in more detail in chapter 3.1.5.

When comparing these high-intensity results to professional soccer, it has been reported that soccer players perform around 11 sprints (≥ 24 km/h, duration > 1 seconds) per match, of which 10% were more than 5 seconds long in duration and 90% were shorter than 5 seconds (Andrzejewski, et al. 2013). Mean total distance of single sprint is reportedly around 21 m and mean total sprint distance covered during a match is around 240 m at highest level in soccer (Andrzejewski et al. 2015). Similarly in rugby, players sprint (> 20 km/h) over 10 times per match (forwards ~11 sprints vs backs ~18 sprints, respectively), average duration being around 3 seconds (McLellan et al. 2011).

Douglas and Kennedy (2019) also studied different in-game dynamics (even strength, penalty kill and power play) during ice hockey match, reporting that during 5 vs. 5 match play most of the distance skated was at high-intensity skating (> 17km/h). Defensemen skate higher skating intensities when the team was on a power play and forwards when the team was killing penalty. According to the authors (Douglas & Kennedy 2019), this is due to tactical decisions, because in penalty kill forwards tend to sprint in turnover situations for a scoring chance, and in power play defensemen usually skate with the puck from the other end creating the offensive play and forwards wait them near the offensive area.

Regarding to overall external load in ice hockey, Neeld et al. (2021) reported that the skating intensity during the week before the match had the greatest impact on team performance overall, which was assessed based on differential of shots on goal. When Douglas et al. (2019) studied women´s national ice hockey team performance by measuring overall external load in one season period, they reported that forwards produced higher intensity measures within match when matches were won versus lost. The authors (Douglas et al. 2019) also reported increase of fatigue between periods when defensive players had lower measured overall skating performance and explosive efforts in second period compared to first and third periods, which differ from those of male´s professional ice hockey. According to Lignell et al. (2018), distance covered by sprint skating is lower in the later stages in the match indicating increased fatigue during the ice hockey match. In parallel, Douglas and Kennedy (2019), as well as Brocherie et al. (2018), reported that the skating intensity and distance seem to drop-off across periods so that in the 1st period skating speed is much higher compared to later phases of the match, while at the same time recovery time increased significantly towards the end of the match indicating significant fatigue development or in-game tactical changes. Brocherie et al. (2018) study also shows that the mean duration and frequency of the sprints decrease in the latter periods. When measuring explosive efforts (sum of high-intensity accelerations, decelerations and change of directions) during simulated match, Vigh-Larsen et al. (2020a) reported decrease of efforts by 9% (269 ± 15) and 10% (266 ± 27) during the second and third period compared to first period (296 ± 31) of the match.

What then causes these changes in high-intensity performance? It has been stated that the majority of external load in team sports consists of high-intensity efforts such as accelerations and decelerations imposing in different physiological and mechanical loading demands on players (Vanrenterghem et al. 2017). According to Little and Williams (2005), acceleration is “the rate of change in velocity that allows a player to reach maximum velocity in minimum amount of time”, which is defined as the rate of change in velocity, while deceleration is more of an immediate or gradual stop or the decrease of movement velocity (Hewit et al. 2011). Sprint efforts in team sports are typically short in duration (e.g. 10-20 m, 2-3 seconds) (Spencer et al. 2005), and half of the total work is reportedly done instantaneously at the beginning of the sprint during the acceleration phase (Cavagna et al. 1971). Based on calculations of movement energetics, short sprints done intermittently has 3-7 times larger energy cost than “linear running” (Zamparo et al. 2015) and even low-intensity accelerations have relatively high metabolic load (Buglione & di Prampero 2013). Majority of high-intensity decelerations, on the other hand, have been shown to last less than one second in duration (Bloomfield et al. 2007), but the mechanical load is reportedly much greater than any other match activity – around 37% more than accelerations with similar intensity in soccer (Terje et al. 2016).

These two activity types affect greater energetic cost than maintaining constant speed (Di Prampero 2005). Accelerating is more energy demanding activity with concentric contractions than decelerations (Hader et al. 2016), whereas repeatedly performed decelerations with high eccentric contractions lead to high mechanical load affecting muscle damage (Guilhem et al. 2016). This can be also shown via post-match marker analysis (Gastin et al. 2019). It should be noted though that the requirements for acceleration and decelerations may be different in terms of eneretics and muscle damage in running-based team sports compared to skating-based ice hockey. Post-match biochemical markers in team sports and in ice-hockey is discussed more in depth later in chapter 3.2.

The load of accelerations and decelerations in ice hockey matches have barely been studied at all, but prior research (Brocherie et al. 2018; Lignell et al. 2018; Douglas and Kennedy 2019) refers the decrease of high-intensity and maximal efforts as the match progresses. Harper et al. (2019) reported in their review and meta-analysis of a high-intensity acceleration and deceleration demands in team sports that in all team sports (apart from American football) the frequency of high-intensity decelerations is greater compared to accelerations. When eccentric load (Farup et al. 2016) and muscle damage (Peñailillo et al. (2014) has been found to significantly affect to the rate of force development, the findings of other team sports suggest that these same findings may apply to ice hockey as well. For example, in soccer a reduction of maximal horizontal power production has seen to be reduced due to distance and frequency of running in high speeds (Nagahara et al. 2016). These changes will inevitably lead to reductions of very high-intensity efforts during the match play (Harper et al. 2019).

3.1.4 Changes in external load metrics during in-season

Most of the prior studies regarding to external load in ice hockey have covered 1-5 matches in the middle of the season, except Douglas et al. (2019) with 26 matches of national women´s team and Neeld et al. (2021) with two full seasons of male division I ice hockey. Lignell et al.

(2018) collected their data from an official NHL match in the middle of the season, while Brocherie et al. (2018) examined time-motion patterns during a single international match (no season phase information available), and Douglas and Kennedy (2019) analyzed the data from 5 matches of the IIHF Under-20 tournament, which was also played in the middle of the season. This information is relevant, because players' responses may vary among teams and competitions due to e.g. individual fitness, technical skill and opposition ability (Brocherie et al. 2018), but also at the different stage of the season (Delisle-Houde et al. 2017). Douglas et al. (2019) also pointed out that the tactical situation in individual matches may have a significant effect on the players´ skating metrics if the team is winning, which may lead to more conservative match tactics and thus also affect to external load without real connection to fatigue. Regarding to Douglas et al. (2019) study, there are still significant differences at least in both speed and physicality in female and male ice hockey (Gilenstam et al. 2011), so the direct comparisons between the studies of male and female players may lead to misinterpretations. Even though the studies by Douglas et al (2019) and Neeld et al. (2021) are novel, because they look at the external load in ice hockey matches through the longitudinal perspective, different skating loads were bundled together into a single external load indicator as well as explosive efforts.

Due to the lack of longitudinal ice hockey specific studies in this area of research, it is reasonable to look at other high-intensity team sports and evaluate the resemblance in external load metrics and the changes in them. For example, in elite level soccer, it has been reported that the total distance and high-intensity running distance covered during the match increases towards the end of the competitive season. These positive changes in elite level soccer have been explained by the lower total match load during the latter phases of the competitive season compared to start and middle of the season. (Mohr et al. 2003; Rampini et al. 2007) Similarly, in Australian football (Ritchie et al. 2016) as well as in Gaelic football (Mangan et al. 2019), it has been discovered that players tend to run more distance overall and cover more "high-speed distance" during the latter stages of the season. According to author groups (Mangan et al. 2019; Ritchie et al. 2016), these results reflect the growing importance of competitive matches towards the end of the season, typically with greater focus on match-specific performance and recovery, and less emphasis on sport-specific training outside of the competitions. It is noteworthy that these studies did not mention possible changes in, for example, sprint speed related metrics, as possible negative changes in sprint running may be reflected positively in changes at lower intensity speeds. When studying running load relationship to soft-tissue injuries during rugby season at elite level, Gabbett and Ullah (2012) pointed out, that when the sprint running (> 7 m/s) meters per match decreased around 37% from pre-season (average of 19.5 meters) towards the end of the season (average of 12.2 meters), the total high-intensity running (5-7 m/s) slightly increased (181.7 meters vs. 188.9 meters) by 4%. Similarly to sprint running, all performed acceleration meters (mild accelerations 0.55-1.11 m/s^2; moderate accelerations 1.12-2.78 m/s^2; maximum acceleration ≥ 2.79 m/s^2) and number of repeated high-intensity efforts (3 or more maximal acceleration sprint efforts, sprint efforts, and tackle efforts with, less than 21 seconds between efforts) decreased from pre-season to late-competition phases of the season, respectively (Gabbett & Ullah 2012).

However, the structure of competitive season, as well as the number and frequency of competitive matches may vary significantly between sports. Thus, a direct comparison between different team sports may not be reasonable. Therefore, whole season skating load analysis in more detail is needed and may give broader insight on fatigue development in ice hockey in addition to positional intensity activity differences.

3.1.5 Methodological comparisons of prior studies

The way by which previous ice hockey specific studies have approached the current subject has varied greatly, perhaps because technology has evolved significantly during the recent years, allowing new methods to be used in ice hockey research. For example, the skating speed threshold categories differs between different studies. Lignell et al. (2018) and Douglas and Kennedy (2019) used similar speeds for the thresholds as have been used previously in soccer (very slow 1 – 10.9 km/h, slow 11 – 13.9 km/h, moderate-speed 14 – 16.9 km/h, fast 17 – 20.9 km/h, very fast 21 – 24 km/h, and sprint > 24 km/h) (Mohr et al. 2012; Mohr et al. 2016b). Brocherie et al. (2018) and Jackson et al. (2016; 2017) used similar locomotor categories for different intensity activity determination as Bracko et al. (1998). Bracko et al. (1998) determined the intensity of skating by the amount of forward lean of the player´s upper body, which may give erroneous results due to subjectivity of determination, even though the reliability was tested according to Jackson et al. (2016; 2017) studies. The categories used were based on specific game related locomotion (including sliding and backward skating), and calculations of mean velocities for each category were done by using the skating time that it took for player to travel between pre-established markers (Bracko et al. 1998). Also, Bracko et al. (1998), Jackson et al. (2016; 2017), Brocherie et al. (2018) and Lignell et al. (2018) used TMA as a measurement method, while Douglas and Kennedy (2019), Douglas et al. (2019) and Neeld et al. (2021) used LPS and wearable monitors for the data collection. In the review of the analysis of team-sport athlete´ activity profile, Sweeting et al. (2017) have recommended that velocity thresholds should be determined an equal bandwidth (e.g. 0 – 5, 5 – 10, 15 – 20, 20 – 25, and ≥ 25 km/h), so that the often arbitrary thresholds could be cross examined.

Comparisons between studies are difficult due to the different technologies and the different velocity thresholds used, which means that the studies may not be fully comparable. However, based on previous research, it can be concluded that in modern ice hockey, players skate at high-intensity and play relatively short shifts in order to be able to keep the performance and intensity level as high as possible throughout the match. Nevertheless, during matches, there is a clear decline in performance towards the end of the match. The reason behind the decrease in performance is most likely high-intensity accelerations and decelerations during the match that are more metabolically demanding and affect higher mechanical loading than high-intensity skating in general. In the next chapter, we take a closer look at the physiological mechanisms that ice hockey matches cause to the body, and which may explain the decline in performance in individual matches and possibly throughout the season.

3.2 Internal load in ice hockey

Internal loads are relative physiological (and psychological) stressors that athlete is being imposed to during the exercise (Bourdon et al. 2017). Typically, during the ice hockey match, players do not necessarily wear any internal load measurement devices, but for research purposes different physiological measurements have been tested to assess the acute and chronic effect of internal load of the sport. Whereas the external loads are objective measures of the work performed, the added internal load measurements will help to better understand the biological adaptations of athletes to the given load and the current level of preparedness (Bourdon et al. 2017). This chapter takes a closer look at commonly used internal load measurements in team sports.

3.2.1 Cardiovascular and respiratory load

Heart rate (HR) is one of the most common method for measuring athletes' internal load (Halson 2014). In ice hockey HR response reflects the intermittent nature of the sport. According to Jackson et al. (2017), HR rapidly increases to near maximum levels (average 90 – 96% of HR_{max}, HR_{peak} 96-100% of HR_{max}) during each shift in ice hockey match. HR also decreases to an average of 63-80% of HR_{max} between shifts, and between periods 51-59% of HR_{max} depending on playing position. Vigh-Larsen et al. (2020a) reported that during the simulated match, mean on-ice HR was highest during the 2nd period, while time spent in the highest HR zones (> 90% HR_{max}) was lowest during the 3rd period. These findings support earlier results made e.g. by Green et al. (1976) and Jackson et al. (2016) regarding ice hockey players cardiovascular load during the match, demonstrating an additionally elevated cardiorespiratory loading (Vigh-Larsen et al. 2020b). Even though the highly elevated HR during each shift does indicate high external load, the decrease of HR between the shifts and periods (recovery phase) does not necessarily associate with the actual metabolic recovery through reoxygenation of muscles (Buccheit 2019), which is tightly coupled with PCr recovery (McCully et al. (1994) as was discussed earlier in the chapter 2.1. Instead, HR recovery between intensive exercise bouts is more likely related to metaboreflex and central command activity explaining peripheral nervous system fatigue through the accumulation of metabolites (Buccheit et al. 2011; Buccheit 2019; Rowell & O´Leary 1990). For this reason, HR recovery does not necessarily have a clear physiological rationale in terms of recovery during intermittent activity according to Buccheit (2019). For clarity, metaboreflex is caused by chemically sensitive neurons in contracting muscles by accumulated metabolites controlling the blood flow and blood volume of that muscle (Boushel 2010), while central command can be seen to relate on locomotor and cardiovascular activity originated neural signals from higher brain centers (Williamson et al. 2006).

HR variability (HRV) measurement, which describes beat-to-beat variability of the heart, has been widely used in sports to monitor the status of post-exercise recovery and readiness via the autonomic nervous system (ANS), more specifically post-exercise sympathetic withdrawal and parasympathetic reactivation of cardiovascular system (Stanley et al. 2013). It has been used for training optimization (Dong 2016) as well as preventing and diagnosing overtraining syndrome (Mourot et al. 2004). According to Dong (2016), long-term HRV changes during prolonged period (> 4 weeks) has been shown to be a good indicator of physiological adaptation in athletes. Changes in these cardiovascular autonomic functions seems to track the time course of homeostasis recovery after intense exercise (Hautala et al. 2001). However, the recovery of cardiovascular system and neuromuscular system are not necessarily parallel, as substantial depletion of muscle glycogen stores and excessive neuromuscular fatigue may occur after prolonged exercise. HRV recovery depends highly on the exercise intensity (Seiler et al. 2007), being most rapid after low-intensity exercise (up to 24h) and most prolonged after high-intensity (at least 48h), while exercise duration seems to have no clear relationship with parasympathetic nervous system recovery status. In individuals with better aerobic fitness, HRV seem to recover more rapidly. (Stanley et al. 2013)

There is short of acute HRV response studies in ice hockey players. Cipryan et al. (2007) studied four junior ice hockey players´ ANS activity and its relationship to performance, resulting that, players with highest ANS scores also performed better in sport overall. Contrary to this, those individuals who had the lowest ANS activity had also the lowest performance level, they recovered more slowly from the load, and the ability to cope with the training load was lower than peers (Cipryan et al. 2007). Long term effect of cardiovascular load to performance will be discussed in more detail in chapter 3.3.

3.2.2 Metabolic stress

Glycogen is an essential substrate during high-intensity exercise by providing a mechanism for ATP resynthesis, and depletion of the glycogen is highly correlating with muscle fatigue (Knuiman et al. 2015). It has been reported that during high-intensity intermittent exercise, the first fibers to become depleted of their glycogen stores are FT fibers (Gollnick et al. 1973). When the exercise is prolonged, glycogen stores are being reduced initially from ST fibers followed by FT fibers, and finally fully depleted from FT fibers (Gollnick et al. 1974). Previous studies have shown a decrease of muscle glycogen concentration levels during an ice hockey match (Green et al. 1978) and under simulated match-play (Vigh-Larsen et al. 2020a), showing approximately two thirds of all ST and FT fibers being depleted of muscle glycogen. Green (1978) has also compared prolonged (low-intensity, 55% VO_{2max}) and intermittent (high-intensity, 120% VO_{2max}) skating, reporting 29% decrease of muscle glycogen stores during continuous skating most of glycogen loss from ST fibers, whereas two-fold greater depletion during intermittent skating most of glycogen loss from FT fiber. In general, recovery of muscle glycogen storages after heavy exercise will require around 24 hours, in which post-exercise food intake can be seen to play a significant role (Coyle 1991). However, eccentric muscle contractions, which are very common in team sports like ice hockey due to fast decelerations, have been found to impair the recovery of muscle glycogen storages (Asp et al. 1995), prolonging the actual recovery time by up to several days (Costill et al. 1990).

When investigating ice hockey players dietary regimens and muscle glycogen variations during the matches, Åkermark et al. (1996) reported that the number of shifts tend to increase while muscle glycogen decreases during the 3rd period. Also, players who spent the most time on ice during the last period had lower muscle glycogen concentration after the match. Those players who had higher muscle glycogen concentration after the match were able to maintain their skating speed and ended up to skate faster during the 3rd period in contrast to those who were glycogen depleted. If the muscle glycogen storages were intentionally replenished before the match the skating distance between 1st and 3rd period did not decrease. (Åkermark et al. 1996)

According to Beneke et al. (2011), blood lactate concentration (BLa) levels is seen as a direct measurement for the energy release of glycolytic pathway, whereas it is sensitive to changes in exercise intensity and duration. Vigh-Larsen et al. (2020a) have reported that BLa is correlated to number of explosive efforts per minute during a match. BLa seem to vary significantly during ice hockey match, as Noonan (2010) reported intra-match BLa values ranging between 4.4 mmol/l and 13.7 mmol/l with a mean value of 8.15 mmol/l. It has also been shown that the position in which players are skating at high intensities increases BLa levels. This is because more of a "sitting" position during high-intensity skating, which causes a decrease of arterial blood flow and therefore increased oxygen desaturation in lower limbs affecting accumulation of lactate. (Ferland et al. 2021; Rundell et al. 1997)

According to Vigh-Larsen et al. (2020a), who measured lactate values not only from antecupital vein but also directly from muscle (MLa), reported that BLa increased during the first period (4.7 ± 2.6 mmol/l) compared to baseline (0.8 ± 0.3 mmol/l) and remained elevated throughout the match (4.9 ± 2.7 mmol/l). In contrast, MLa increased more than fivefold during the first period (37.8 ± 20.1 mmol/kg) compared to baseline measurement (6.9 ± 2.7 mmol/kg) but was "only" threefold in the third period (19.6 ± 12.0 mmol/kg) compared to baseline. This may be related to the observation stated by the authors (Vigh-Larsen et al. 2020a) that the number of high-intensity efforts decreased around 10% towards the end of the match, which is therefore also reflected in the change of glycolytic metabolism rate leading also lower lactate production in the muscle. The reason why MLa decreased towards the end of the match and BLa remained elevated is probably due to lactate shuttle mechanism (Brooks 1986), wherein the lactate produced in the cytosol of muscle cells (Spriet et al. 2000) is actively transported from the source to the bloodstream and to other muscles for oxidation, but also for other uses, such as the liver for gluconeogenesis and the brain as a source of energy (Brooks 1986; Brooks et al. 2021; Schulman & Rothman 2001).

3.2.3 Neuromuscular fatigue and muscle stress

By the definition, neuromuscular fatigue is decreased capacity of a muscle or muscle group to generate force/power output (Vøllestad 1997), and it is responsible for acute and prolonged reduction in muscle function caused by especially eccentric muscle action leading to muscle damage (Byrne et al. 2004). Typically muscle damage is measured through increased myocellular protein levels in the blood (Armstrong et al. 1983). Measured creatine kinase (CK) is a common indirect indicator of training intensity and muscle damage caused by an exercise, principally located in muscle areas where ATP consumption is high (Koch 2014). CK also acts as an indicator of training status (e.g. overreaching) (Brancaccio 2007). CK is an enzyme which has a significant role in the energy homeostasis in skeletal muscle metabolism: CK is being used to rephosphorylize ATP by using PCr as a phosphate donor after ATP is being consumed during muscle contraction to form of ADP (adenosine diphosphate). In other words, CK catalyzes reversible reaction acting as a buffer for ATP. (Sahlin & Harris 2011)

Resting plasma CK is reported around 100 U/L (units per litre) in healthy human (Pennington 1981; cited by Jones et al. 1986). Depending on the given exercise, the peak CK response could elevate as high as 25000 U/L in consequence of high eccentric load (Nosaka & Clarkson, 1996), whereas post-match (post-24h) CK levels e.g. in soccer have reportedly varied between ~700-900 U/L (Mohr et al. 2016a) and in rugby reported average value of 1081 U/L (Takarada 2003). Mohr et al. (2016a) also reported that post-match muscle stress response varies if multiple matches have been played in short period of time, such in one week, indicating a compromise of recovery between the matches. Similarly, McLellan et al. (2010) reported that CK levels remained elevated for several days indicating prolonged muscle stress status after rugby matches. The volume of muscle damage has reported to be dependent on the duration and the intensity of exercise, the latter having higher effect (Tiidus & Ianuzzo 1983), but as Takarada (2003) have reported, in addition to high-intensity accelerations and decelerations, physical contacts with opponents during the match also affects the amount of muscle damage observed. Ice hockey being a physical sport, players perform average of 15 body checks per match (Brocherie et al. 2018).

There is a short of reviewed analysis regarding to acute post-match biochemical changes and muscular stress in ice hockey. Halonen (2020) reported in his master´s thesis that in elite level serum CK levels were elevated by 22% immediately after competitive ice hockey match and increased to 39% compared to baseline level 12h after the match. Lignell et al. (2018) reported 1-2 -fold lower post-24h plasma CK levels than observations made in soccer (Mohr et al. 2016a) indicating that the degree of muscle damage after ice hockey match is lower than after a soccer match. The reason for this could be the overall shorter exercise time compared to e.g. soccer, with skating possibly affecting less muscle stress (e.g. elevated CK levels) than running due to lower impact force and eccentric load. However, ice hockey often has fewer recovery days between the matches. (Lignell et al. 2018)

In addition to CK concentrations, countermovement jump (CMJ) has been reported as a useful indirect assessment for the neuromuscular status as an indicator of fatigue (Gathercol et al. 2015). It is an external load measurement and has been seen as cost-effective way to measure athlete´s neuromuscular and recovery status via maximal performance (Taylor et al. 2012). To author´s knowledge, there is a shortage of reviewed analysis including CMJ measurements performed immediately after and/or exact post-match time on ice hockey. Halonen (2020) reported in his master´s thesis, that CMJ height and maximum power in CMJ was decreased 12 hours after match with elite ice hockey players. Whitehead et al. (2019) determined the overall in-season fatigue via jumping assessment, but this will be discussed later in chapter 3.3, which discusses the impact of the season on overall performance in more detail. However, in other team sports, studies including CMJ assessments have been made and results from these may also provide an indication how acute fatigue in ice hockey manifests itself in the post-match neuromuscular function.

In soccer, high-intensity efforts have been found to be tightly related not only with post-match elevated CK levels but also with decreased peak power production measured via CMJ (De Hoyo et al. 2016; Russell et al. 2016; Shearer et al. 2017). All three research groups reported that high-intensity activities are related to post-match fatigue responses for at least the following 24 hours, but no longer after 48 hours. Similar findings have been made for rugby, where peak power output has decreased for 48 hours after the match (Johnston et al. 2014; McLellan et al. 2011). Johnston et al. (2014) also reported that players with greater high-intensity running ability and strength of lower extremities recovered faster from post-match fatigue despite these players had greater internal and external loads during the matches. It should be noted that in Johnston et al. (2014) study the fatigue was assessed only for two competitive matches separated by seven days between them, so a broader interpretation of fatigue would require more matches to be examined.

The recovery time between competitive matches seems to be important. At the professional level, in soccer there are 1-3 matches per week (Oliveira et al. 2019), while in rugby competitive matches are separated 5-10 days between them (Murray et al. 2014), and in ice hockey there are typically 2-3 matches per week (Brocherie et al. 2018). Although such assessments appear to be good indicators of the overall demands of match-play, acute CK levels, in particular, do not appear to have a direct significance between different matches when there is more than two days recovery time between matches (Scott et al. 2016). Doeven et al. (2018) have stated in their systematic review of post-match recovery and biochemical markers in team ball sports, that in terms of performance (e.g. CMJ) players might be physically ready after 48 hours after previous match, but biochemical markers need usually longer time to recover increasing the risk of inadequate recovery in the long run.

Cormack et al. (2012) have reported that in Australian football, fatigue during the match affects the movement of the players so that players run at lower speeds and do less accelerations and decelerations. As the authors (Cormack et al. 2012) concluded, this may be due to a decrease of movement efficiency, which is reflected in sports with repeated sprints as decrement of mechanical parameters (e.g. vertical stiffness of leg spring) eventually leading altered movement strategy and slower running speeds (Girard et al. 2011). Gannon et al. (2021) deduced that in ice hockey, movement behavior due to fatigue, could reduce skating performance through decrements in skating efficiency and capacity of high-intensity efforts.

3.3 Prolonged effect of ice hockey specific load to performance

In the previous chapter it was discussed how much the exercise and match load affects acutely after match as well as few days after on athlete´s performance. This chapter addresses the effect of high frequency of matches and sport specific training on athlete´s physical fitness and an overall performance during a rather long competitive season. Douglas et al. (2019) reported uneven training load for world-class women ice hockey players between ice hockey matches and trainings, trainings being less consumptive than matches. Contradictory, according to Allard et al. (2020), professional male ice hockey players seem to have constant training load and intensity throughout the season, except on the match day morning training, a.k.a "morning skate", which has relatively low training volume than in other training sessions. As an example of weekly volume of training load in elite level, the NHL players in a study by Brocherie et al. (2018) had approximately 3-4 matches, 2-3 recovery sessions, 2-3 on-ice training sessions, and 1-2 off-ice conditioning sessions per week. Similarly, players in European leagues had 1-2 matches, 1-2 recovery sessions, 4-5 on-ice training sessions, and 2-3 off-ice conditioning sessions per week during the in-season period (Brocherie et al. 2018). The aforementioned clearly indicates, that at the top level, the training volumes in addition to actual competitive matches are high and there is not necessarily enough time left for the actual recovery. This is almost inevitably reflected in performance during a long competitive season.

When studying collegiate level ice hockey players, Delisle-Houde et al. (2017) found that players were able to maintain or even improve their pre-season fitness levels during the first half of the season. This was reflected in the decrease of body fat percentage, post-exercise lactate levels and HR during the prolonged exercise. However, from mid- to post-season these parameters increased above pre-season levels indicating detraining during the latter half of the season. (Delisle-Houde et al., 2017) Prokop et al. (2015) reported similar findings regarding to body composition changes during the off- and in-season when studying collegiate ice hockey players fluctuations in body composition measures, reporting leaner body mass during the first half of competitive season. In contrast to Delisle-Houde et al. (2017) study, Prokop et al. (2015) did not report the results from mid-season to end of the same season, but instead, they used results from the end of the previous season as a reference, when the body composition was almost identical to mid-season. The changes in body composition (increase of fat mass) are associated with lower skating speed (Potteiger et al. 2010; Peyer et al. 2011), with Potteiger et al. (2010) stating that excess fat mass affects the amount of total mass moved on ice without contribution to force production affecting skating speed negatively.

When studying collegiate ice hockey player´s performance throughout the hockey season Durocher et al. (2008b) found that skating velocity at lactate threshold (LT) improved from pre-season to mid-season but was not maintained at post-season. LT is seen as a work rate at which blood lactate starts to accumulate (Ivy et al. 1980), but its use as a movement intensity/fatigue marker is somewhat controversial due to current understanding of the role of lactate during muscle contraction and the lack of physiological evidence of such "tipping point" during exercise (Brooks 1985; Brooks 2021; Poole et al. 2021). The authors (Durocher et al. 2008b) also reported the decrease of maximal aerobic capacity towards the end of the season (pre-season 48.7 +/- 0.8ml/kg/min vs. post-season 45.0 +/- 1.1ml/kg/min), whereas no similar decrement of aerobic capacity have been reported by Minkoff (1982) or Daub et al. (1983), results that can be said to be outdated or at least incomparable due to the evolution of the ice hockey as a sport over the years. It should be noted, however, that Durocher et al. (2008b) studied collegiate level ice hockey with clearly lower mean VO_{2max} values than professional hockey players have today and is being recommended to have (Ferland et al. 2021). That being said, besides the decrease of overall fitness level, the reason for the low aerobic capacity values may be due to the fact that with athletes, the maximum aerobic capacity test is usually performed until voluntary exhaustion, like within the incremental protocol the authors (Durocher et al. 2008a) used, in which chronic fatigue state of the neuromuscular system may affect such maximal performance and overall result.

Whitehead et al. (2019) determined the effect of in-season demands via CMJ assessment with collegiate ice hockey players. All the measurements were done on a weekly basis, but no immediate post-match or post-24h measurements were made. The authors (Whitehead et al. 2019) reported a gradual decline of power production over the course of ice hockey season. Gannon et al. (2021) speculated, based on the results of their study involving professional ice hockey players, that observed decrement in countermovement depth towards the end of the competitive season may be associated with modifications in eccentric function of neuromuscular system. This could also be reflected in altered skating strategy through reduced efficiency and acceleration capacity (Gannon et al. 2021). It has been shown that structural qualities of skeletal muscle can be increased by doing eccentric load resistance training (e.g.

Vikne et al. 2006). However, experiments with rodents suggest that high velocity eccentric contractions lead to decreased muscle fiber sizes and muscle mass as well as decrease of force production, supporting the idea of acute fatigue affected by eccentric load especially in team sports with greater amount of high-intensity decelerations compared to accelerations (Harper et al. 2019). To support this, Green et al. (2010) found that the cross-sectional area (CSA) of different muscle fiber types tend to decrease with no effect on muscle capillaries surrounding muscle fibers due to the full season of competitive matches and ice hockey related intensive training at university level (figure 2).

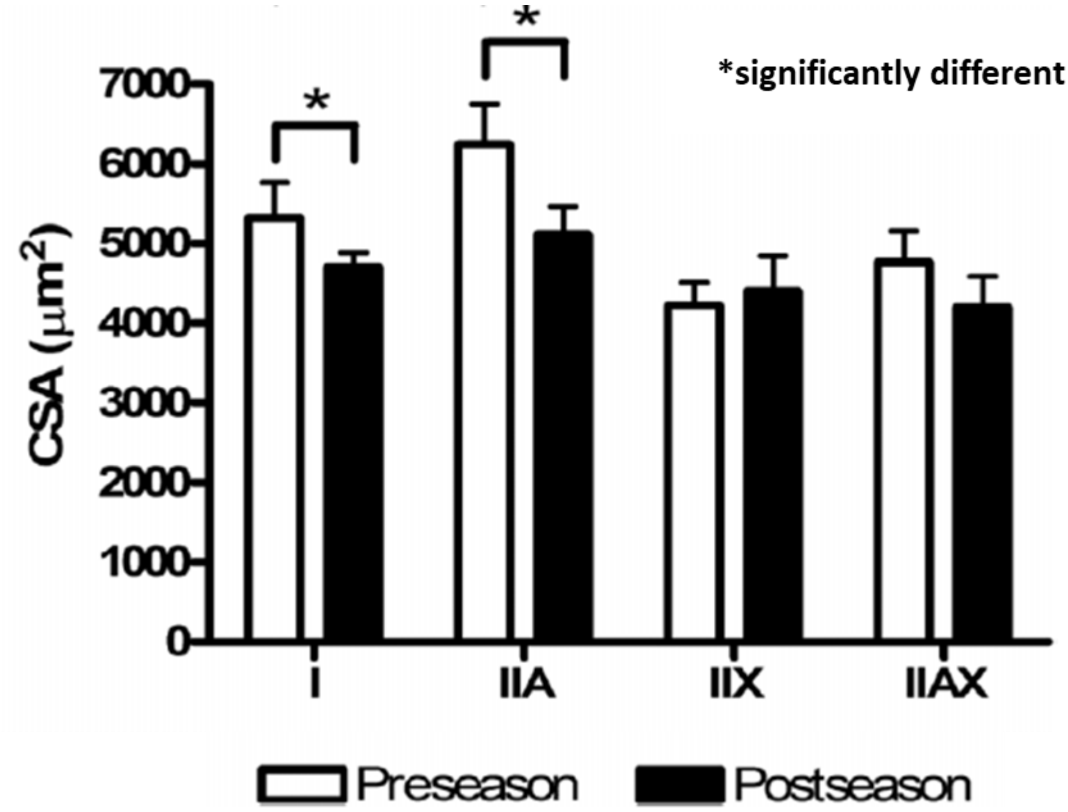


FIGURE 2 The cross-sectional area of muscle fiber-specific types (I, IIA, IIX & IIAX) in vastus lateralis muscle in response to a season of hockey (Green et al. 2010).

According to Laurent et al. (2014) these changes in skeletal muscle architecture could be the reason for the loss of lean body mass with athletes. In terms of performance, there may be a cause-and-effect relationship here as well, because muscle-fat mass ratio is associated with skating performance (Peyer et al. 2011; Potteiger et al. 2010), affecting the force production through which skating speed decreases (Potteiger et al. 2010). In their study, Laurent et al.

(2014) found significantly lower mean power output at the end of the collegiate ice hockey season vs pre-season during the repeated high-intensity exercise while the peak power output stayed consistent. This indicates that players were able to generate high lower-body effort during the initial part of the sprint, but towards the end of the season player´s repeated high-intensity performance level decreased due to impaired recovery ability with increased perceived fatigue (Laurent et al. 2014). As the authors (Laurent et al. 2014) stated, it seems that the high-impact nature of the game may influence negatively on athlete´s power production and capacity to maintain it, as well as the ability to recover between shifts and matches as the season progresses.

When looking at professional soccer, Haugen (2018) found that players improved their single sprint runs and CMJ results from pre-season to off-season with long competitive season between. However, it was not explicitly reported in the study (Haugen 2018) when the tests were carried out during the competitive season which lasted over 6 months. This may distort the interpretation, especially when in soccer the in-season internal load has been shown to be lower than off-season (Jeong et al. 2011). Additionally, in soccer overall load during competitive season is highly dependent on players´ match starting status (starter vs. on the bench) (Anderson et al. 2016), which does not manifest in a similar way in ice hockey due to the unlimited free substitutions during the on-going match. Contrary to Haugen (2018) findings, Malone et al. (2015) reported that average meters covered in professional soccer training session with sprint running (> 5.5 m/s) decreased towards the end of the soccer season around 40% with % HR_{max} increasing ~7% indicating fatigue.

In rugby, it has been reported that aerobic capacity, speed- and power characteristics, as well as body composition improved from pre- to mid-season, leading to reduction of these characters towards the end of the competitive season with non-elite rugby players (Gabbett 2005). This is supported by the findings from elite rugby players as well, when number of sprint runs with performed acceleration efforts was found to decline from pre-season to late-competition phases of the season, respectively, indicating deterioration of maximal efforts during match-play as the season progresses (Gabbett & Ullah 2012). With division I players, the corresponding findings were quite different, when Dubois et al. (2020) reported that no significant changes were observed during the full competitive season in strength and power (CMJ assessment) or aerobic capacity.

There is relatively limited number of studies regarding ANS monitoring and its effect on season-long performance, but studies from elite professional soccer players (Naranjo et al. 2015) and speed skaters (Iizuka et al. 2020) indicate that fatigue status increases over the course of the competitive season based solely on HRV data. However, Flatt et al. (2017) stated that response of parasympathetic HRV is highly individual based on fitness and fatigue status. In professional ice hockey, the constant cumulative effects of weekly load (Allard et al 2021) may cause uneven recovery of ANS and therefore may reflect as overreaching terms of performance along with other factors covered in this chapter.

Green et al. (2010; 2012) suggested that these kind of physiological changes during the season are caused of the extreme demands of the game, which may lead to negative adaptations and even overtraining. This is likely to be reflected in skating variables at different stages of the competitive season, especially at high-intensity skating and at maximal efforts like accelerations and decelerations. There are very few studies on the effect of competitive season on external load in team sports, and none referring to actual change of high-intensity skating, acceleration and deceleration in competitive season in professional ice hockey. Prior studies relating to effect of ice hockey season on internal load have been conducted mainly by studying collegiate or non-professional level ice hockey players, of which season is typically much shorter, there is less travelling stress, and the match and practice intensity is somewhat lower than in professional level (Cox et al. 1995). Therefore, it is assumed that any changes of performance at the top level are more significant.

4 PURPOSE OF THE STUDY, RESEARCH QUESTIONS AND HYPOTHESES

The purpose of this study was to measure skating load in Finnish elite league ice hockey players across the competitive season and evaluate possible changes in different skating variables in different phases of the season by playing positions. Season was divided into four quarters (Q1 – Q4), through which the general variation in players´ skating was examined. The second aim was to study differences between playing positions (centers, wingers, defensemen) through skating load metrics across the season. To author´s knowledge, this is the first longitudinal study to measure ice hockey players´ playing positional skating metrics during the whole competitive season.

The research questions and hypotheses are following:

1. Does the measured skating metrics change towards the end of the season (Q1 vs Q4) and between the different quarters of the season (Q1, Q2, Q3 and Q4)?

H1a: Yes. Number of high-intensity and maximal accelerations and decelerations will decrease from Q1 to Q4.

H1b: Yes. Time spent at sprint speed, and therefore also the relative time and distance skated at sprint speed will decrease towards the end of the season, from Q1 to Q4, due to the decrease of high-intensity and maximal efforts of accelerations and decelerations.

Argument: Prolonged load of high-intensity and sport specific activity throughout the season will affect negatively on players ability to perform constantly in high level across the season. The assumption is that ice hockey does not differ significantly from other team sports regarding the statement that the number of high-intensity decelerations in the game is greater compared to accelerations (Harper et al. 2019). Repeatedly performed decelerations with high eccentric contractions have shown to lead to muscle damage (Guilhem et al. 2016), reflected also via post-match marker analysis (Gastin et al. 2019). Even though studies from individual matches indicate that the internal load from the sport specific exercise in ice hockey does not necessarily last longer than 24h (Halonen 2020; Lignell et al. 2018; Mohr et al. 2016a), the weekly load in ice hockey is so high during the competitive season (Allard et al. 2020), that the effects are likely to accumulate towards the end of the season due to a lack of recovery (McLellan et al. 2010; Mohr et al. 2016a). Prior studies have shown that the season long physiological stress and inability to maintain needed physical qualities due to intense match schedule throughout the competitive season leads to negative changes in players anthropometrics (Delisle-Houde et al. 2017), muscle architecture (Green et al. 2010) and neuromuscular status (Gannon et al. 2021; Whitehead et al. 2019), which affects negatively on players ability to produce power and capacity to maintain it (Laurent et al. 2014). Therefore, it is reasonable to assume that this will have a negative effect on the number of maximum efforts over the prolonged competitive season.

2. Are the measured skating metric changes visible in different playing positions (C, W, D) during the season (Q1-Q4)?

   H2: Yes. Forwards (centers and wingers), who skate more in high-intensity speeds and therefore also perform more maximum efforts (sprints, accelerations and decelerations), will decrease their performance level with these maximal efforts towards the end of the season (Q1 vs Q4), whereas similar decrement to maximum performance is not being detected with defensemen.

Argument: According to Allard et al. (2020) wingers and centers have higher absolute intensity and external load per playing minute than defensemen. Prior research shows that forwards cover 56% of their in-shift distance at high-intensity speed (Douglas & Kennedy 2019) and approximately one-fourth of the total skating distance is performed by sprinting (Lignell et al. 2018). High-intensity and maximum efforts causes fatigue, manifested in a reduced sprint skating duration and distance in later stages in the match (Lignell et al. 2018; Brocherie et al. 2018; Douglas & Kennedy 2019). The fatigue will accumulate as the season progresses while the sport-specific load remains constant, as shown in the hypothesis of the research question 1.

3. Do forwards have different movement requirements when they are grouped according to tactical roles (centers and wingers)?

   H3: No. The movement behavior and locomotion demand of centers and wingers do not differ from each other vastly enough to be considered a significant difference.

Argument: The difference between centers and wingers is not as significant as the difference between forwards and defensemen that this would significantly be reflected in the skating variables of full competitive season (Allard et al. 2020). Regardless of the playing position, forwards have similar aerobic capacity profile according to Ferland et al. (2021). If the roles are being viewed as a generalization assuming that wingers primarily seek the route to offensive end to fight the puck, while center are rather playmakers with devoting defensive responsibilities (NHL 2021), then possible skating-specific differences between forward roles may emerge. Therefore, if any differences occur, they are reflected in the maximum speed, as well as in the number of maximum efforts, such as accelerations and decelerations in favor of the wingers. Nevertheless, the existing literature does not support this kind of generalization.

5 METHODS

The aim of this study was to investigate ice hockey players external load via skating metrics over the course of a single ice hockey season at males´ elite level. The study was based on the data collected from the Finnish national ice hockey league teams. Different skating variables were chosen as the skating load measurements. Data was collected during each match-play via Wisehockey analytics platform which is based on LPS (details in chapter 6.3). This study has been executed by using ethical principles and has been approved by the Ethical Committee of The Central Finland Health Care District (appendix 1).

5.1 Participants

Total of 16 teams participated in the competitive season of 2019-2020 in the Finnish elite ice hockey league. Participation in the study was presented to club management and coaching staff of all 16 teams, and nine teams gave the permission to gathered data from their players. Each player within the team had the right to refuse from participating and, hence, informed written consent was obtained from all participants before participation. There was variation in the numbers of players who took part per team. Those players who had been transferred during the season from “a permission team” to “a non-permission team” were also included in the overall sample, and vice versa. However, in all transfer cases, a player´s personal willingness to participate overwrote a team’s permission. Also, goalkeepers were excluded from the data.

The initial data included skating data from a total of 282 players. Of these players, those who had played at least 50% of the season matches (≥ 30 matches), and at least 4 matches in each quarter (Q1 – Q4) of the 2019-2020 season were selected to the final study. The final data thus included skating data of 146 players (n) (age 17 - 39 years, mean age 25.7 ± 5.1 years).

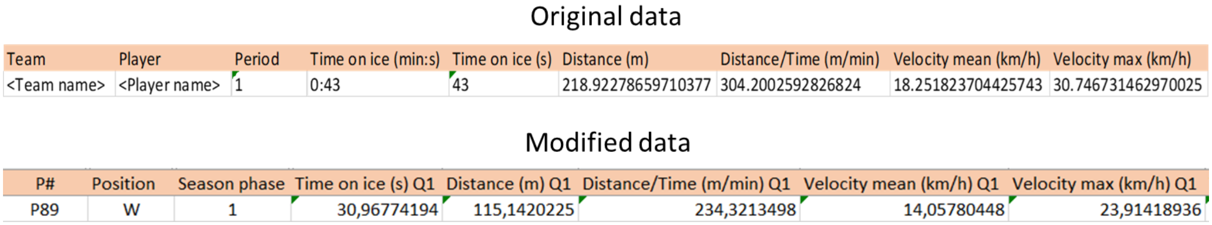
5.2 Study design

In the season 2019-2020 no playoff-series were played in the Liiga due to a Covid19 pandemic. Because of this, only the data of regular season matches (total of 372 matches) was collected and analyzed between 13.9.2019 – 12.3.2020. Each team played total of 60 matches during the regular season. Season was divided into four quarters (Q1-Q4) (table 1) based on the ice hockey national teams Euro Hockey Tour competition schedule (EHT schedule 2019). Comparison analysis was made between matches played in different quarters.

TABLE 1 Season divided into four quarters (Q1-Q4) based on Euro Hockey Tour tournament.

Season quarters	Timeline	Matches included
Q1	13.9.2019 – 2.11.2019	115
Q2	12.11.2019 – 13.12.2019	73
Q3	18.12.2019 – 7.2.2020	105
Q4	12.2.2020 – 12.3.2020	79
Total	13.9.2019 – 12.3.2020	372

Bitwise Corporation (developer of Wisehockey analytics platform) provided the raw data. The results were processed in Excel, where single row contained data for a single shift of a subject (figure 3). First, after receiving the raw data from Bitwise, subjects were pseudonymized by author by replacing the names with a numeric code (P#). Subsequently, playing position information (defenseman = D, center = C, winger = W) as well as season phase (= quarter) information (#) was added to each line. Thereafter, the data from each shift was averaged, and for the total match time and skating distance per match, the data was first summed and then averaged. Figure 3 represents how the original data provided by Bitwise and the author edited data differ from each other.



Original data

Team	Player	Period	Time on ice (min:s)	Time on ice (s)	Distance (m)	Distance/Time (m/min)	Velocity mean (km/h)	Velocity max (km/h)
<Team name>	<Player name>	1	0:43	43	218.92278659710377	304.2002592826824	18.251823704425743	30.746731462970025

Modified data

P#	Position	Season phase	Time on ice (s) Q1	Distance (m) Q1	Distance/Time (m/min) Q1	Velocity mean (km/h) Q1	Velocity max (km/h) Q1
P89	W	1	30,96774194	115,1420225	234,3213498	14,05780448	23,91418936

FIGURE 3 Part of the information of subject´s shift data. Player-specific identification information (team name, player name) was removed from original data row (above) and replaced with pseudonymity identifier (P#). Playing position information (C, W, D) and season phase information (1, 2, 3, 4) was added to modified data.

All the players were divided into three subgroups based on their playing position: centers (n = 27), wingers (n = 70), and defensemen, (n = 49). Playing position information was collected from the official website of Liiga (Liiga 2020b), which publishes match-specific lineups for each league match. Typically, the playing position information is described as lineups, where lines 1, 2 and 3 have one C, two W´s (left wing & right wing) and two D´s (figure 4). If less than 20 skaters are being addressed for a match, the fourth line is usually prescribed as shorthanded, including typically three forward players and one defenseman (figure 4). Since some players´ playing position changed between matches, the playing position was determined according to the position where over 50% of matches were played.

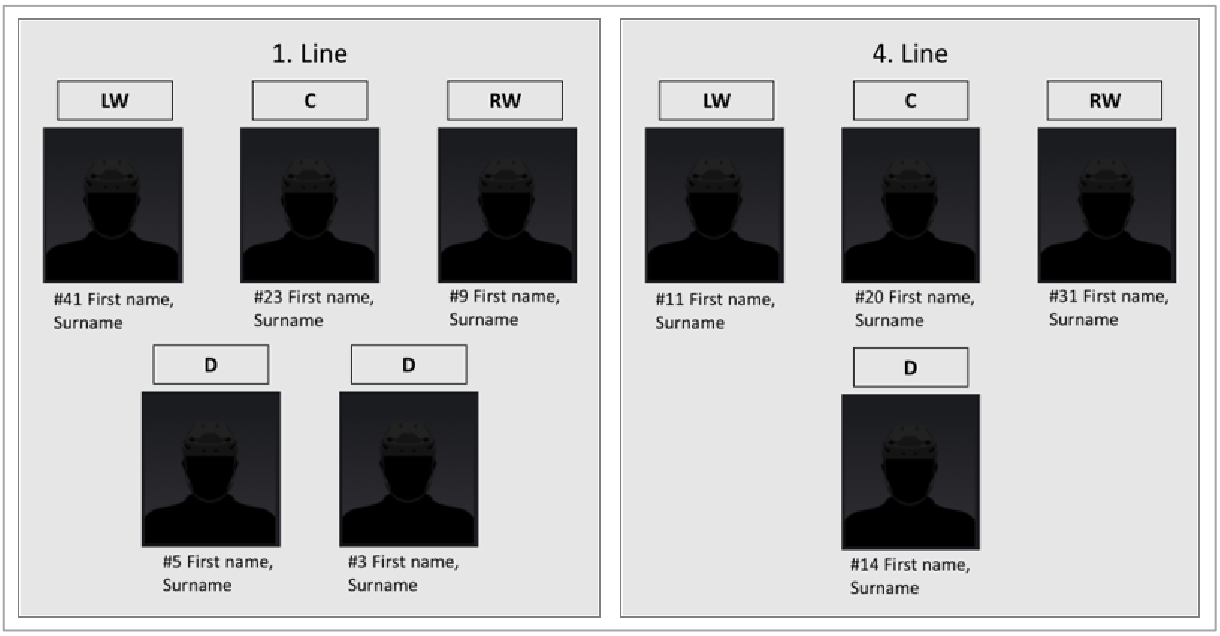


FIGURE 4 Traditional (1. line) and shorthanded (4. line) lineup formations from the Liiga-website.

The skating data was collected via Wisehockey, which is an ice hockey analytics platform (figure 8). The system consists of two main elements: Bluetooth-based (Bluetooth Low Energy, BLE) tracking via LPS and real-time data analytics. Each ice hockey player had their own positioning tag modules (figure 5) attached into player´s jersey enabling real time speed and movement tracking. The hardware was based on the Quuppa Intelligent Locating System^{TM} using location algorithms and Angle-of-Arrival (AoA) angle measurement system (figure 6). The LPS antennas (and the system) were placed on the roof of every Liiga ice hockey arena at the beginning of the 2019-2020 season (Wisehockey 2019). The antennas captured a signal emitted from the player tag and send it to a positioning engine for calculating the player´s tag position. Frequency range used by Quuppa is 2.4 GHz, latency being around 100 milliseconds and the capacity up to 400 location events per second per channel (Quuppa 2021). The Quuppa Intelligent Locating System^{TM} has been validated to be accurate in team sports in research use by Figueira et al. (2018). The raw data used in this study was not directly from Quuppa, but instead filtered through Bitwise algorithms, which have not yet been validated.

FIGURE 5 Bluetooth-based positioning tag modules were installed in the player´s jerseys and weights 6 grams (Wisehockey 2020).

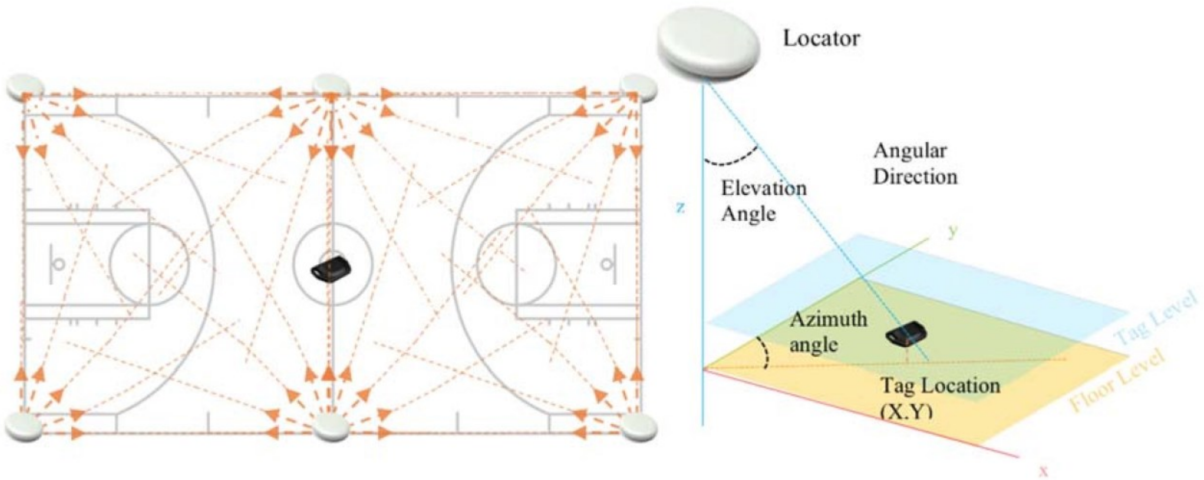


FIGURE 6 Locators (antennas) measure the tag location based on the Angle-of-Arrival signal processing method (Figueira et al. 2018).

5.3 Skating variables

Skating statistics were calculated automatically using the data from the positioning system used. Thresholds for six different velocity ranges were set with equal bandwidth of 5 km/h (table 2) based on the recommendation of Sweeting et al. (2017) and Malone et al. (2017). Different velocity threshold limits and ranges were categorized from a high level into low-intensity skating as well as high-intensity skating, similar to Lignell et al. (2018), and with more specifically into six different categories from very low-speed skating to sprint skating, similar to Lignell et al. (2018) and Douglas and Kennedy (2019). Similarly to velocity thresholds, acceleration and deceleration thresholds were also set to be equal bandwidth, by using commonly used high-intensity acceleration and deceleration threshold of 3 m/s^2 (Harper et al. 2019), with equal bandwidth of 1 m/s^2 from 0 m/s^2 to 3 m/s^2. Four different acceleration and deceleration threshold limits, and four acceleration and deceleration threshold ranges were set (table 3).

TABLE 2 Categories for different skating velocity thresholds used.

Descriptor		**Thresholds (km/h)**	
		Limits	**Ranges**
Low-intensity skating	Very low-speed skating	≥ 0	0 - < 5
	Slow-speed skating	≥ 5	≥ 5 - < 10
	Moderate-speed skating	≥ 10	≥ 10 - < 15
High-intensity skating	High-speed skating	≥ 15	≥ 15 - < 20
	Very high-speed skating	≥ 20	≥ 20 - < 25
	Sprint skating	≥ 25	≥ 25

TABLE 3 Categories for different acceleration and deceleration threshold limits and ranges used.

Descriptor		**Thresholds (m/s^2)**	
		Limits	**Ranges**
Accelerations	Maximal acceleration	≥ 3	≥ 3
	High-intensity acceleration	≥ 2	≥ 2 - < 3
	Intermediate acceleration	≥ 1	≥ 1 - < 2
	Low-intensity acceleration	≥ 0	> 0 - < 1
Decelerations	Low-intensity deceleration	≤ 0	< 0 - < -1
	Intermediate deceleration	≤ -1	≤ -1 - < -2
	High-intensity deceleration	≤ -2	≤ -2 - < -3
	Maximal deceleration	≤ -3	≤ -3

Skating time was measured as time on ice per shift (seconds) and total match time (minutes, seconds), as well as relative time (%) player spent skating in different velocity ranges (0 - < 5, ≥ 5 - < 10, ≥ 10 - < 15, ≥ 15 - < 20, ≥ 20 - < 25, ≥ 25 km/h) per shift. Distance was measured as skated meters per shift and total meters per match, as well as skated meters per time unit (meters per minute). Players skating velocity metrics were measured as maximum velocity per shift (km/h) and mean velocity per shift (km/h). In addition, it was measured how many times players exceeded for at least one (1) second different velocity limits (≥ 0, ≥ 5, ≥ 10, ≥ 15, ≥ 20, ≥ 25 km/h) during a shift, meaning that player needed to skate at least one second over the velocity limit. Also, it was measured how many times players made over 0.5 second accelerations and decelerations per shift with different threshold limits (acc: ≥ 0, ≥ 1, ≥ 2, ≥ 3 m/s^2; dec: ≤ 0, ≤ -1, ≤ -2, ≤ -3 m/s^2), meaning that players needed to maintain the given acceleration / deceleration threshold at least 0.5 seconds for the effort to be recorded. In addition, it was measured without time limit that how many times players skate in different acceleration / deceleration ranges (acc: > 0 - < 1, ≥ 1 - < 2, ≥ 2 - < 3, ≥ 3 m/s^2; dec: < 0 - < -1, ≤ -1 - < -2, ≤ -2 - < -3, ≤ -3 m/s^2) during a shift. This means that, an effort will be recorded every time player skates in one of the threshold ranges regardless of how much time has been spent in threshold range in question. For example, if player accelerated over 3 m/s^2, the player must have accelerated through the lower acceleration threshold ranges, which meant that one effort is marked for each of these acceleration ranges. When the acceleration decreases, e.g.

from ≥ 3 m/s^2 to $\geq 1 - < 2$ m/s^2, one effort will be marked for $\geq 1 - < 2$, $\geq 2 - < 3$ m/s^2 and ≥ 3 m/s^2 threshold ranges, because the movement is still accelerating, although the acceleration is lower than before. Deceleration, to slow or stop the body´s center of mass (Hewit et al. 2011), is also considered in a similar way: in order to make fast deceleration (≤ -3 m/s^2) the deceleration must go through all the lower deceleration ranges, which will count as one effort made per range etc. All the skating variables used in this study are shown in the table 4.

TABLE 4 Skating variables used in this study

Main variable	Variable	Units
Accelerations / decelerations	Accelerations over 0.5 sec threshold limits per shift	quantity
	Decelerations over 0.5 sec threshold limits per shift	quantity
	Accelerations in different threshold ranges per shift	quantity
	Decelerations in different threshold ranges per shift	quantity
Time	Time on ice per shift	s
	Time on ice per match	min:s
	Relative time in different velocity ranges per shift	%
	Time in different velocity ranges per shift	s
Distance	Distance on ice per shift	m
	Distance on ice per match	m
	Distance in different velocity ranges per shift	m
Skating velocities	Maximum velocity per shift	km/h
	Mean skating velocity per shift	km/h
	Number of over 1 sec visits over different velocity limits per shift	quantity

5.4 Statistical analysis

Microsoft Excel 16 (Microsoft Corporation, Redmond, United States) and IBM SPSS Statistics 26 -software (International Business Machines Corp, New York, United States) were used for statistical analysis. Data normality was checked by using a Shapiro-Wilk test for all other groups except wingers, for whom the Kolmogorov-Smirnov test was used because the group size exceeded well over 50 participants. Main effects and possible interactions between season quarters and playing positions were examined by using repeated-measures ANOVA. In case of identified significance, a Bonferroni post-hoc test was used to outline the differences between season quarters or playing positions. The criterion level for statistical significance was set at $p \leq 0.05$. Star symbols are being used in the tables and figures to illustrate the statistical significance ($p < 0.001$ = ***, $p < 0.01$ = **, $p < 0.05$ = *). All results in this study are presented as mean ± standard deviation (SD) in the text and tables.

6 RESULTS

6.1 Accelerations and decelerations

According to repeated measure ANOVA, the number of accelerations lasting more than 0.5 seconds decreased towards the end of the season (figure 7). This happens in every four different acceleration limits measured, respectively (table 5). Post-hoc analysis with Bonferroni correction addressed that at the lowest acceleration threshold (≥ 0 m/s^2) accelerations decreased around 2% from Q1 (10.8 ± 0.8) and from Q2 (10.8 ± 0.8) to Q4 (10.6 ± 0.8) ($p<0.05$) respectively. At the ≥ 1 m/s^2 threshold, accelerations decreased around 3% from Q1 (5.0 ± 0.4) to Q4 (4.8 ± 0.5) ($p<0.001$), similarly around 3% from Q2 (5.0 ± 0.4) to Q4 ($p<0.01$), and 2% from Q3 (4.9 ± 0.4) to Q4 ($p<0.05$). At the ≥ 2 m/s^2, there was significant decrease of accelerations towards the Q4 when post-hoc analysis addressed, that accelerations decreased around 5% from Q1 (1.68 ± 0.27) to Q4 (1.60 ± 0.30) ($p<0.001$), 4% from Q2 (1.66 ± 0.28) to Q4 ($p<0.01$), and 3% from Q3 (1.65 ± 0.27) to Q4 ($p<0.01$). At the highest acceleration threshold (≥ 3 m/s^2), there was 5% decrease of acceleration detected from Q1 (0.42 ± 0.11) to Q4 (0.40 ± 0.14) ($p<0.01$). Changes in two highest threshold limits throughout the season are represented in the figure 7. All the season quarter sphericity values are represented in the table 5. There were no significant differences found within interaction between season quarters and playing position. Only playing positional differences was found via post-hoc pairwise comparisons at the lowest acceleration threshold (> 0 m/s^2) limit when wingers (10.6 ± 0.8) had around 3% lower mean scores compared to defensemen (10.9 ± 0.7) ($p<0.05$) across the season (Table 5). All the playing position sphericity values are represented in the table 5.

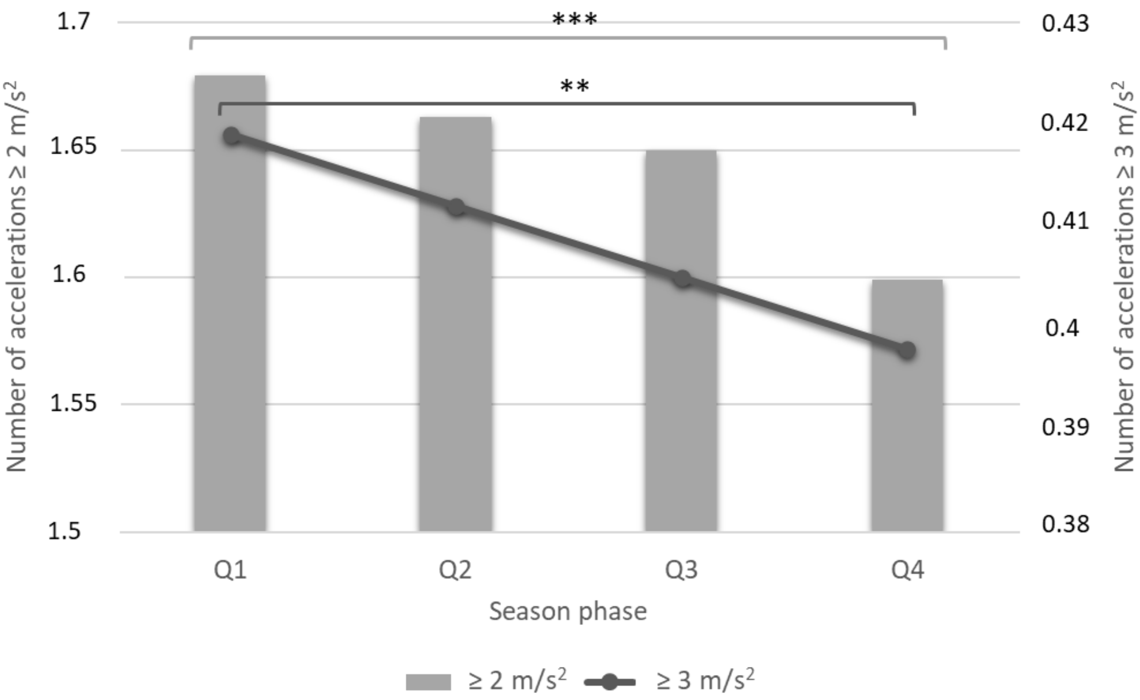


FIGURE 7 Mean number of accelerations over 0.5 sec over different high-intensity threshold limits per shift in different quarters of the season. Bar graphs represents accelerations over threshold ≥ 2 m/s^2. Line graphs represents accelerations over threshold ≥ 3 m/s^2.

TABLE 5 Number of accelerations over 0.5 seconds in different threshold limits per shift in different quarters of the season by playing position.

Threshold (m/s^2)	Playing positions	Q1	Q2	Q3	Q4	F-value^a	Post-hoc^a	QD	F-value^b	Post-hoc^b	PD
≥ 0	Center	10.62 ± 0.88	10.63 ± 0.82	10.46 ± 0.83	10.45 ± 0.83	(2.930, 419.017) = 4.189, p<0.05**	p<0.05*, p<0.05*	Q1 > Q4, Q2 > Q4	(2, 143) = 4.450, p<0.05*	p<0.05*	W < D
	Winger	10.64 ± 0.71	10.74 ± 0.77	10.52 ± 0.85	10.44 ± 0.84						
	Defence	11.02 ± 0.80	10.90 ± 0.72	10.88 ± 0.74	10.86 ± 0.72						
≥ 1	Center	4.96 ± 0.50	4.93 ± 0.44	4.90 ± 0.38	4.80 ± 0.45	(3, 429) = 9.213, p<0.001***	p<0.001***, p<0.01**, p<0.05*	Q1 > Q4, Q2 > Q4, Q3 > Q4	(2, 143) = 0.257, p=0.773	N/D	N/D
	Winger	5.00 ± 0.46	4.98 ± 0.46	4.95 ± 0.46	4.80 ± 0.49						
	Defence	5.02 ± 0.44	4.98 ± 0.44	4.95 ± 0.46	4.91 ± 0.40						
≥ 2	Center	1.66 ± 0.28	1.67 ± 0.25	1.64 ± 0.24	1.60 ± 0.31	(3, 429) = 9.872, p<0.001***	p<0.001***, p<0.01**, p<0.01**	Q1 > Q4, Q2 > Q4, Q3 > Q4	(2, 143) = 0.767, p=0.466	N/D	N/D
	Winger	1.71 ± 0.28	1.69 ± 0.30	1.68 ± 0.29	1.62 ± 0.33						
	Defence	1.65 ± 0.25	1.63 ± 0.25	1.61 ± 0.27	1.57 ± 0.25						
≥ 3	Center	0.42 ± 0.12	0.42 ± 0.13	0.40 ± 0.13	0.39 ± 0.15	(3, 429) = 4.715, p<0.01**	p<0.01**	Q1 > Q4	(2. 143) = 0.771, p=0.464	N/D	N/D
	Winger	0.43 ± 0.14	0.42 ± 0.15	0.42 ± 0.14	0.41 ± 0.15						
	Defence	0.40 ± 0.11	0.39 ± 0.11	0.39 ± 0.12	0.38 ± 0.11						

m/s^2 = acceleration threshold limits. Q1-Q4 = season quarters. Value^a = Statistical significance change within the group on a season quarter basis. Value^b = Statistical significance change between groups. Post-hoc^a / Post-hoc^b = post-hoc test significance. QD = season quarter differences. PD = playing position differences. N/D = no difference found.

Similarly to accelerations, the numbers of performed decelerations lasting more than 0.5 seconds decreased towards the season end at every threshold except at the lowest threshold (< 0 m/s^2) (Table 6). After post-hoc analysis with Bonferroni corrections, it was discovered that at the threshold zone ≤ -1 m/s^2 there was around 3% decrease of decelerations from Q1 (4,97 ± 0.43) to Q4 (4.82 ± 0.43) ($p<0.001$), as well as 3% decrease from Q2 (4.95 ± 0.44) to Q4 ($p<0.01$). At the threshold zone ≤ -2 m/s^2 the decrease of decelerations was around 4% from Q1 (2.31 ± 0.30) to Q4 (2.21 ± 0.31) ($p<0.001$), and around 3% from Q2 (2,28 ± 0.31) to Q4 ($p<0.01$), and 2% from Q3 (2.27 ± 0.29) to Q4 ($p<0.05$). At the highest threshold zone (≤ -3 m/s^2) it was discovered that there was 3% decrease of performed decelerations from Q1 (1.05 ± 0.19) to Q3 (1.01 ± 0.19) ($p<0.05$), around 6% decrease from Q1 to Q4 (0.98 ± 0.20) ($p<0.001$), 4% decrease from Q2 (1.02 ± 0.20) to Q4 ($p<0.01$), as well as 3% decrease from Q3 and Q4 ($p<0.05$). Changes in two highest threshold limits throughout the season are represented in the figure 8. All the season quarter sphericity values are represented in the table 6. There were no significant differences found within interaction between season quarters and playing position. Playing positional difference was detected at the two highest threshold zones (≤ -2 m/s^2 and ≤ -3 m/s^2) (table 6). Post-hoc tests with Bonferroni corrections revealed that defensemen (2.15 ± 0.25) decelerated 8% less compared to centers (2.34 ± 0.27) ($p<0.01$) and 7% less compared to wingers (2.32 ± 0.32) ($p<0.01$) at ≤ -2 m/s^2 threshold. At the ≤ -3 m/s^2 threshold, defensemen (92 ± 0.14) decelerated 15% less than centers (1.07 ± 0.17) ($p<0.01$) overall, and 14% less than wingers (1.06 ± 0.22) ($p<0.001$) throughout the season. All the playing position sphericity values are represented in the table 6.

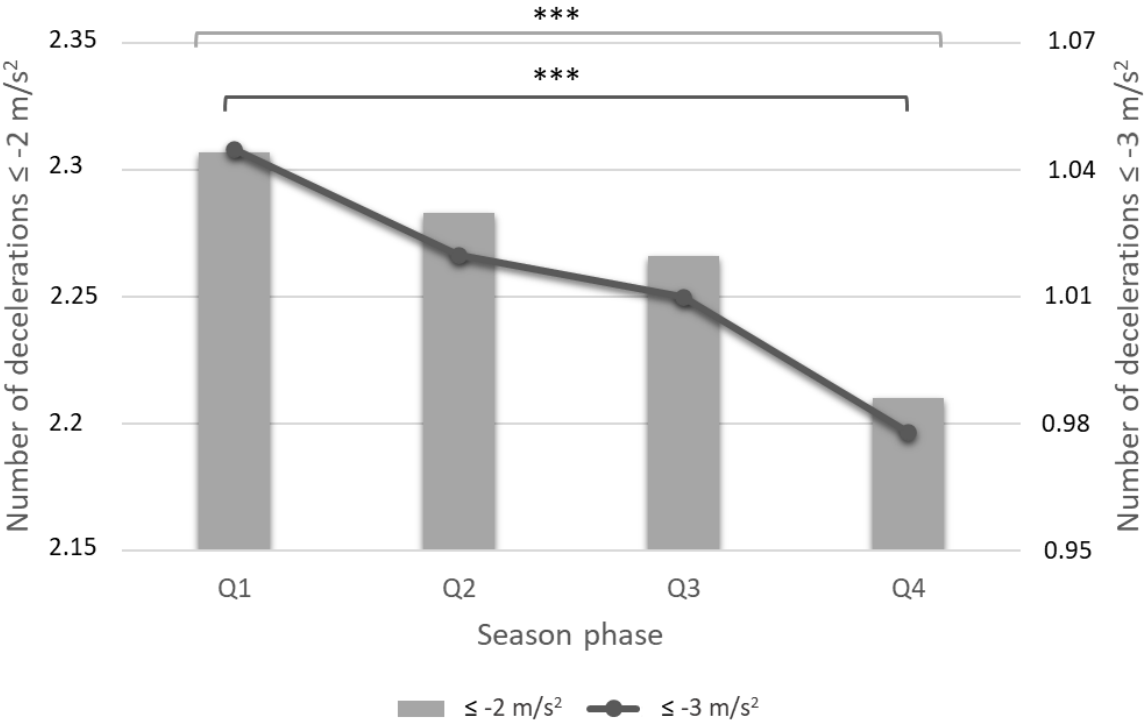
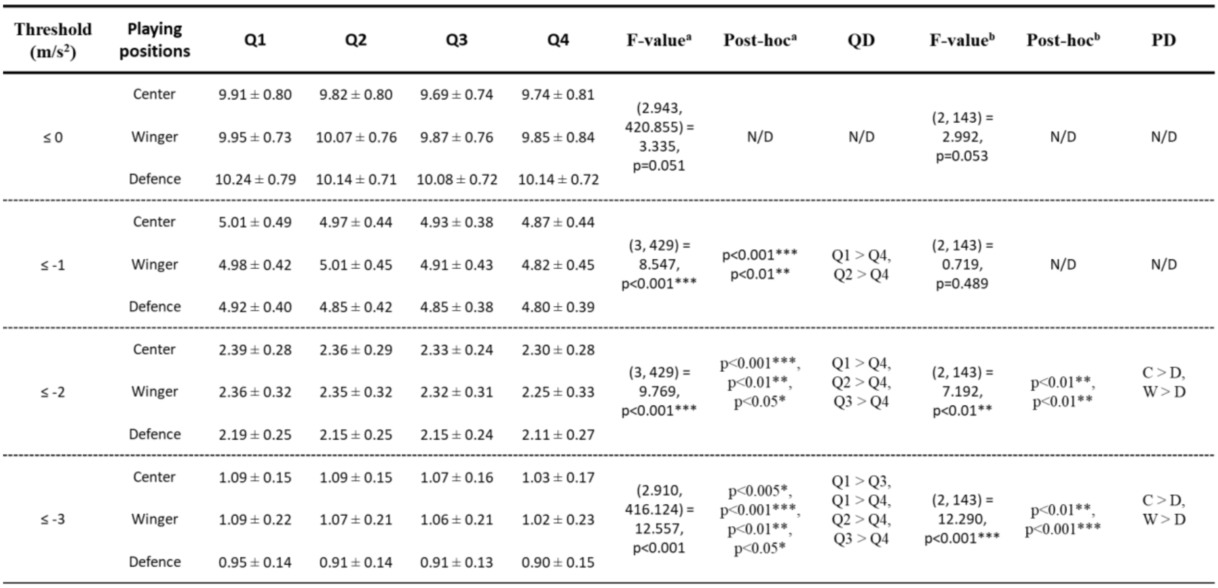


FIGURE 8 Mean number of decelerations over 0.5 sec in different threshold limits per shift in different quarters of the season. Bar graphs represents decelerations over threshold ≤ -2 m/s^2. Line graphs represents decelerations over threshold ≤ -3 m/s^2.

TABLE 6 Number of decelerations over 0.5 seconds over different threshold limits per shift in different quarters of the season by playing position.



Threshold (m/s^2)	Playing positions	Q1	Q2	Q3	Q4	F-value[a]	Post-hoc[a]	QD	F-value[b]	Post-hoc[b]	PD
≤ 0	Center	9.91 ± 0.80	9.82 ± 0.80	9.69 ± 0.74	9.74 ± 0.81	(2.943, 420.855) = 3.335, p=0.051	N/D	N/D	(2, 143) = 2.992, p=0.053	N/D	N/D
	Winger	9.95 ± 0.73	10.07 ± 0.76	9.87 ± 0.76	9.85 ± 0.84						
	Defence	10.24 ± 0.79	10.14 ± 0.71	10.08 ± 0.72	10.14 ± 0.72						
≤ -1	Center	5.01 ± 0.49	4.97 ± 0.44	4.93 ± 0.38	4.87 ± 0.44	(3, 429) = 8.547, p<0.001***	p<0.001*** p<0.01**	Q1 > Q4, Q2 > Q4	(2, 143) = 0.719, p=0.489	N/D	N/D
	Winger	4.98 ± 0.42	5.01 ± 0.45	4.91 ± 0.43	4.82 ± 0.45						
	Defence	4.92 ± 0.40	4.85 ± 0.42	4.85 ± 0.38	4.80 ± 0.39						
≤ -2	Center	2.39 ± 0.28	2.36 ± 0.29	2.33 ± 0.24	2.30 ± 0.28	(3, 429) = 9.769, p<0.001***	p<0.001***, p<0.01**, p<0.05*	Q1 > Q4, Q2 > Q4, Q3 > Q4	(2, 143) = 7.192, p<0.01**	p<0.01**, p<0.01**	C > D, W > D
	Winger	2.36 ± 0.32	2.35 ± 0.32	2.32 ± 0.31	2.25 ± 0.33						
	Defence	2.19 ± 0.25	2.15 ± 0.25	2.15 ± 0.24	2.11 ± 0.27						
≤ -3	Center	1.09 ± 0.15	1.09 ± 0.15	1.07 ± 0.16	1.03 ± 0.17	(2.910, 416.124) = 12.557, p<0.001	p<0.005*, p<0.001***, p<0.01**, p<0.05*	Q1 > Q3, Q1 > Q4, Q2 > Q4, Q3 > Q4	(2, 143) = 12.290, p<0.001***	p<0.01**, p<0.001***	C > D, W > D
	Winger	1.09 ± 0.22	1.07 ± 0.21	1.06 ± 0.21	1.02 ± 0.23						
	Defence	0.95 ± 0.14	0.91 ± 0.14	0.91 ± 0.13	0.90 ± 0.15						

m/s^2 = deceleration threshold limits. Q1-Q4 = season quarters. Value[a] = Statistical significance change within the group on a season quarter basis. Value[b] = Statistical significance change between groups. Post-hoc[a] / Post-hoc[b] = post-hoc test significance. QD = season quarter differences. PD = playing position differences. N/D = no difference found.

Logarithm transformation was done for the data regarding to acceleration and deceleration thresholds skated in different threshold ranges per shift due to data skewness. Here, the statistic values are reported from the transformed data and mean values are reported from the original data. The ANOVA results pointed that, players performed significantly less accelerations (table 7) and decelerations (table 8) per shift in each threshold ranges in Q1 compared to all other quarters of the season, respectively. The increase from the start of the season was somewhat similar between each acceleration and deceleration thresholds, e.g. the higher the threshold, the greater the relative change. For example, at the lowest thresholds (> 0 - < 1, < 0 - < -1 m/s^2) players performed around 3% less both accelerations and decelerations in Q1 (60.3 ± 6.3, 58.7 ± 6.5) than in Q4 (62.2 ± 6.2, 60.8 ± 6.3) ($p<0.001$, $p<0.001$). Similarly, at the second lowest threshold range (≥ 1 - < 2, ≤ -1 - < -2 m/s^2) players performed 4% less accelerations and 5% less decelerations in Q1 (47.3 ± 6.6, 44.3 ± 6.9) than in Q4 (49.2 ± 6.4, 46.7 ± 6.7) ($p<0.001$, $p<0.001$), 6% less accelerations and decelerations at the second highest threshold ranges (≥ 2 - < 3, ≤ -2 - < -3 m/s^2) in Q1 (30.0 ± 6.9, 28.3 ± 6.6) compared to Q4 (31.8 ± 6.9, 30.2 ± 6.7) ($p<0.001$, $p<0.001$), and at the highest thresholds (≥ 3 , ≤ -3 m/s^2) 7% less accelerations and decelerations in Q1 (11.3 ± 3.6, 11.0 ± 3.3) than in Q4 (12.1 ± 3.7, 11.8 ± 3.5) ($p<0.001$, $p<0.001$). Changes in two highest acceleration threshold ranges are represented in the figure 9. Similarly, changes in two highest deceleration threshold ranges are represented in the figure 10. All the season quarter sphericity values are shown in the table 7 and the table 8. There were no significant differences found within interaction between season quarters and playing positions. Also, no statistical significance was found between playing positions.

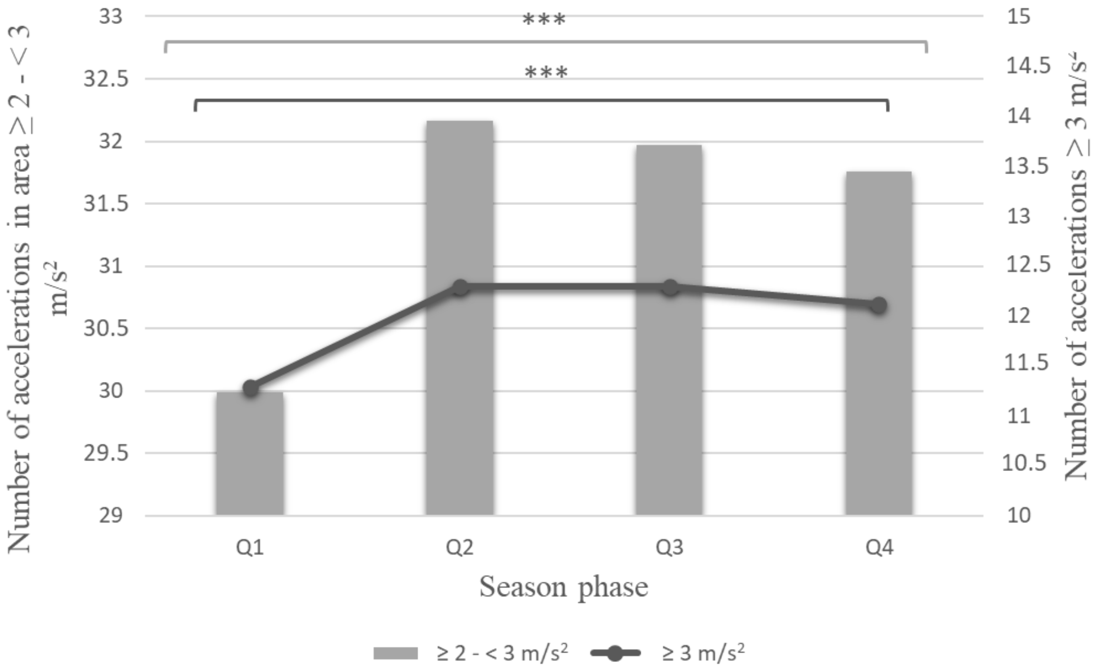


FIGURE 9 Mean number of accelerations in different threshold ranges per shift in different quarters of the season. Bar graphs represents decelerations over threshold range of ≥ 2 - < 3 m/s^2. Line graphs represents accelerations in threshold range of ≥ 3 m/s^2. Significance represented only between quarters Q1 vs Q4.

TABLE 7 Number of accelerations in different threshold ranges per shift in different quarters of the season by playing position.

Threshold (m/s^2)	Playing positions	Q1	Q2	Q3	Q4	F-value^a	Post-hoc^a	QD	F-value^b	Post-hoc^b	PD
> 0 - < 1	Center	59.7 ± 5.9	61.3 ± 6.0	60.9 ± 5.1	61.5 ± 6.0	(2.946, 421.316) = 12.256, p<0.001***	<0.001***, <0.001***, <0.001***	Q1 < Q2, Q1 < Q3, Q1 < Q4	(2, 143) = 2.642, p=0.075	N/D	N/D
	Winger	59.4 ± 5.8	62.3 ± 6.4	61.1 ± 5.8	61.5 ± 6.4						
	Defence	62.0 ± 7.1	63.7 ± 6.7	63.5 ± 6.6	63.7 ± 5.7						
≥ 1 - < 2	Center	47.2 ± 6.5	49.1 ± 6.5	48.9 ± 5.8	48.9 ± 6.1	(2.945, 421.172) = 18.538, p<0.001***	<0.001***, <0.001***, <0.001***	Q1 < Q2, Q1 < Q3, Q1 < Q4	(2, 143) = 1.098, p=0.336	N/D	N/D
	Winger	46.4 ± 6.3	49.4 ± 7.0	48.5 ± 6.3	48.7 ± 6.7						
	Defence	48.5 ± 7.0	50.4 ± 7.0	50.4 ± 6.9	50.2 ± 6.0						
≥ 2 - < 3	Center	30.1 ± 7.2	32.1 ± 7.2	32.1 ± 6.9	31.7 ± 6.9	(2.901, 414.837) = 23.631, p<0.001***	<0.001***, <0.001***, <0.001***	Q1 < Q2, Q1 < Q3, Q1 < Q4	(2, 143) = 0.264, p=0.769	N/D	N/D
	Winger	29.5 ± 6.9	32.1 ± 7.5	31.5 ± 7.0	31.5 ± 7.2						
	Defence	30.6 ± 6.7	32.3 ± 7.0	32.5 ± 7.1	32.1 ± 6.5						
≥ 3	Center	11.4 ± 3.9	12.3 ± 4.0	12.4 ± 4.0	12.2 ± 3.8	(2.880, 411.778) = 23.235, p<0.001***	<0.001***, <0.001***, <0.001***	Q1 < Q2, Q1 < Q3, Q1 < Q4	(2. 143) = 0.101, p=0.904	N/D	N/D
	Winger	11.1 ± 3.7	12.3 ± 4.0	12.2 ± 3.9	12.1 ± 3.8						
	Defence	11.4 ± 3.3	12.3 ± 3.5	12.4 ± 3.7	12.2 ± 3.4						

m/s^2 = acceleration threshold ranges. Q1-Q4 = season quarters. Value^a = Statistical significance change within the group on a season quarter basis. Value^b = Statistical significance change between groups. Post-hoc^a / Post-hoc^b = post-hoc test significance. QD = season quarter differences. PD = playing position differences. N/D = no difference found.

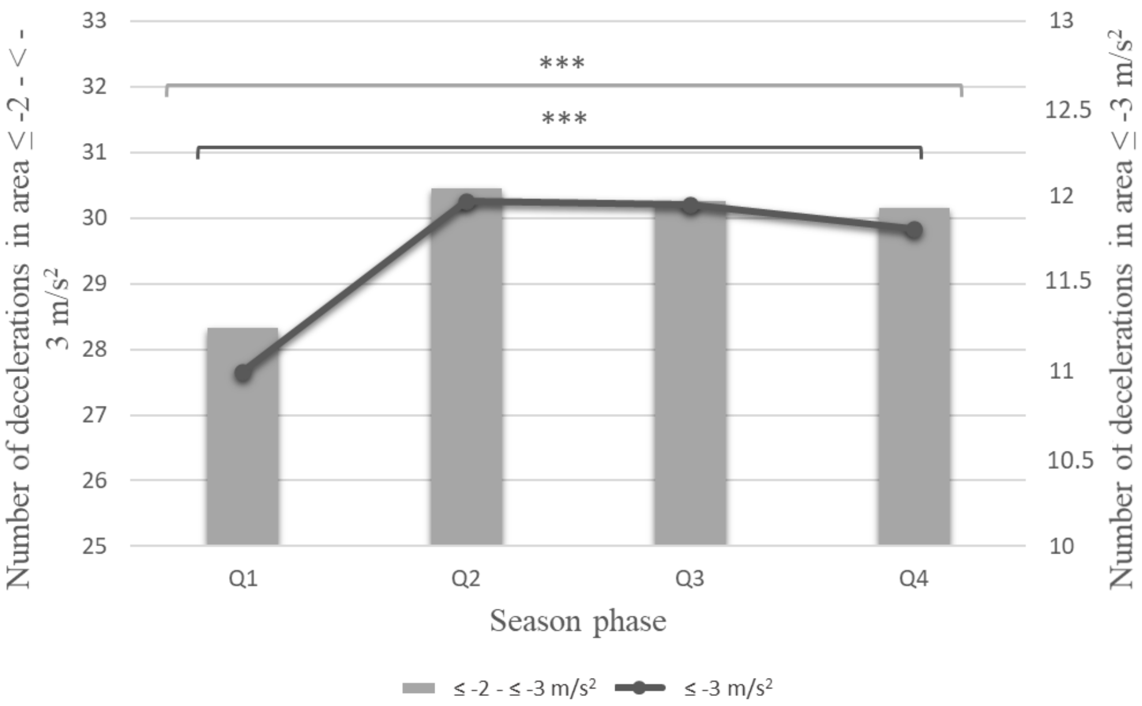


FIGURE 10 Mean number of decelerations in different threshold ranges per shift in different quarters of the season. Bar graphs represents decelerations over threshold range of ≤ -2 - < -3 m/s^2. Line graphs represents decelerations in threshold range of ≤ -3 m/s^2. Significance represented only between quarters Q1 vs Q4.

TABLE 8 Number of decelerations in different threshold ranges per shift in different quarters of the season by playing position.

Threshold (m/s^2)	Playing positions	Q1	Q2	Q3	Q4	F-value^a	Post-hoc^a	QD	F-value^b	Post-hoc^b	PD
< 0 - < -1	Center	58.0 ± 6.1	59.6 ± 6.3	59.4 ± 5.3	60.0 ± 6.1	(2.957, 422.909) = 13.456, p<0.001***	<0.001***, <0.001***, <0.001***	Q1 < Q2, Q1 < Q3, Q1 < Q4	(2, 143) = 2.459, p=0.089	N/D	N/D
	Winger	57.8 ± 5.8	60.8 ± 6.6	59.6 ± 6.0	60.1 ± 6.7						
	Defence	60.5 ± 7.4	62.1 ± 6.9	62.0 ± 6.8	62.2 ± 5.8						
≤ -1 - < -2	Center	44.1 ± 6.8	46.0 ± 7.1	45.8 ± 6.2	46.1 ± 6.6	(2.955, 422.548) = 19.972, p<0.001***	<0.001***, <0.001***, <0.001***	Q1 < Q2, Q1 < Q3, Q1 < Q4	(2, 143) = 0.901, p=0.408	N/D	N/D
	Winger	43.6 ± 6.6	46.5 ± 7.3	45.6 ± 6.7	46.0 ± 7.1						
	Defence	45.5 ± 7.3	47.4 ± 7.4	47.5 ± 7.3	47.4 ± 6.4						
≤ -2 - < -3	Center	28.6 ± 6.9	30.5 ± 7.2	30.4 ± 6.8	30.2 ± 6.9	(2.900, 414.754) = 24.528, p<0.001***	<0.001***, <0.001***, <0.001***	Q1 < Q2, Q1 < Q3, Q1 < Q4	(2, 143) = 0.169, p=0.845	N/D	N/D
	Winger	27.9 ± 6.6	30.4 ± 7.3	29.9 ± 6.6	30.0 ± 6.9						
	Defence	28.8 ± 6.5	30.5 ± 6.9	30.7 ± 7.0	30.4 ± 6.4						
≤ -3	Center	11.2 ± 3.7	12.2 ± 3.7	12.2 ± 3.8	11,9 ± 3.6	(2.870, 410.460) = 24.455, p<0.001***	<0.001***, <0.001***, <0.001***	Q1 < Q2, Q1 < Q3, Q1 < Q4	(2. 143) = 0.067, p=0.935	N/D	N/D
	Winger	10.9 ± 3.4	12.0 ± 3.7	11.9 ± 3.6	11.8 ± 3.6						
	Defence	11.0 ± 3.1	11.8 ± 3.4	12.0 ± 3.5	11.8 ± 3.3						

m/s^2 = deceleration threshold ranges. Q1-Q4 = season quarters. Value^a = Statistical significance change within the group on a season quarter basis. Value^b = Statistical significance change between groups. Post-hoc^a / Post-hoc^b = post-hoc test significance. QD = season quarter differences. PD = playing position differences. N/D = no difference found.

6.2 Time on ice

Centers´ average shift time throughout the season was 32.5 (± 2.5) seconds, while wingers spent average of 32.8 (± 2.4) seconds and defensemen average of 33.5 (± 2.4) seconds on ice per shift. There was no significant difference between playing positions (F(2,143) = 2.342, p=0.100), nor season phase (F(2.906, 415.572) = 1.619, p=0.186) and within interaction between season quarter and playing position (F(5.812, 415.572) = 0.629, p=0.696) when using Huynh-Fledt correction, regarding to playing time per shift during the season (figure 11).

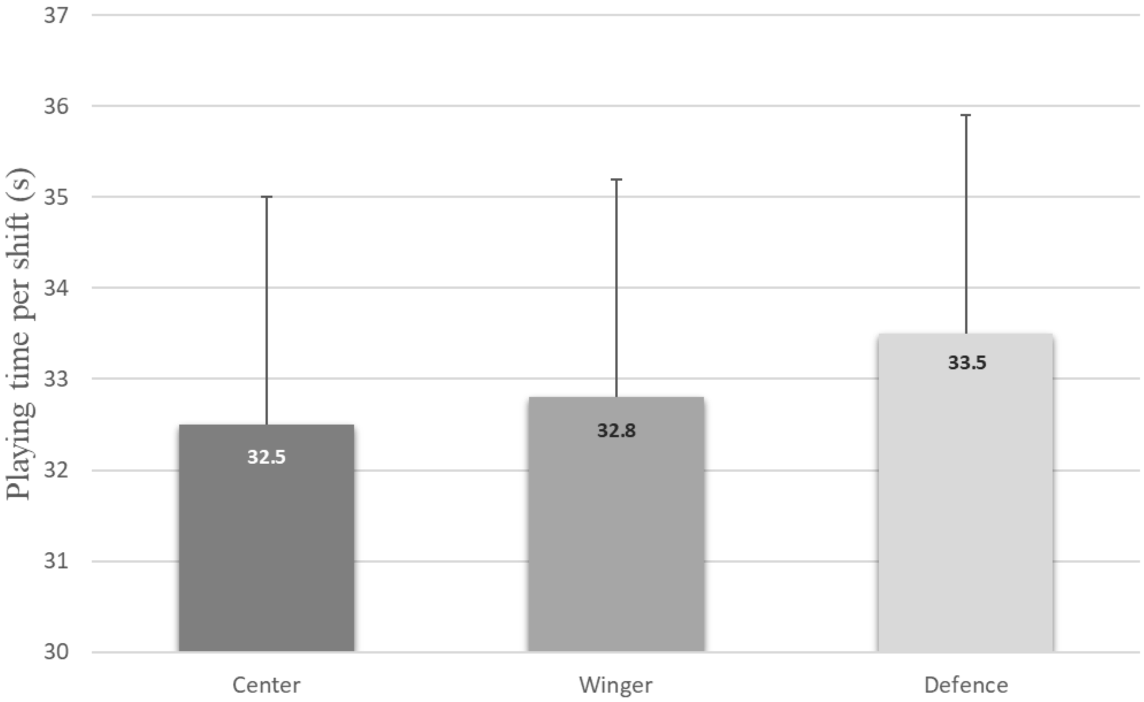


FIGURE 11 Mean playing time (s) per shift across the season by playing position.

Centers´ average playing time per match was 13:02 (± 2:23) minutes, while wingers spent average of 12:19 (± 2:27) minutes and defensemen average of 14:56 (± 2:48) minutes on ice per match. There was no significant difference between different quarters of the season (F(2.808, 401,519) = 1.178, p=0.317) nor within the interaction between season quarters and playing position (F(5.616, 401.519) = 0.957, p=0.450) was found when using Huynh-Feldt correction. However, significant difference was discovered between playing positions (F(2, 143) = 19.174, p<0.001). Post-hoc tests with Bonferroni correction revealed that when the mean playing time per match was investigated, defense players spent approximately 13% more time on ice compared to centers (p<0.01) and 18% more time on ice compared to wingers (p<0.001) (figure 12), with no statistical significance found between centers and wingers (p=0.488).

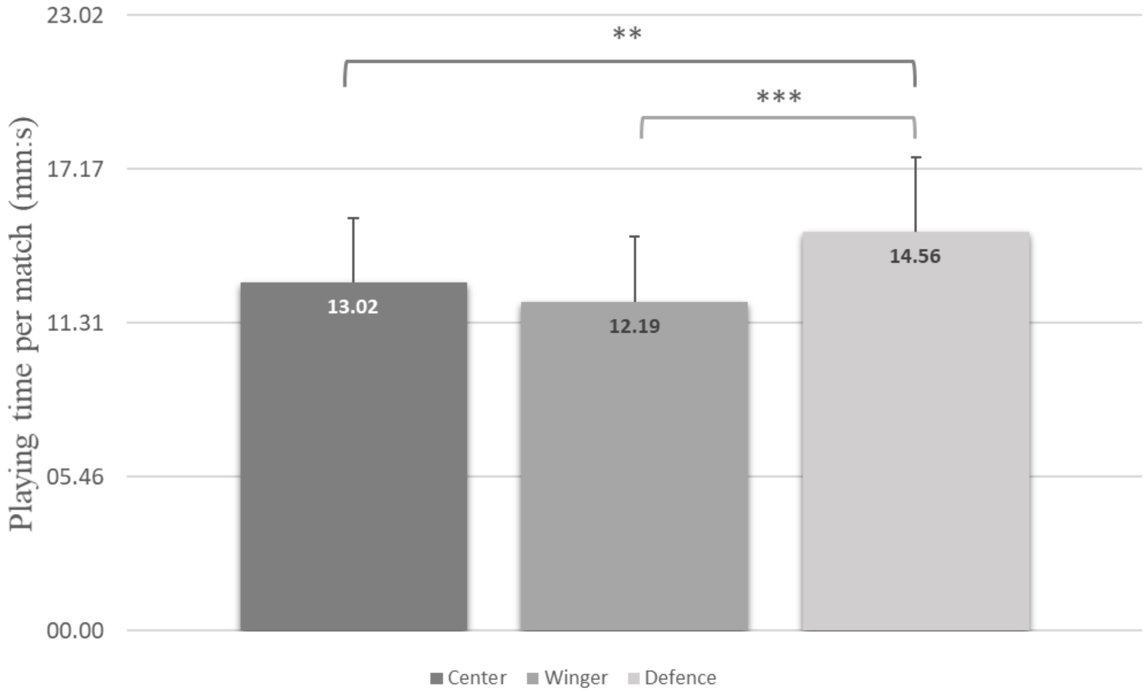


FIGURE 12 Average playing time (mm:s) per match across the season by playing position.

When investigating the relative time spent in different velocity ranges (% total in range of all ranges), no significant difference was found within the interaction between season quarter and playing position in any velocity ranges. Significant difference was found between season quarters Q1 and Q3 when players spent approximately 3% (p<0.05) more time in lowest velocity range (0 - < 5 km/h) in the beginning of the season (11.0 ± 2.0%) than in Q3 (10.7 ± 1.9%). All the sphericity and post-hoc test values are shown in the table 9.

There were significant positional differences found at each of the velocity zones (table 9). Figure 13 represents, that defensemen (11.7 ± 1.9%) spent 18% more time in the velocity range 0 - < 5 km/h than centers (9.7 ± 1.6%) (p<0.001) and 10% more time compared to wingers 10.6 ± 2.0%) (p<0.001). Defensemen (18.2 ± 2.0%) also spent 22% more time compared to centers (14.2 ± 1.9%) (p<0.001) and 16% (p<0.001) more time compared to wingers (15.2 ± 1.8%) in the velocity range of ≥ 5 - < 10 km/h. Defensemen (26.2 ± 1.6%) also spent approximately 26% more time than centers (19.4 ± 1.7%) (p<0.001) and 22% more time compared wingers (20.4 ± 1.8%) (p<0.001) in the velocity range 10 - < 15 km/h, as well as approximately 4% (25.9 ± 2.0%) more time than centers (24.8 ± 1.5%) (p<0.05) and 5% more time compared to wingers (24.6 ± 1.7%) in the velocity range of ≥ 15 - < 20 km/h (p<0.01). Figure 13 represents also that wingers spent more time overall in the low-intensity ranges than centers: approximately 9%

more time in the range of 0 - < 5 km/h (p<0.05), 7% more time in the range of ≥ 5 - < 10 km/h (p<0.05), and also 5% more time in the range of ≥ 10 - < 15 km/h (p<0.01) (table 9)

On the contrary, defensemen (14.0 ± 2.0%) spent 35% less time than centers (21.6 ± 2.3%) in the high-intensity range (≥ 20 - < 25 km/h) (p<0.001) and 62% (4.0 ± 1.2%) less time sprinting (≥ 25 km /h) than centers (10.4 ± 2.8%) (p<0.001) (Figure 14). And similarly, defensemen spent 30% less time in the range of ≥ 20 - < 25 km/h (p<0.001) and 56% less time sprinting (≥ 25 km /h) (p<0.001) compared to wingers (19.9 ± 2.3%, 9.2 ± 2.7%). Centers also spent 8% more time in the very high-intensity range (≥ 20 - < 25 km/h) (p<0.01) and 12% more time with sprinting (≥ 25 km /h) (p<0.05) compared to wingers (figure 14). All the season quarter and playing position sphericity and post-hoc test values are represented in the table 9.

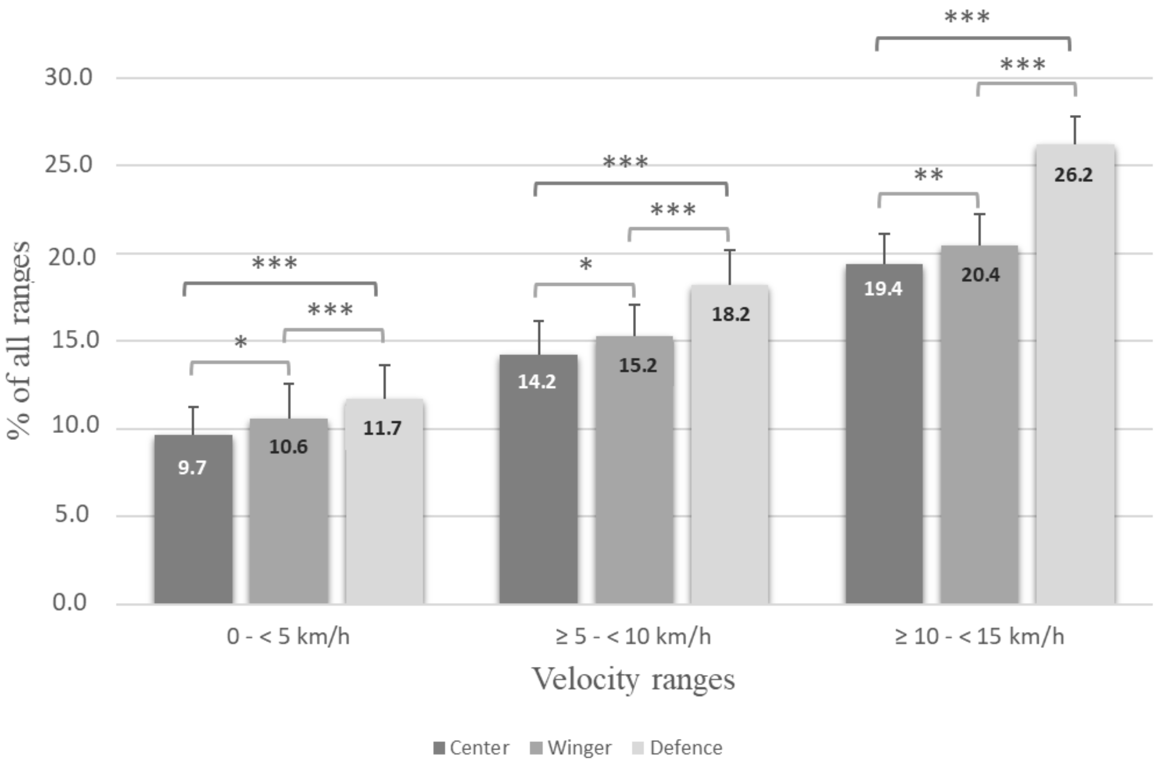


FIGURE 13 Mean relative time (%) skated in different low-intensity velocity ranges of all ranges per shift across the season by playing position.

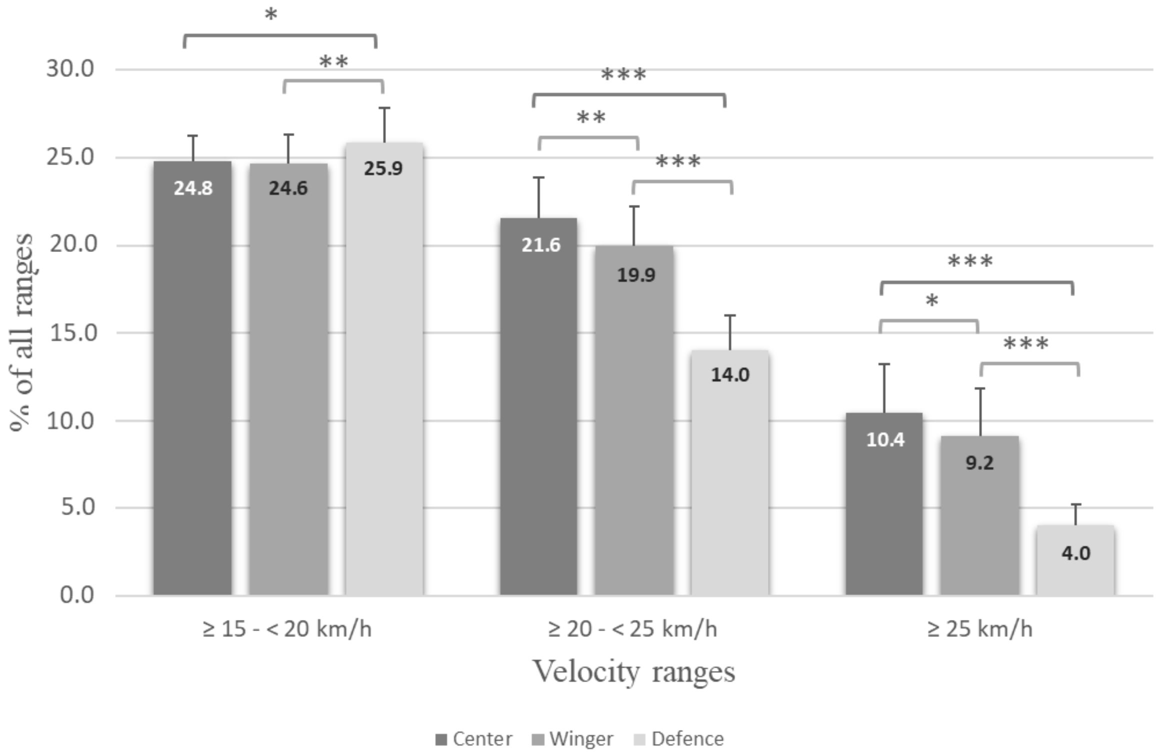


FIGURE 14 Mean relative time (%) skated in different high-intensity velocity ranges of all ranges per shift across the season by playing position.

TABLE 9 Mean relative time (%) skated in different velocity ranges per shift in four season quarters by playing position.

	Km/h	Playing position	Q1	Q2	Q3	Q4	F-value^{a}	Post-hoc^{a}	QD	F-value^{b}	Post-hoc^{b}	GD
Low-intensity skating	0 - < 5	Center	9.9 ± 2.0	9.6 ± 1.8	9.5 ± 1.3	9.6 ± 1.4	F(2.823, 403,623) = 2.798^{H}, p<0.05*	p<0.05	Q1 > Q3	F(2, 143) = 14.092, p<0.001***	p<0.05*, p<0.001***, p<0.001***	C < W, C < D, W < D
		Winger	10.7 ± 2.0	10.6 ± 2.0	10.5 ± 1.9	10.5 ± 2.0						
		Defence	12.0 ± 1.7	11.7 ± 1.8	11.5 ± 1.9	11.7 ± 2.0						
	≥ 5 - < 10	Center	14.4 ± 2.2	14.3 ± 2.0	14.1 ± 1.6	14.1 ± 1.7	F(3, 429) = 0.598, p=0.616	N/D	N/D	(2, 143) = 62.916, p<0.001***	p<0.05*, p<0.001***, p<0.001***	C < W, C < D, W < D
		Winger	15.4 ± 1.7	15.3 ± 1.8	15.2 ± 1.7	15.1 ± 1.8						
		Defence	18.2 ± 2.0	18.0 ± 2.1	18.3 ± 1.9	18.3 ± 2.0						
	≥ 10 - < 15	Center	19.2 ± 1.9	19.4 ± 1.7	19.4 ± 1.7	19.5 ± 1.7	F(3, 429) = 2.495, p<0.05*	N/D	N/D	(2, 143) = 258.530, p<0.001***	p<0.01**, p<0.001***, p<0.001***	C < W, C < D, W < D
		Winger	20.3 ± 1.7	20.6 ± 1.7	20.4 ± 1.7	20.4 ± 1.9						
		Defence	25.8 ± 1.8	26.2 ± 1.5	26.4 ± 1.7	26.3 ± 1.4						
High-intensity skating	≥ 15 - < 20	Center	24.4 ± 1.3	24.7 ± 1.5	24.9 ± 1.4	25.0 ± 1.7	F(3, 429) = 1.444, p=0.229	N/D	N/D	(2, 143) = 9.328, p<0.001***	p<0.05*, p<0.001***	C > D, W < D
		Winger	24.7 ± 1.7	24.7 ± 1.6	24.6 ± 1.7	24.6 ± 1.9						
		Defence	25.7 ± 2.0	25.9 ± 2.0	25.9 ± 2.0	25.9 ± 2.0						
	≥ 20 - < 25	Center	21.6 ± 2.8	21.6 ± 2.4	21.7 ± 2.1	21.3 ± 2.0	F(3, 429) = 1.247, p=0.358	N/D	N/D	(2, 143) = 176.025, p<0.001***	p<0.01**, p<0.001***, p<0.001***	C > W, C > D, W > D
		Winger	19.9 ± 2.3	19.8 ± 2.3	20.1 ± 2.2	20.0 ± 2.2						
		Defence	14.2 ± 1.9	14.1 ± 2.1	14.0 ± 2.1	13.8 ± 1.9						
	≥ 25	Center	10.5 ± 3.0	10.4 ± 3.0	10.3 ± 2.6	10.5 ± 2.8	F(2.928, 418,717) = 0.367^{H}, p=0.747	N/D	N/D	(2, 143) = 107.950, p<0.001***	p<0.05*, p<0.001***, p<0.001***	C > W, C > D, W > D
		Winger	9.0 ± 2.5	9.0 ± 2.5	9.2 ± 2.7	9.4 ± 3.0						
		Defence	4.1 ± 1.2	4.0 ± 1.2	4.0 ± 1.3	3.9 ± 1.3						

Km/h = velocity ranges. Q1-Q4 = season quarters. Value^{a} = Statistical significance change within the group on a season quarter basis. Value^{b} = Statistical significance change between the groups. Post-hoc^{a} / Post-hoc^{b} = post-hoc test significance. QD = season quarter differences. PD = playing position differences. N/D = no difference found.

With time skated in different velocity ranges per shift, it was discovered that players skated approximately 5% less in Q3 (3.8 ± 0.8 sec) than in Q1 (4.0 ± 0.8 sec) in the slowest velocity range of 0 - < 5 km/h (Table 10), and no other significant differences was found between quarters at different velocity ranges. Also, there was no significant interaction found between quarters and playing positions in any of the velocity ranges. When investigating differences between playing positions, it was noticed that in the three lowest skating intensities (0 - < 5 km/h, ≥ 5 - < 10 km/h, ≥ 10 - < 15 km/h) defensemen spent (4.3 ± 0.7 sec, 6.4 ± 0.9 sec, 8.9 ± 0.9 sec) 20%, 23% and 26% more time in seconds compared to centers (3.4 ± 0.7 sec, 4.9 ± 0.8 sec, 6.5 ± 0.8 sec) ($p<0.001$, $p<0.001$, $p<0.001$), and 11%, 17% and 22% more time compared to wingers (3.8 ± 0.8 sec, 5.3 ± 0.7 sec, 6.9 ± 0.9 sec) ($p<0.001$, $p<0.001$, $p<0.001$) (figure 15). According to results, defensemen spent (8,5 ± 0.9 sec) 6% more time in the velocity range of ≥ 15 - < 20 km/h compared to wingers (8.0 ± 1.0 sec) ($p<0.05$). In very high-intensity (≥ 20 - < 25 km/h) and with sprint speed (≥ 25 km/h) speed, centers (6.7 ± 0.9 sec, 3.1 ± 0.8 sec) spent 34% and 60% more time than defensemen (4.4 ± 0.6 sec, 1.2 ± 0.4 sec) ($p<0.001$, $p<0.001$), and similarly wingers (6.3 ± 0.8 sec, 2.7 ± 0.8 sec) spent 29% and 55% more time in the two highest velocity ranges (≥ 20 - < 25 km/h, ≥ 25 km/h) than defensemen ($p<0.001$, $p<0.001$). Also, centers spent 6% more time skating in high-intensity speed and 13% more time sprinting per shift compared to wingers ($p<0.05$, $p<0.05$), respectively (figure 16). All the season quarter and playing position sphericity and post-hoc test values are represented in the table 10.

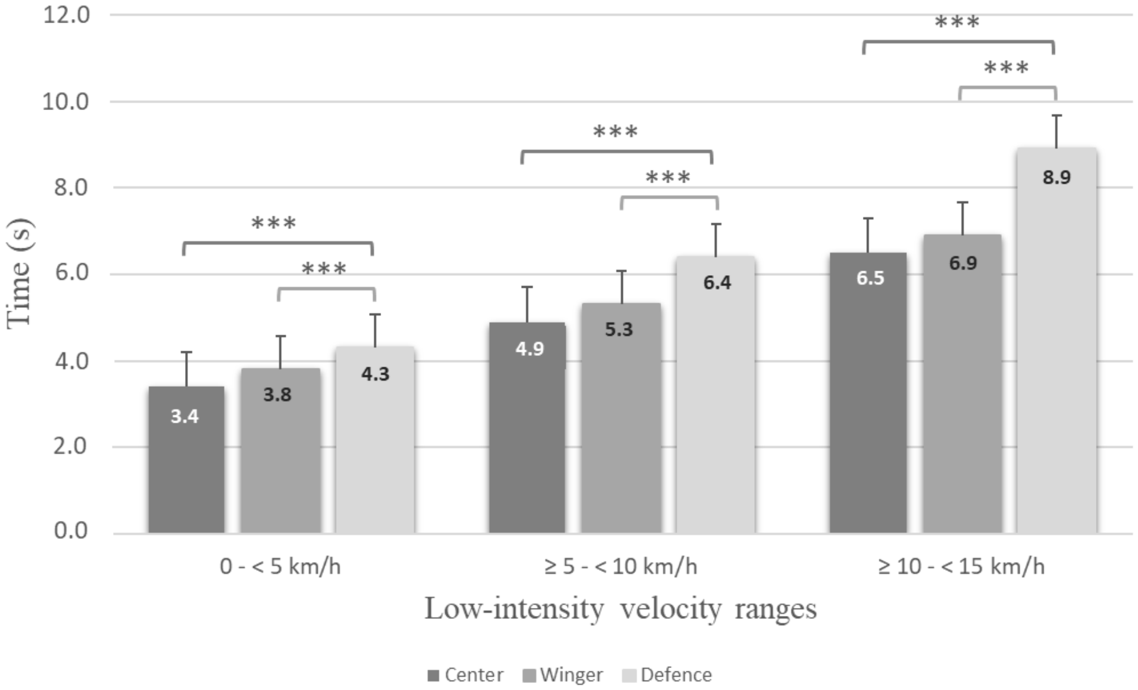


FIGURE 15 Mean total time spent in different low-intensity velocity ranges per shift across the season by playing position.

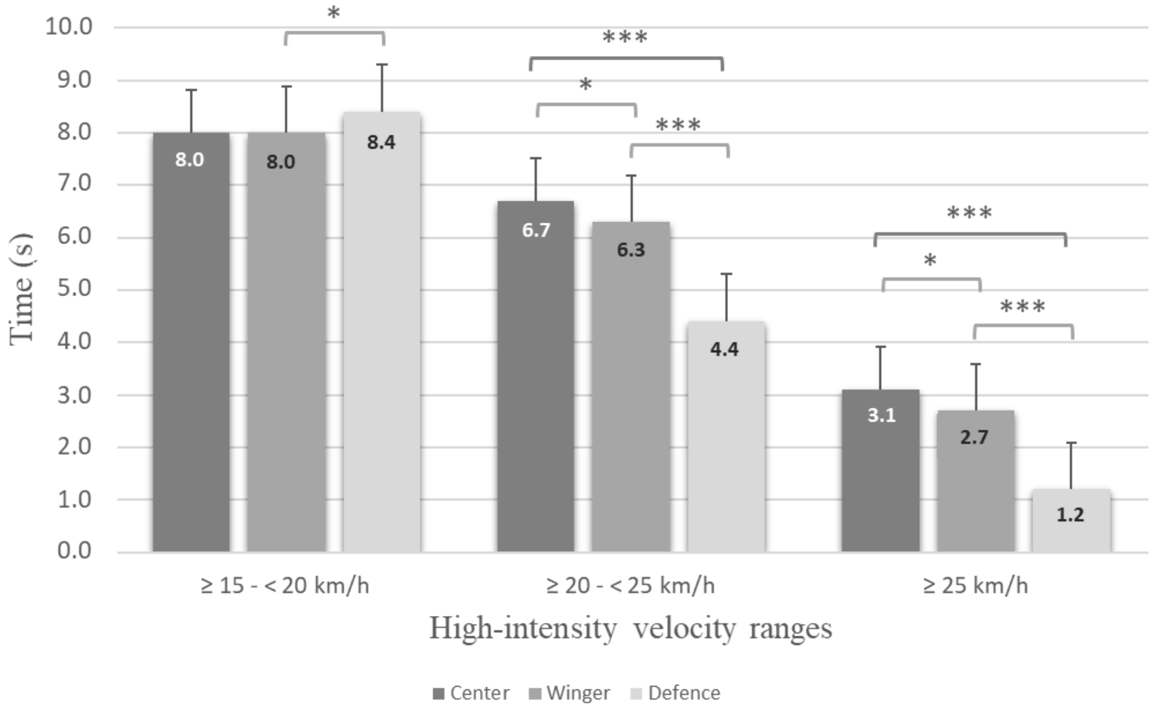


FIGURE 16 Mean total time spent in different high-intensity velocity ranges per shift across the season by playing position.

TABLE 10 Mean time skated in different velocity ranges per shift in four season quarters by playing position.

	Km/h	Playing position	Q1	Q2	Q3	Q4	F-value^a	Post-hoc^a	QD	F-value^b	Post-hoc^b	GD
Low-intensity skating	0 - < 5	Center	3.5 ± 0.8	3.4 ± 0.8	3.3 ± 0.6	3.4 ± 0.6	F(2.765, 66.980) = 5.712^H, p<0.01**	p<0.01**	Q1 > Q3	F(2, 143) = 15.566, p<0.001***	p<0.001***, p<0.001***	C < D, W < D
		Winger	3.8 ± 0.8	3.8 ± 0.8	3.7 ± 0.7	3.7 ± 0.8						
		Defence	4.4 ± 0.7	4.3 ± 0.7	4.1 ± 0.7	4.2 ± 0.8						
	≥ 5 - < 10	Center	5.0 ± 0.9	5.0 ± 0.8	4,8 ± 0.7	4.9 ± 0.8	F(2.863, 409.427) = 2.083^H, p<0.105	N/D	N/D	F(2, 143) = 46.258, p<0.001***	p<0.001***, p<0.001***	C < D, W < D
		Winger	5.4 ± 0.7	5.4 ± 0.7	5.3 ± 0.7	5.3 ± 0.8						
		Defence	6.4 ± 0.9	6.3 ± 0.9	6.4 ± 0.9	6.4 ± 0.9						
	≥ 10 - < 15	Center	6.6 ± 0.8	6.6 ± 0.7	6.4 ± 0.7	6.5 ± 0.9	F(3, 429) = 1.121, p<0.340	N/D	N/D	F(2, 143) = 114.710, p<0.001***	p<0.001***, p<0.001***	C < D, W < D
		Winger	6.9 ± 0.8	7.0 ± 0.8	6.8 ± 0.9	6.9 ± 1.0						
		Defence	8.8 ± 1.0	8.9± 0.8	8.9± 1.0	8.9± 0.9						
High-intensity skating	≥ 15 - < 20	Center	8.0 ± 0.8	8.0 ± 0.7	8.0 ± 0.7	8.0 ± 0.9	F(2.852, 407.879) = 0.500^H, p<0.711	N/D	N/D	F(2, 143) = 4.490, p<0.05*	p<0.05*	W < D
		Winger	8.0 ± 0.8	8.1 ± 1.0	8.0 ± 1.0	8.0 ± 1.1						
		Defence	8.4 ± 0.9	8.5 ± 0.9	8.5 ± 0.9	8.5 ± 0.9						
	≥ 20 - < 25	Center	6.8 ± 1.1	6.8 ± 0.9	6.8 ± 0.8	6.7 ± 0.9	F(2.938, 420.118) = 0.989^H, p<0.397	N/D	N/D	F(2, 143) = 130.367, p<0.001***	p<0.05**, p<0.001***, p<0.001***	C > W, C > D, W > D
		Winger	6.2 ± 0.8	6.3 ± 0.9	6.3 ± 0.8	6.3 ± 0.8						
		Defence	4.5 ± 0.6	4.5 ± 0.7	4.4 ± 0.6	4.4 ± 0.7						
	≥ 25	Center	3.1 ± 0.8	3.1 ± 0.9	3.1 ± 0.7	3.1 ± 0.8	F(2.914, 416.699) = 0.350^H, p<0.783	N/D	N/D	F(2, 143) = 108.820, p<0.001***	p<0.05**, p<0.001***, p<0.001***	C > W, C > D, W > D
		Winger	2.7 ± 0.7	2.7 ± 0.8	2.7 ± 0.8	2.8 ± 0.8						
		Defence	1.3 ± 0.4	1.2 ± 0.3	1.2 ± 0.4	1.2 ± 0.4						

Km/h = velocity ranges. Q1-Q4 = season quarters. Value^a = Statistical significance change within the group on a season quarter basis. Value^b = Statistical significance change between the groups. Post-hoc^a / Post-hoc^b = post-hoc test significance. QD = season quarter differences. PD = playing position differences. N/D = no difference found.

6.3 Skating distance

Centers skated average of 139 (± 12) meters per shift, while wingers skated 136 (± 11) meters and defensemen 125 (± 10) meters when on ice (figure 17). There was no significant difference found between quarters of the season (F(2.920, 417.557) = 2.122, p<0.099), nor interaction between season quarters and playing position (F(5.840, 417.557) = 0.636, p=0.099) when using Huynh-Fledt correction. Though, significant difference between playing positions was found (F(2, 143) = 27.121, p<0.001). After post-hoc tests with Bonferroni corrections the result was that defensemen skated 11% less distance compared to centers (p<0.001) and 8% less compared to wingers (p<0.001) throughout the season, but statistical significance was not found between centers and wingers (p=0.479).

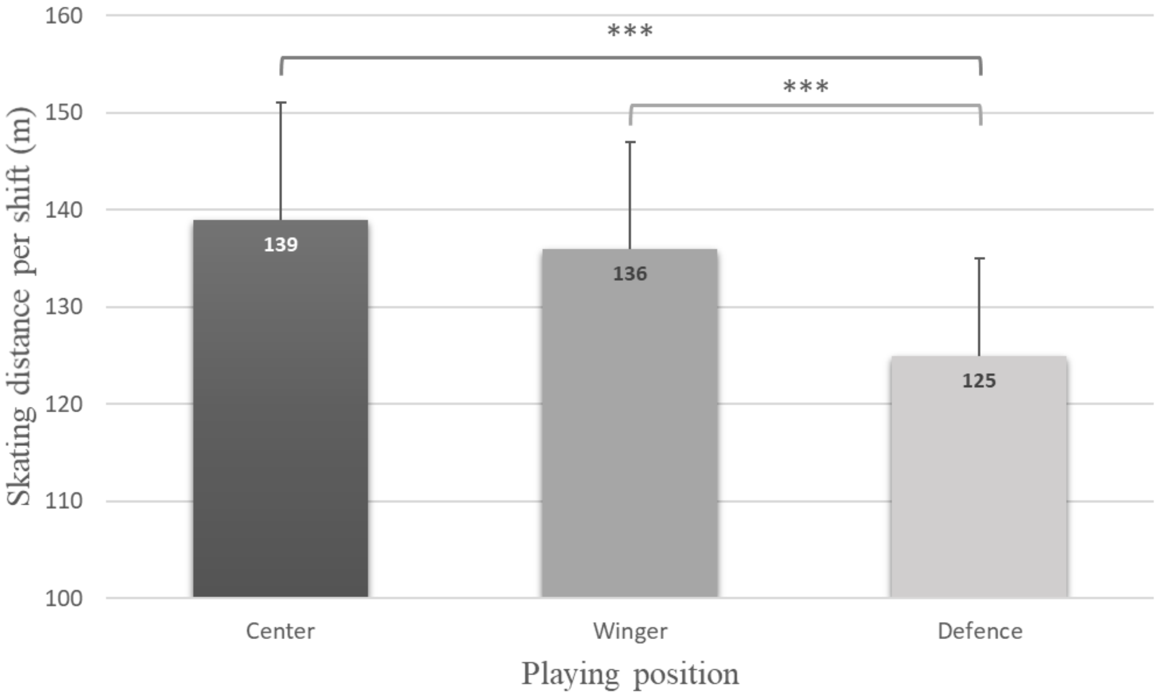


FIGURE 17 Mean skating distance (m) per shift across the season by playing position.

No difference was found for skating distance per match between different season quarters (F(2.806, 401.248) = 1.525, $p<0.210$) nor within the interaction between season quarters and playing positions (F(5.612, 401.248) = 1.058, $p=0.386$) when using Huynh-Feldt correction. However, there was difference found between playing positions (F(2, 143) = 4.656, $p<0.05$). After post-hoc tests with Bonferroni correction it was revealed that wingers (3057 ± 606 m) skated 8% less meters per match than defensemen (3331 ± 621 m) ($p<0.05$). No statistical significance found between centers and wingers ($p=0.62$) or between centers and defensemen ($p=1.0$) (figure 18).

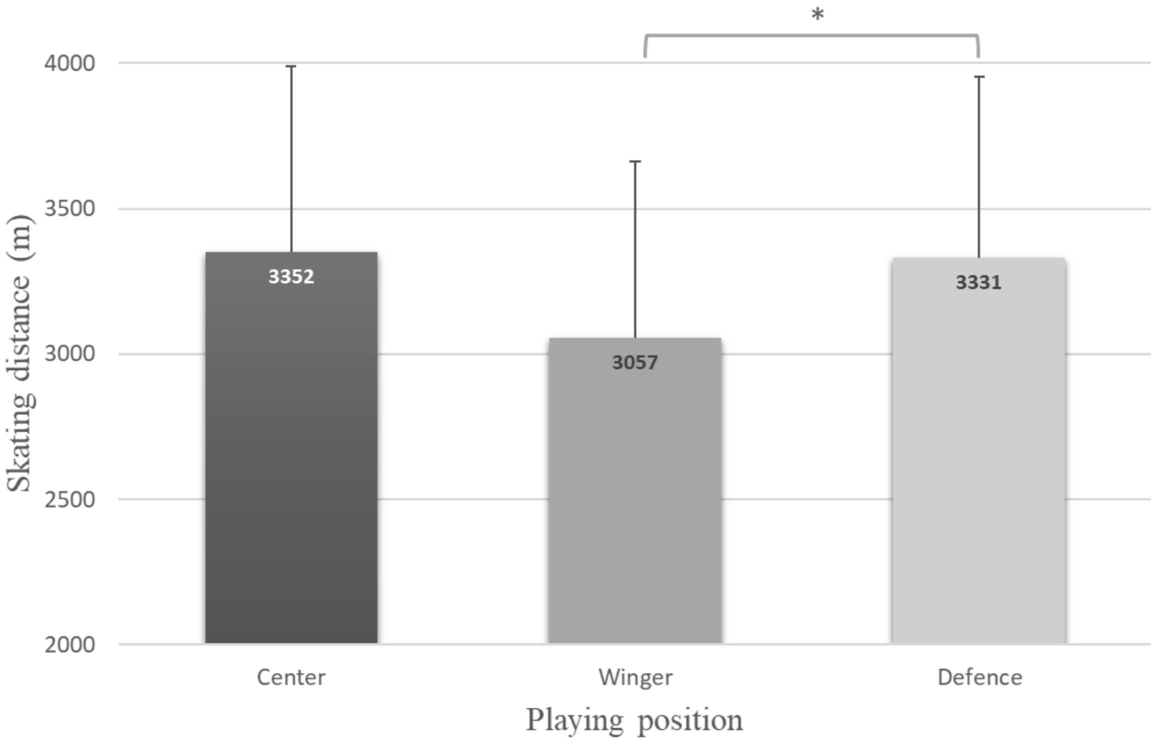


FIGURE 18 Average **s**kating distance (m) per match across the season by playing position.

When exploring distances skated in different velocities during a shift, there was no significant differences between season quarters or within interaction between season quarters and playing position (table 11). However, playing positional differences was found, when defensemen skated significantly more distance per shift with lower velocities while wingers and centers skated more distance in very high speeds (figure 19). At the velocity 0 - < 5 km/h, defensemen (3.7 ± 0.8 m) skated approximately 19% more distance than centers (3.0 ± 0.7 m) and 12% more distance than wingers (3.3 ± 0.7). Defensemen (14.0 ± 2.0) also skated 22% more distance within the velocity range of ≥ 5 - < 10 km/h than centers (10.9 ± 1.7 m) and 17% more distance than wingers (11.7 m ± 1.7). Similarly at the velocity range of ≥ 10 - < 15 km/h, defensemen (31.1 ± 3.2 m) skated 26% more distance than centers (23.1 ± 2.7) and 21% more distance than wingers (24.4 ± 3.2 m) (figure 20).

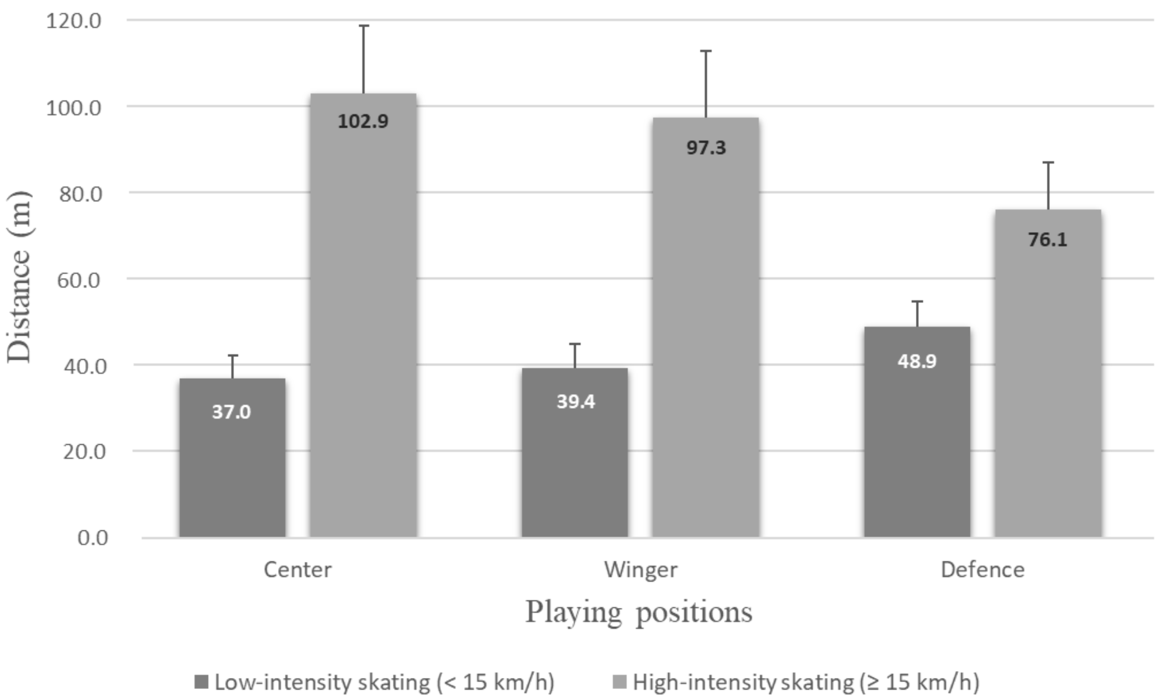


FIGURE 19 Mean total distance (m) skated in low-intensity vs high-intensity skating speed per shift across the season by playing position.

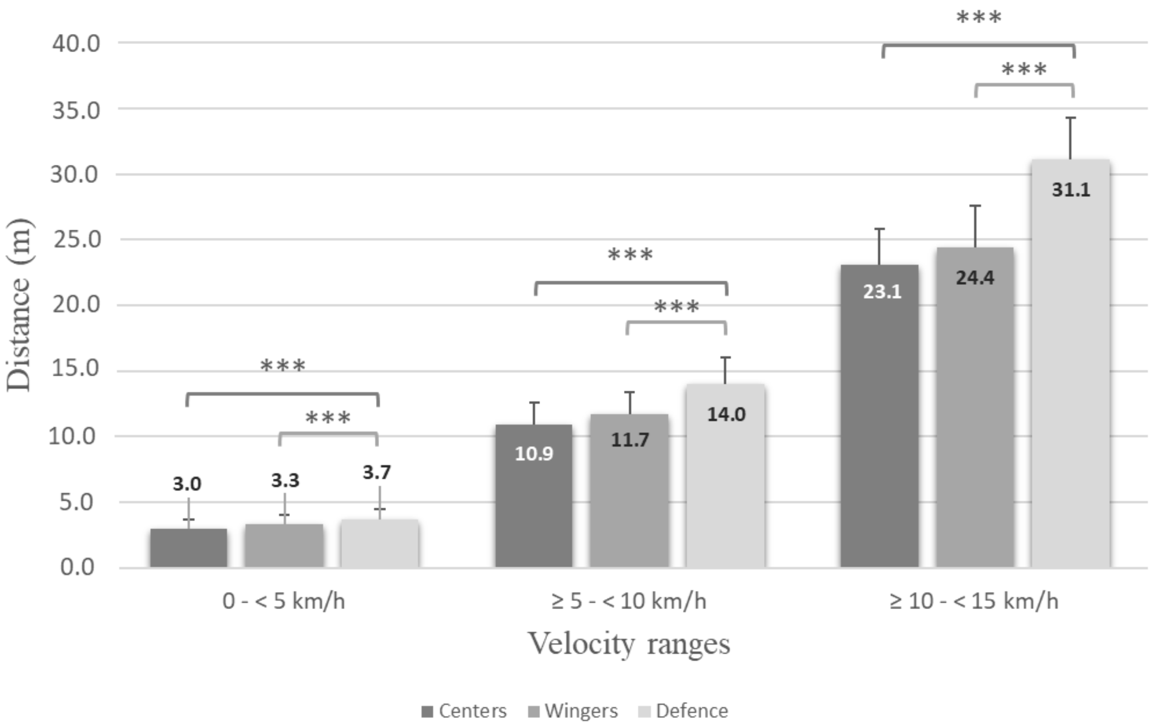


FIGURE 20 Mean total distance skated in different low-intensity velocity ranges per shift across the season by playing position.

On the contrary, in the very high-velocity range (≥ 20 - < 25 km/h), defensemen (26.8 ± 3.9 m) skated 35% less distance than centers (41.1 ± 5.5 m) and 30% less distance than wingers (38.1 ± 4.9 m), whereas centers also skated 7% more distance than wingers. Similarly, centers (23.1 ± 6.4 m) skated approximately 61% more sprint (≥ 25 km/h) distance per shift than defensemen (9.0 ± 2.8 m) while wingers (20.4 ± 5.9 m) also skated 56% more distance by sprinting than defensemen when on ice (figure 21). All the season quarter and playing position sphericity and post-hoc test values are represented in the table 11.

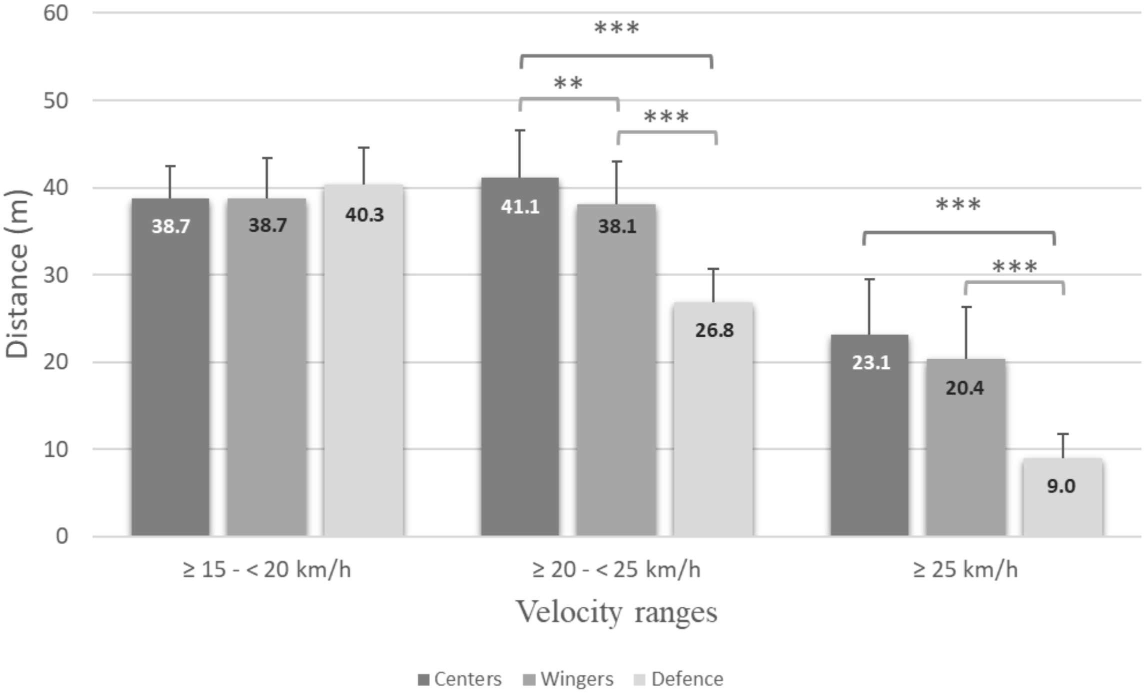
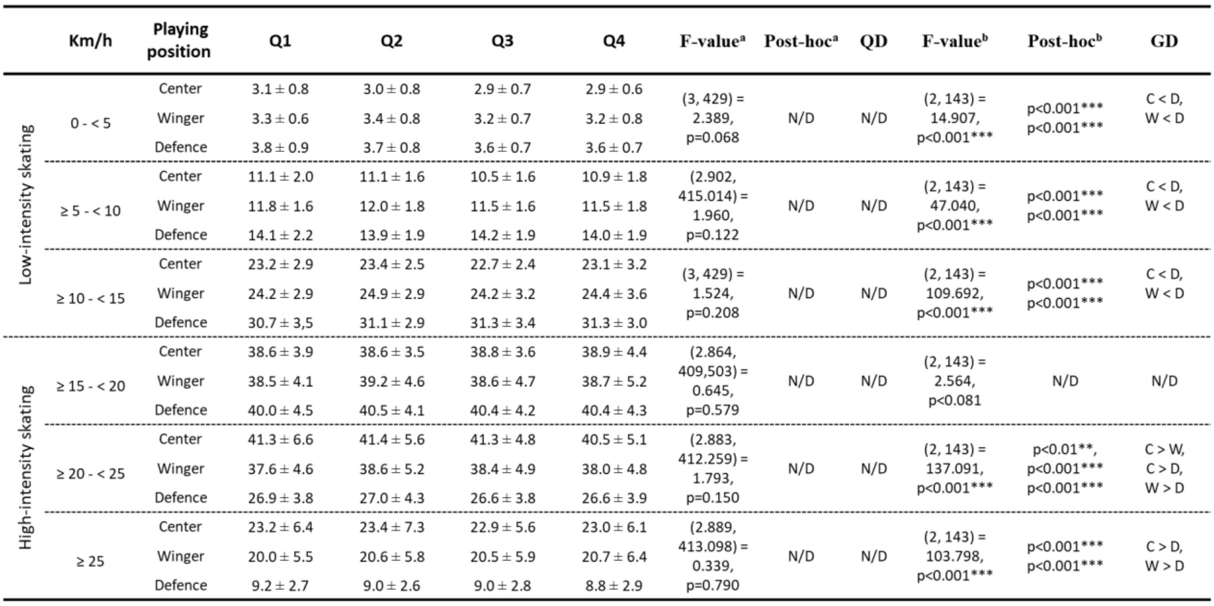


FIGURE 21 Mean total distance skated in different high-intensity velocity ranges per shift across the season by playing position.

TABLE 11 Total distance skated in different velocity ranges per shift shift across the season by playing position.



	Km/h	Playing position	Q1	Q2	Q3	Q4	F-value^a	Post-hoc^a	QD	F-value^b	Post-hoc^b	GD
Low-intensity skating	0 - < 5	Center	3.1 ± 0.8	3.0 ± 0.8	2.9 ± 0.7	2.9 ± 0.6	(3, 429) = 2.389, p=0.068	N/D	N/D	(2, 143) = 14.907, p<0.001***	p<0.001*** p<0.001***	C < D, W < D
		Winger	3.3 ± 0.6	3.4 ± 0.8	3.2 ± 0.7	3.2 ± 0.8						
		Defence	3.8 ± 0.9	3.7 ± 0.8	3.6 ± 0.7	3.6 ± 0.7						
	≥ 5 - < 10	Center	11.1 ± 2.0	11.1 ± 1.6	10.5 ± 1.6	10.9 ± 1.8	(2.902, 415.014) = 1.960, p=0.122	N/D	N/D	(2, 143) = 47.040, p<0.001***	p<0.001*** p<0.001***	C < D, W < D
		Winger	11.8 ± 1.6	12.0 ± 1.8	11.5 ± 1.6	11.5 ± 1.8						
		Defence	14.1 ± 2.2	13.9 ± 1.9	14.2 ± 1.9	14.0 ± 1.9						
	≥ 10 - < 15	Center	23.2 ± 2.9	23.4 ± 2.5	22.7 ± 2.4	23.1 ± 3.2	(3, 429) = 1.524, p=0.208	N/D	N/D	(2, 143) = 109.692, p<0.001***	p<0.001*** p<0.001***	C < D, W < D
		Winger	24.2 ± 2.9	24.9 ± 2.9	24.2 ± 3.2	24.4 ± 3.6						
		Defence	30.7 ± 3,5	31.1 ± 2.9	31.3 ± 3.4	31.3 ± 3.0						
High-intensity skating	≥ 15 - < 20	Center	38.6 ± 3.9	38.6 ± 3.5	38.8 ± 3.6	38.9 ± 4.4	(2.864, 409,503) = 0.645, p=0.579	N/D	N/D	(2, 143) = 2.564, p<0.081	N/D	N/D
		Winger	38.5 ± 4.1	39.2 ± 4.6	38.6 ± 4.7	38.7 ± 5.2						
		Defence	40.0 ± 4.5	40.5 ± 4.1	40.4 ± 4.2	40.4 ± 4.3						
	≥ 20 - < 25	Center	41.3 ± 6.6	41.4 ± 5.6	41.3 ± 4.8	40.5 ± 5.1	(2.883, 412.259) = 1.793, p=0.150	N/D	N/D	(2, 143) = 137.091, p<0.001***	p<0.01**, p<0.001*** p<0.001***	C > W, C > D, W > D
		Winger	37.6 ± 4.6	38.6 ± 5.2	38.4 ± 4.9	38.0 ± 4.8						
		Defence	26.9 ± 3.8	27.0 ± 4.3	26.6 ± 3.8	26.6 ± 3.9						
	≥ 25	Center	23.2 ± 6.4	23.4 ± 7.3	22.9 ± 5.6	23.0 ± 6.1	(2.889, 413.098) = 0.339, p=0.790	N/D	N/D	(2, 143) = 103.798, p<0.001***	p<0.001*** p<0.001***	C > D, W > D
		Winger	20.0 ± 5.5	20.6 ± 5.8	20.5 ± 5.9	20.7 ± 6.4						
		Defence	9.2 ± 2.7	9.0 ± 2.6	9.0 ± 2.8	8.8 ± 2.9						

Km/h = velocity ranges. Q1-Q4 = season quarters. Value^a = Statistical significance change within the group on a season quarter basis. Value^b = Statistical significance change between the groups. Post-hoc^a / Post-hoc^b = post-hoc test significance. QD = season quarter differences. PD = playing position differences. N/D = no difference found.

6.4 Skating velocities

No significant difference was found between the season quarters in either maximum skating velocity (F(2.901, 414.876) = 2.514, p=0.06) or the mean skating velocity (F(2. 861, 409.121) = 0.455, p=705) with Huynh-Feldt corrections used. Maximum velocity for all players was 27.0 ± 1.6 km/h. Mean velocity throughout the season for all players was 14.9 ± 1.1. Similarly, no significant difference was found within the interaction between season quarters and playing position in maximum skating speed (F(5.5802, 414.876) = 0.228, p=0.965) nor in mean skating speed (F(5.722, 409.121) = 0.541, p=0.769) with Huynh-Feldt corrections used. Playing position differences was found in both maximum (F(2, 143) = 0.453, p<0.001) and mean skating velocity (F(2, 143) = 103.921, p<0.001). Centers (28.0 ± 1.3 km/h) and wingers (27.6 ± 1.3 km/h) had significantly higher mean maximum skating velocity per shift than defensemen (25.6 ± 0.9 km/h), respectively (p<0.001) (figure 22). Also, centers (15.8 ± 0.8 km/h) had higher mean skating velocity compared to wingers (15.3 ± 0.8 km/h) (p<0.01), and defensemen (13.7 ± 0.6 km/h) had significantly lower mean skating velocities than centers and wingers (p<0.001) (figure 23).

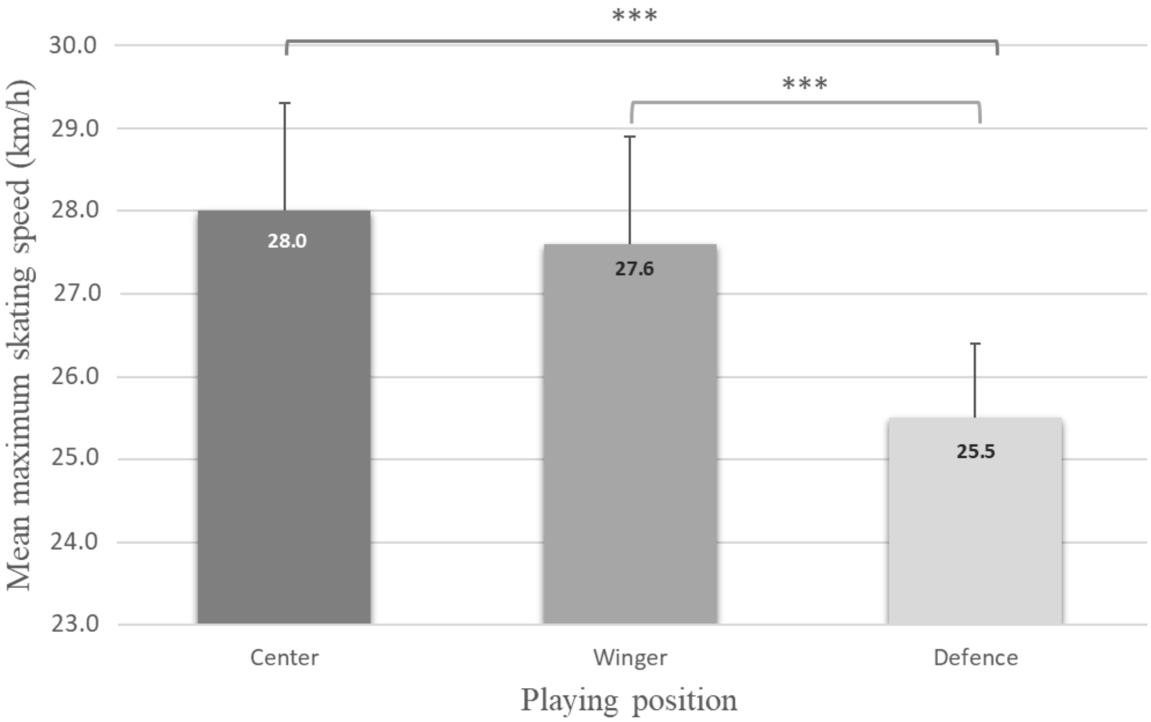


FIGURE 22 Mean maximum skating velocity (km/h) per shift across the season by playing position.

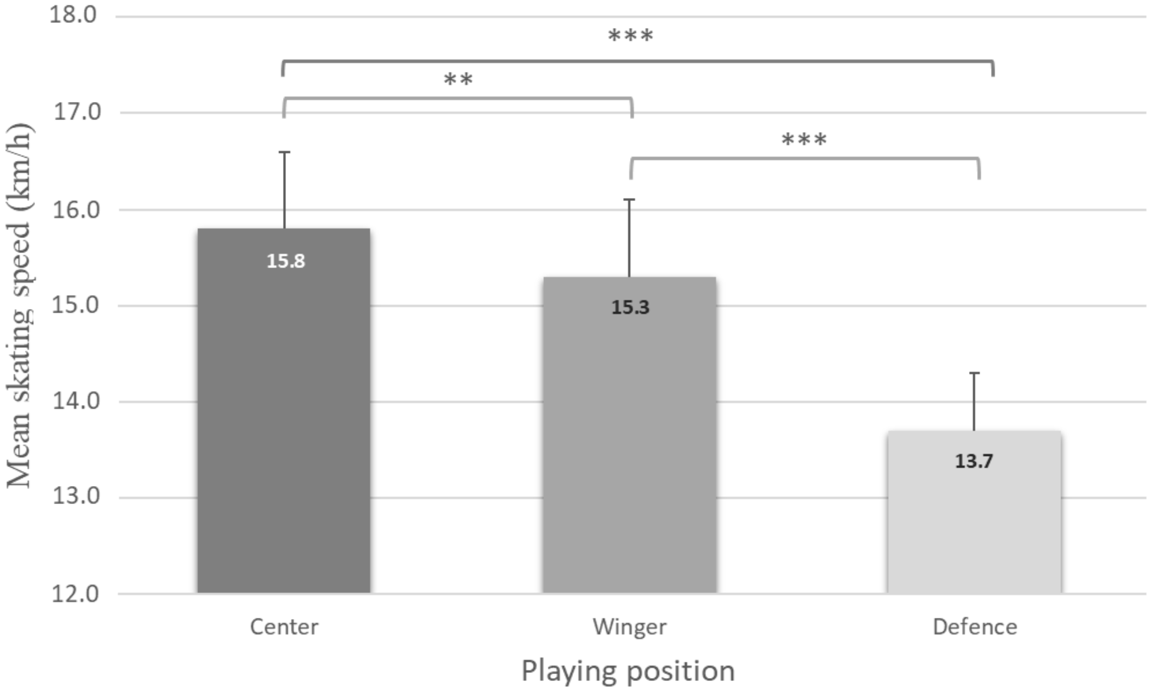


FIGURE 23 Mean skating velocity (km/h) per shift across the season by playing position.

All the players had the same value in count over 1 second over 0 km/h limit per shift with no difference found between season quarters or playing positions (Table 12). When investigating other limits, it was discovered that there was a difference between season quarters at the velocity limit of ≥ 15 km/h ($p<0.05$) km/h and ≥ 20 km/h ($p<0.05$). Post-hoc pairwise comparison with Bonferroni corrections addressed, that players passed the limit ≥ 15 km/h somewhat 2% less in Q1 (3.3 ± 0.3) than in Q2 (3.4 ± 0.3) with significance ($p<0.05$). Similarly, 2% difference and significance were found after post-hoc pairwise comparison in the velocity limit ≥ 20 km/h between Q3 (2.14 ± 0.44) and Q4 (2.10 + 0.42) ($p<0.05$). All the season quarter sphericity values are represented in the table 12. There were no significant differences found within interaction between season quarters and playing position.

Several significant playing positional differences was found within the limits of ≥ 5 km/h ($p<0.001$), >10 km/h ($p<0.001$), ≥ 20 km/h ($p<0.001$) and ≥ 25 km/h ($p<0.001$) (Table 12). Post-analysis revealed that at the limit of ≥ 5 km/h defensemen (3.4 ± 0.3) had 8% higher mean scores than centers (3.1 ± 0.3) ($p<0.001$) and 5% higher scores than wingers (3.2 ± 0.3) ($p<0.01$). At the limit of ≥ 10 km/h defensemen (4.0 ± 0.3) had 13% higher mean scores compared to centers (3.5 ± 0.3) ($p<0.001$) and 10% higher score than wingers (3.6 ± 0.3) ($p<0.001$). When it comes to high-intensity limits, defensemen (1.7 ± 0.2) had 32% less over 1 second visits at the limit of ≥ 20 km/h compared to centers (2.5 ± 0.3 ($p<0.001$) and 28% less compared to wingers (2.3 ± 0.3) ($p<0.001$). Similarly, defensemen (0.4 ± 0.1) had 59% less over 1 second visits at the sprint limit (≥ 25 km/h) than centers (0.9 ± 0.2) ($p<0.001$) and 55% less than wingers (0.8 ± 0.2) ($p<0.001$) (figure 24). All the playing position sphericity values are represented in the table 12.

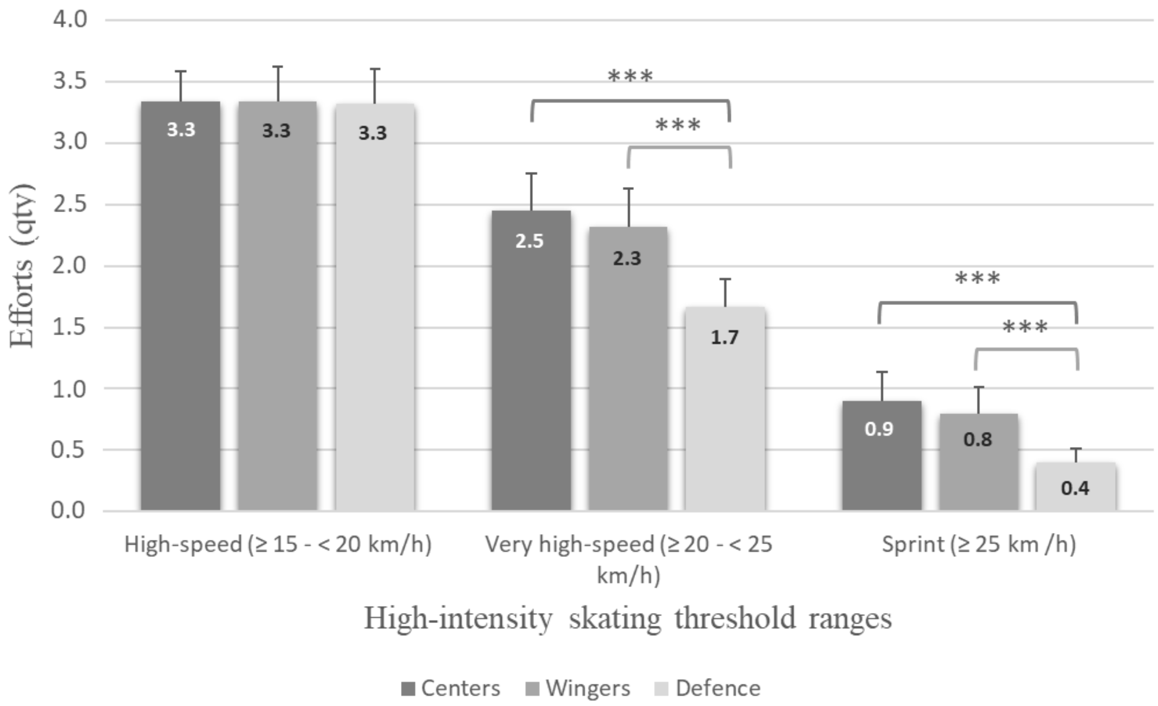


FIGURE 24 Mean number of over 1 second visits over different high-intensity velocity limits per shift across the season by playing position.

TABLE 12 Number of over 1 second visits over different velocity limits per shift in each season quarter by playing position.

	Km/h	Playing position	Q1	Q2	Q3	Q4	F-value^a	Post-hoc^a	QD	F-value^b	Post-hoc^b	PD
Low-intensity skating	≥ 0	Center	0.5 ± 0.0	0.5 ± 0.0	0.5 ± 0.0	0.5 ± 0.0	N/A	N/A	N/A	N/A	N/A	N/A
		Winger	0.5 ± 0.0	0.5 ± 0.0	0.5 ± 0.0	0.5 ± 0.0						
		Defence	0.5 ± 0.0	0.5 ± 0.0	0.5 ± 0.0	0.5 ± 0.0						
	≥ 5	Center	3.13 ± 0.36	3.14 ± 0.35	3.08 ± 0.28	3.10 ± 0.32	(2.916, 417.011) = 2.625, p=0.052	N/D	N/D	(2, 143) = 9.564, p<0.001***	p<0.001***, p<0.01**	C < D, W < D
		Winger	3.26 ± 0.30	3.26 ± 0.31	3.21 ± 0.30	3.19 ± 0.34						
		Defence	3.41 ± 0.33	3.40 ± 0.35	3.39 ± 0.36	3.38 ± 0.32						
	≥ 10	Center	3.43 ± 0.29	3.47 ± 0.29	3.45 ± 0.23	3.44 ± 0.29	(3, 429) = 2.037, p=0.108	N/D	N/D	(2,143) = 45.431, p<0.001***	p<0.001***, p<0.001***	C < D, W < D
		Winger	3.54 ± 0.27	3.59 ± 0.28	3.54 ± 0.28	3.52 ± 0.32						
		Defence	3.93 ± 0.34	3.97 ± 0.35	3.98 ± 0.34	3.92 ± 0.31						
High-intensity skating	≥ 15	Center	3.31 ± 0.29	3.36 ± 0.26	3.37 ± 0.22	3.33 ± 0.22	(2.970, 424.779) = 3.474, p<0.05*	Q1<Q2	p<0.05*	(2, 143) = 0.085, p=0.919	N/D	N/D
		Winger	3.32 ± 0.26	3.38 ± 0.28	3.36 ± 0.29	3.31 ± 0.30						
		Defence	3.29 ± 0.31	3.34 ± 0.25	3.34 ± 0.25	3.33 ± 0.30						
	≥ 20	Center	2.46 ± 0.34	2.46 ± 0.34	2.49 ± 0.25	2.40 ± 0.27	(2.929, 418.910) = 3.718, p<0.05*	Q3>Q4	p<0.05*	(2, 143) = 116.945, p<0.001***	p<0.001***, p<0.001***	C > D, W > D
		Winger	2.30 ± 0.30	2.35 ± 0.33	2.33 ± 0.31	2.29 ± 0.31						
		Defence	1.67 ± 0.23	1.67 ± 0.23	1.66 ± 0.24	1.66 ± 0.24						
	≥ 25	Center	0.93 ± 0.23	0.94 ± 0.28	0.93 ± 0.20	0.92 ± 0.23	(3, 429) = 0.576, p=0.631	N/D	N/D	(2, 143) = 123.146, p<0.001***	p<0.001***, p<0.001***	C > D, W > D
		Winger	0.83 ± 0.20	0.85 ± 0.21	0.84 ± 0.22	0.84 ± 0.23						
		Defence	0.39 ± 0.10	0.38 ± 0.11	0.37 ± 0.11	0.37 ± 0.12						

Km/h = velocity ranges. Q1-Q4 = season quarters. Value^a = Statistical significance change within the group on a season quarter basis. Value^b = Statistical significance change between. Post-hoc^a / Post-hoc^b = post-hoc test significance. QD = season quarter differences. PD = playing position differences. N/A = information not available. N/D = no difference found.

7 DISCUSSION

The main purpose of this study was to investigate how the competitive season affects the sport-specific external load in ice hockey, more precisely, how skating behavior changes during the ice hockey season and whether this is reflected in different playing positions. In addition, the secondary purpose was to produce new information regarding the playing positions in ice hockey. The previous studies have largely focused on ice hockey players as a whole or the differences between forwards and defensemen, while forwards have not been categorized separately as centers and wingers even though these players can be seen to have quite different tactical role on ice when the puck is on play.

The main findings in this study were that acceleration and deceleration performances changed significantly during the competitive season. Contradictory, other skating metrics (skating distance, skating speed or metrics with different velocity thresholds) did not demonstrate significant changes or the changes appeared on a low threshold level therefore having no meaningful affect to overall performance. An interesting new finding was that centers outperformed both wingers and defensemen at high-intensity skating in nearly all measured metrics. Overall, defensemen performed more skating in low-intensity velocity ranges and forwards skated significantly more in very high-intensity velocity ranges, which is supported by the prior sport specific research. In this study, no association was found between playing positions and skating metric changes in different quarters of the season.

7.1 Changes in skating performance during the ice hockey season

In this study, the most significant changes were related to acceleration and deceleration performances during the full ice hockey season. The decrement of over 0.5 second prolonged efforts (high-intensity and maximal accelerations and decelerations) towards the end of the season followed the rule, the higher the threshold, the greater the change. The biggest deterioration of performances was seen in the prolonged maximal accelerations (≥ 3 m/s^2) and maximal decelerations (≤ -3 m/s^2), when the number of efforts made per shift decreased 5% and 6% from Q1 to Q4, respectively. Also, both accelerations and decelerations in the other thresholds decreased almost identically overall.

Although the decrease of these efforts during the season was statistically significant, it should be noted that the players performed prolonged maximal decelerations only about once per shift and maximal accelerations once every other shift. Hence, the magnitude of these prolonged maximal efforts was not that high. In contrast, especially prolonged high-intensity decelerations ($\leq$ -2 m/s^2) occurred more often on a shift-by-shift basis (mean 2.2 ± 0.2), while prolonged high-intensity accelerations ($\geq$ 2 m/s^2) were also performed at least once in every shift on average (mean 1.6 ± 0.2), respectively. Interestingly, a similar decrease in results was not observed when accelerations and decelerations were measured without time limit in different threshold ranges. On the contrary, number of these accelerations and decelerations in different threshold ranges per shift increased from the first quarter, after which the results remained almost identical until the end of the season. The degree of these accelerations and decelerations in different threshold ranges during a shift was many times greater than efforts over 0.5 seconds. Based on these findings, the initial hypothesis (H1a) is partially accepted, regardless of the results from efforts measured without time limit.

If interpreted above results correctly, the first quarter of the season will act as a tapering phase to achieve delayed supercompensation associated with non-functional overreaching after the weeks-long pre-season phase on ice hockey (Kutáč et al. 2017). If the high-volume and high-intensity activity is prolonged, as in ice hockey, where the competitive season typically lasts around 8 months at elite level (Wörner et al. 2019), it can lead to functional overreaching, or even overtraining syndrome whereupon overall performance capacity is being reduced (Bell et al. 2020). The first intuition is that the level of performance potentiated during the early phase of the season as shown by other ice hockey specific studies (e.g. Delisle-Houde et al. 2017; Durocher et al. 2008b). As the season progresses, the decrement of performance, with the need of prolonged high power production activities, like long duration accelerations, supports the findings by Laurent et al. (2018) regarding to lower mean power output and increased perceived fatigue in post-season during the repeated sprints. As regards to high power output during the initial phase of the sprint, it remained the same in comparison to pre-season (Laurent et al. 2018), as demonstrated with this study´s short accelerations. However, this does not yet explain why players fatigue has been found to increase via single maximal effort assessments at the end of the season (Gannon et al. 2021; Whitehead 2019), because decrement of accelerations and decelerations in different threshold ranges were not observed.

One possible explanation may be that these skating variables are gathered on ice, but the testing carried out with players is done off-ice (e.g. CMJ). This indicates that off-ice testing does not correlate preciously enough with information gathered on ice. Thus, technologies which allow testing to be more sport specific and including relevant factors, such as state of fatigue, are needed if not to replace but to add to traditional testing methods.

Another explanation may be that prolonged accelerations and decelerations require more from force-velocity characteristics, the physical attributes, which seem to deteriorate towards the end of the season in ice hockey. These prolonged efforts also put more strain to neuromuscular system, which may reflect as a decrease in prolonged acceleration and deceleration efforts. On the other hand, short efforts (without time limit) do not have a similar requirement for force-velocity characteristics and the effect on overall load is not as great, which may be reflected in an increase of these short efforts from Q1 to latter phases of the competitive season - possibly indicating accustomization to the match-load and intensity after early phase of the season.

The decrease of prolonged accelerations and decelerations during the competitive ice hockey season could be related with the overall number of these maximum efforts made during shifts and matches. Harper et al. (2019) stated that the frequency of high-intensity decelerations is higher compared to accelerations in team sports. Results from this study support this statement, when it was found that ice hockey players performed around 28% more prolonged high-intensity decelerations (≤ -2 m/s^2) compared to high-intensity accelerations (≥ 2 m/s^2), and 60% more maximal decelerations (≤ -3 m/s^2) compared to maximal accelerations (≥ 3 m/s^2) per shift, respectively (table 5, table 6). Contrary to this, number of accelerations and decelerations performed in different threshold ranges are close to identical (table 7, table 8), but the mean ratio between prolonged high-intensity and maximal accelerations to short accelerations (without time limit) with high-intensity ($\geq 2 - < 3$ m/s^2) and maximal thresholds (≥ 3 m/s^2) were 1:20 and 1:30, respectively. Similarly, the mean ratios between prolonged high-intensity decelerations and maximal decelerations to decelerations without time limit ($\leq -2 - < -3$ m/s^2, ≤ -3 m/s^2) were 1:13 and 1:12, respectively. Hence, players performed prolonged decelerations more frequently than accelerations. Although the magnitude of these prolonged maximal efforts are not that high per shift, but together with overall high-intensity and maximal efforts made in both matches and training sessions daily and weekly basis (Allard et al. 2020; Brocherie 2018; Wörner et al. 2019), with the effect of high metabolic (Buglione & di Prampero 2013; Hader, et al. 2016; Zamparo et al. 2015) and neuromuscular load (Terje, et al. 2016; Guilhem et al. 2016) is more likely to accumulate which then manifests as negative adaptations of the neuromuscular system in long term (Green et al. 2010; Harper et al. 2019).

Another interesting finding was the number of accelerations and decelerations without time limit. These types of accelerations and decelerations occurred much more during each shift than those with set time limit. By looking at these efforts made, it can be observed that very few explosive efforts during the shift actually led to e.g. sprint performances. This has also been demonstrated in soccer, with Varley and Aughey (2013) reporting, that around 85% of all maximal accelerations did not exceed even defined high-intensity running velocity threshold (> 4.17 m/s^2). In this study it was found that around 95% of all maximal accelerations (mean 12.0 ± 3.8 for all players) performed per shift did not lead to over 1 second sprint (≥ 25 km/h) effort (mean 0,7 ± 0.3 for all players), whereas approximately 83% of these short maximal efforts did not lead to very high-intensity (≥ 20 - < 25 km/h) skating bout (mean 2.1 ± 0.4 for all players) during a shift, respectively.

It was also hypothesized (H1b) that when maximal efforts decrease, this also affects the high-intensity skating, more precisely the time spent in sprint speed, as well as relative time and distance skated in sprint speed per shift. Findings contrast with the hypothesis, because no difference was found between different quarters of the season regards to overall sprint skating metrics, with the exception of small decrease within the numbers of over 1 second of high-intensity skating (≥ 20 km/h) bouts from Q3 to Q4, although this was not reflected in skating distance, or the time spent in the high-intensity skating range over the same period of time. Regarding to constant results of sprint skating (≥ 25 km/h), the reason may be that the velocity limit used in this study was too low, and the limit does not reflect the maximal effort that players in top level need to perform when exceeding the sprint limit time and time again during the season. The reason for this interpretation is that Brocherie et al. (2018) reported players performing mean of ~7 shifts and ~5-6 sprints (> 30 km/h) (with performance decrement in 3rd period) per period, whereas Douglas & Kennedy (2019) reported similarly total of ~19 sprints (> 24 km/h) per match with average sprint speed being 25.5 km/h. In this study, where the mean maximum skating speed was 27.0 (± 1.6) km/h for all players per shift, with centers averaging up to 28.0 (± 1.3) km/h, forwards averaged 0.8 - 0.9 over 1 second sprints per shift which states quite similar number of sprint performances per shift and per match compared to Brocherie et al. (2018) and Douglas and Kennedy (2019) findings, if the number of shifts per period are somewhat equal between the leagues on average. So, these recent studies, which have looked at speeds and volumes of sprint skating, has reached the same conclusion on the number of sprints performed per shift/match regardless of the speed limit. This in turn would indicate that the limits used may not give a true reflection of players´ actual sprint efforts during the match. Sprint velocity threshold issue is an important information for future research and thus is addressed more closely in the following.

In this study, it was found that centers perform on average less than once over 1 second bout at sprint speed (≥ 25 km/h) per shift (figure 24). In order to match the over 3 second mean time they spent in sprint skating range per shift (figure 16), they must perform multiple short (< 1 sec) sprint speed bouts. This 3 second mean time is relatively short compared to average sprint time of ~ 6 seconds per shift reported by Brocherie et al (2018), and single sprint duration of 2-3 seconds in team sports in general reported by Spencer et al. (2005). If the 25 km/h is anywhere near the players´ actual sprint speed, such a repeatedly done sprints in 30 second shift time, being fairly short duration, would be really taxing in metabolic wise (Zamparo et al. 2015). It is therefore reasonable to assume that players very rarely skate at their actual sprint speed during the match because in ice hockey there is not usually enough space and time to accelerate to full speed and maintain it. This assumption is supported by the findings of di Prampero et al. (2005) regarding to maximum running acceleration which is stated to be achieved during the first five strides, but if the subject is forced to change the direction during this time, the maximum acceleration and therefore the maximum speed is never achieved. This may also explain why mean distance of single high-intensity skating bout is reportedly only 15 - 16 meters (Lignell et al. 2018). As a comparison, average sprint distance per shift in this study for all players was 17.5 m (± 0.4 m) (table 11), thus being significantly player position dependent. When looking at the prolonged acceleration efforts in this study, the ratio between accelerations and sprints are close to 1:2 for all players, suggesting that every other maximal sprint is not preceded by maximal acceleration. This leads to yet another question: if the 25 km/h velocity limit is not valid as a sprint speed, is the maximal acceleration limit (≥ 3 m/s^2) used in this study high enough to be maximal for ice hockey players? Thus, the speed and acceleration threshold limits used in other team sports may not be valid for use in ice hockey. As players move differently in ice hockey than in other team sports simply because of the ice and skates, the different limits should therefore be looked at more closely in the future in order to acquire more suitable limits for ice hockey. However, it should be noted that the speed limits used are both method- and algorithm-specific within sports.

The decrease of prolonged accelerations and decelerations towards the end of the season does not appear to have much of an effect on the other skating variables measured in this study. Few skating variables demonstrated some change (e.g. the 5% decrease of skating time in the velocity range of 0 - < 5 km/h between season phases Q1 and Q3), but the changes appeared on a such low-intensity level that they cannot be seen as a relevant factor to overall external load. The reason for this may be that either the load from the accelerations and decelerations do not correlate directly with other variables or that the threshold limits used are too low in order for the affect to appear. The missing correlation, however, most likely plays more important role as the explosive efforts rarely lead e.g to maximal speeds as discussed earlier.

An interesting finding was that players seemed to be in constant motion during the match, when evaluating the number of visits over different velocity limits per shift. All the players had the result of 0.5 (± 0.0) (table 12) indicating that after they start to skate, the single effort at the slowest velocity threshold (≥ 0 km/h) does not reset at any point during the shift. When comparing this to observation of Brocherie et al. (2018) findings, that around 15% of players´ total effective playing time was standing still, with Jackson et al. (2016) having similar findings with around 7% for female ice hockey players, the findings in this study are quite opposite directing players to be in constant movement when on ice and puck is on play. It should be noted that both of these author groups used TMA as a measurement method and they had much broader skating velocity thresholds, with standing motionless being 0 km/h and gliding without any propulsion action being 11 km/h, which could distort the actual findings. One reason that in this study players were found to be in constant motion all the time or at least exceeded the speed of lowest velocity threshold (> 0 km/h) could be that the positioning tag modules were installed in the player´s jerseys and not in player´s skates. Therefore, even if player was standing still when on ice, the upper body may still be in a small movement, in which case the LPS system interprets it as a movement. This result may slightly distort the proportion of the two slowest skating limits (≥ 0 km/h, ≥ 5 km/h), but it does not have a significant effect on the total skating load though.

The 2019-2020 ice hockey season covered in this study was exceptional compared to previous seasons in the Liiga, as the playoff-series were not played at all due to the Covid19 pandemic. Because the changes observed were limited to acceleration and deceleration variables only during the competitive season, the question remains, whether the skating metric results would have shown some changes if the playoff-series had been included in this study. The previous studies of the players´ physiological changes during the season have covered matches of full ice hockey season with playoffs (Delisle-Houde et al. 2017) or significantly more matches compared to this study (Gannon et al. 2021).

To the extent that the data from this study is comparable, the skating metrics during matches does not differ significantly due to the length of the matches. In playoffs, for example, the duration of matches may be extended with several extra time periods, which may lead to different statistics in skating variables. In addition, in playoff-series each match often has a greater overall importance compared to individual matches during the regular season. This could be one of the topics for further research.

All in all, the hypotheses reflecting the skating load changes during the season in different playing positions (H2) can be rejected. This is because overall association between playing positions and skating metric changes in different phases of the season was not found. For example, with prolonged accelerations and decelerations, results decreased almost identically for each of three playing position, indicating that the changes in these metrics are not playing position dependent, even when there was playing positional differences in the number of performances.

It seems that the sport specific load is somewhat universal and not playing position specific when evaluating ice hockey throughout the season. Accelerations and decelerations do have similar impact on players whether the playing role is defensive or offensive. Similarly to interaction between playing position and season quarters (with the exception of high-intensity efforts), no other significant changes were seen during the season when assessing the skating load metrics. This also supports the idea that skating with constant speed, even if it is in high-intensity or sprint speed, is not as fatiguing in the long run as the reports from individual matches may suggest (di Prampero 2005), when e.g. Brocherie et al. (2018), Lignell et al. (2018), and Douglas and Kennedy (2019) have all reported the decrease of performance towards the end of the match. Although, the majority of the in-match load in ice hockey comes from high-intensity skating (≥ 15 km/h) during the season (table 11), the evidence from this study suggest that it does not load the neuromuscular system or energy systems that much that it would have a significant long-term effect on the high-intensity movement ability itself.

Based on this study, the acute physiological stress, from the matches and trainings, does not appear to have long-lasting or cumulative impact on overall sport specific performance over the competitive season when looking at the results of skating with different intensities during the season. However, prolonged explosive performances (accelerations and decelerations) are affected negatively. This finding supports observations from soccer (Malone et al. 2015) and from rugby (Gabbett et al. 2005; Gabbett & Ullah 2012). The results in this area of research are not entirely unanimous. Therefore more researches are needed where internal and external loads are combined in the research design.

7.2 Playing position differences in skating metrics

One of the main goals of this study was to look at how skating variables differ between forwards when these players are grouped based on playing position into centers and wingers according to their tactical role of the game. Although the results suggest that the differences between centers and wingers are not as clear as comparison between forwards and defensemen, it can be observed that centers skate at higher skating intensities during the shifts (figure 21, figure 23) compared to wingers, and more meters per match compared to wingers (figure 18) (being a non-significant finding though), while the time spent on ice is somewhat identical between forward positions (figure 11, figure 12). Thus, the results indicate that centers have higher overall external load based on overall high-intensity skating metrics and therefore the hypothesis (H3) will be rejected. There is lack of sport specific research regarding this topic. Other team sports do not provide evidence to support the differences between centers and wingers, because in this regard ice hockey differs as a sport, e.g. in terms of the dynamics of the lineups on the field during the match and the surface the match is played on. To author´s knowledge, only Allard et al. (2020) have studied in-match load differences between different playing positions including wingers as a separate playing position without any significant differences found between ice hockey forwards.

The space and the time players have when on ice may explain partly the findings, as discussed earlier with players possibilities to skate with high speeds during a shift in discussion chapter 7.1. If the role of forwards is being viewed in such a high generalization as being done in the article of NHL (2021), it is conceivable that when centers are more of playmakers, they often have the responsibilities to bring the puck up from the defensive area. This is when the player has typically the possibility to accelerate freely without immediate interference from the opponent. Similarly, centers also have a different defensive obligation compared to wingers, in which case the centers must also quickly skate back from offensive end to own defensive area to support defensemen when opponent is making a counterattack. Wingers, on the other hand, seek the route to the offensive end from close to opponent´s defensive area, to fight for the puck. In this regard, centers typically have more free space to accelerate to higher skating velocities and maintain the speed longer than wingers. This type of generalization where centers and wingers are forced to move tightly in a certain area of the rink is unlikely to apply in actual match situations. However, since there are clear differences in the roles of the forward players, which also appear with in-match skating, the differences between centers and wingers should be examined in more detail both on- and off-ice in future studies.

In addition to the differences between centers and wingers, this study provides support for the prior studies regarding different external load of defensemen and forwards in general. When looking at skating intensities, forwards spend significantly more time (figure 14, figure 16) and skate more distance (figure 21) per shift with very high-intensity (≥ 20 km/h) and sprinting (≥ 25 km/h) speeds compared to defensemen, also reflected in the number of high-intensity and maximal decelerations (table 13). These findings differ from previous studies, when Lignell et al. (2018) stated, that players skate around 45% of their skating distance with high-intensity speed (> 17 km/h), while in this study players averaged around 69% of their skating distance in high-intensity speed (> 15 km/h) (table 11). Douglas and Kennedy (2019) reported that defensemen performed more sprint meters on average compared to forwards (assumption of even strength), whereas in this study centers sprinted 61% more distance than defensemen and wingers 56% more than defensemen per shift, respectively (table 11). Douglas and Kennedy (2019) reported similar findings as in this study (figure 10, figure 12, figure 18), with forwards covering over 56% of their shift distance in high-intensity skating speed (> 17 km/h) averaging of 90 “high-intensity meters” per shift. On the contrary, Brocherie et al. (2018) reported 17.6% (± 6.0%) of effective shift time being high-intensity skating (> 22 km/h), including high-intensity backward skating (> 18 km/h), which differs from this study when even defensemen alone skated around 18% (± 3%) of their shift time in very high-intensity speed (> 20 km/h), not to mention forwards, of which wingers skated over 29% (± 5%), and centers around 32% (± 5%) in very high-intensity speeds including sprinting, respectively. All these findings are opposite compared to Bracko et al. (1998) and Jackson et al. (2017) suggestions that players spend less than 5% on high-intensity skating when on ice. Alisse et al. (2019) are citing

Montgomery et al. (2004) observations that positional skating intensity differences can also be explained by the statement that forwards skate less backwards (6%) than defensemen (19,2%). In principle, backward skating requires proficient technique (Alisse et al. 2019) and it is typically always significantly slower skating style than forward skating even when done at high-intensity speed (Bracko et al. 1998). Based on these results, it can be concluded that when evaluating individual matches, misinterpretations may occur regarding players´ skating intensities. In addition to technologies, the thresholds used also have a significant effect on the results. It should be noted that differences in results may well be affected by differences between ice hockey leagues, e.g. rink size.

Of all players, defensemen had higher overall on-ice time per match, but there were no significant differences between playing positions when evaluating shift time (figure 14). This would suggest that defensemen play higher number of shifts during the match than forwards. These findings are in line with previous studies (Douglas & Kennedy 2019; Lignell et al. 2018) in which defensemen have been found to have the highest total playing time per match on average. In contrast, Lignell et al. (2018) reported much higher mean shift time (+ 49%) for defensemen than forwards had, compared to findings in this study (+ 2-3%). The high relative difference can be explained with the fact that the authors (Lignell et al. 2018) reported significantly lower mean shift time (22.3 ± 1.6 seconds for defensemen and 15.2 ± 0.9 seconds for forwards, respectively) in overall compared to this study (33.0 ± 2.4 seconds for all players with no significant difference found between playing positions) and other similar studies (Brocherie et al. 2018; Douglas & Kennedy 2019). Besides shift time, also total match time was somewhat lower in this study (mean 13:20 ± 2:49 minutes for all players) compared to other studies with 5 international ice hockey matches (16.1 ± 3.6 minutes) (Brocherie et al. 2018) or one match in the NHL (mean of 17.3 ± 1.1 minutes) (Lignell et al. 2018). One significant factor that could explain the lower playing times in this study may be that players were found to skate more at higher intensities compared to other studies, which also encourages players to skate for a shorter time as Brocherie et al. (2018) have summarized it. In addition, tactics may also affect playing time. For example, whether the playing time is being distributed evenly across the team or if it is being reduced to 2-3 playing lines during the match depending on the preferred tactics.

The differences in skating intensities between playing positions were reflected clearly on the distances skated during matches, when forwards skated more distance per shift than defensemen. Nevertheless, as can be seen from the results, wingers skated less distance per match than centers and defensemen, respectively. However, statistical significance was observed only between defensemen and wingers (figure 18), which may be explained by differences in sample sizes between centers and two other playing positions. Similarly to playing time, prior studies from modern ice hockey have reported significantly higher skating distance values compared to this study, when Lignell et al. (2018) reported higher mean skating distances overall (4606 ± 219 m), per playing position (forwards 4237 ± 248 m, defensemen 5445 ± 337 m, respectively), as well as higher skating distance per time unit (forwards 283 ± 7 m/min, defensemen 247 ± 8 m/min, respectively) for the players in the NHL. Douglas and Kennedy (2019) reported higher skating distances per match (forwards 3681 ± 1058 m, defensemen 4002 ± 768 m, respectively) and per shift (forwards 161 ± 90 m, defensemen 142 ± 80 m, respectively) than found in this study. The reason for the higher skating distance per time unit in the Lignell et al. (2018) study could simply be the effective playing time difference being 54% lower for forwards and 33% lower for defensemen compared to what was reported in this study. Otherwise, the distance skated during shifts and matches is mainly explained by the number of shifts made and, for the study of Douglas and Kennedy (2019), also the duration of shifts. The results regarding wingers´ performance is somewhat difficult to explain in other way than differences in game role, especially when centers have different high-intensity skating profile than wingers, but the time on ice is somewhat identical throughout the season.

As stated earlier, possible explanation for the lower playing times in this study compared to referenced studies may be the skating intensities. In this study players´ mean maximum speed per shift was above the defined sprint speed (≥ 25 km/h), mean maximum speed being ~ 27 km/h for all players, with centers skating on average at the highest maximum and mean speeds, while the defensemen had the lowest skating speed values, respectively (figure 22, figure 23). When comparing skating speeds between studies, the average maximum skating speed in this study was around 6% higher compared to what Lignell et al. (2018) reported for all players (25.5 ± 0.1 km/h) in their study. Douglas and Kennedy (2019) reported, with 5 match average and with assumption of even strength, around 3-4% lower maximum skating speed (26.9 ± 5.0 km/h) and 5-8% lower mean skating speed (14.5 ± 3.5 km/h) for forwards, and 3% lower maximum speed (24.9 ± 5.0 km/h) and 8% lower mean speed (12.6 ± 3.2 km/h) for defensemen, respectively, compared to what was reported in this study.

Above results indicate that players in Finnish elite ice hockey league play less minutes and skate less meters in total per match than players in the NHL or during the international matches, but at the same time players skate with higher skating intensities. One factor influencing to the results of different studies may be the size of the rink in the NHL (Lignell et al. 2018) and the junior elite championship matches (Douglas & Kennedy 2019), which are typically played on a smaller rinks than matches in Europe (Brocherie et al. 2018) and in the Liiga. This has a particular effect when a smaller rink is likely to give players less room to accelerate and skate with very high intensities compared to bigger rinks. Differences in results may also be explained by differences between league levels, but also by measurement methods used, with Brocherie et al. (2018), Lignell et al. (2018) and Jackson et al. (2016) reported using TMA based video analysis for the determination of velocities as well as calculations of the skating distances covered in a match and with different velocities. On the contrary, Douglas and Kennedy (2019) used more similar wearable indoor positioning system based on LPS technology to that was used in this study. It should be noted that the results may also be affected by the algorithms used by different equipment manufacturers as well as different data filtering methods (Prisca et al. 2020).

The thresholds used in other studies differs from the thresholds used in this study. This has also an affect e.g. on skating distances when using TMA, because skating distances, inter alia, were calculated by using total time and mean velocity in different speed threshold categories according to Brocherie et al. (2018). Douglas and Kennedy (2019), on the other hand, used same categories and velocity thresholds as Lignell et al. (2018), which are previously used in soccer (e.g. Mohr et al. 2012; Mohr et al. 2016b), which then were validated for ice hockey through pilot testing. The authors (Lignell et al. 2018) determined low-intensity skating as a speed of 1-16.9 km/h and high-intensity skating speed being greater than 17 km/h with sprint skating being over 24 km/h. Brocherie et al. (2018) used the specific locomotor categories with mean low-intensity skating being ~15 km/h and high-intensity skating being ~22 km/h, with sprint being as ~30 km/h. Whereas in this study equal bandwidth thresholds (0–5, 5–10, 10–15, 15–20, 20-25, > 25 km/h) were used based on the recommendations of Malone et. al. (2017) and Sweeting et al. (2017), with low-intensity skating being categorized as < 15 km/h and high-intensity skating speed being ≥ 15 km/h. The use of these different velocity thresholds is justifiable, which however, makes the comparison between studies challenging.

Douglas and Kennedy (2019) reported mean shift time based on match situation (penalty kill, power play, or even strength), which reportedly affected at least maximum skating speed, average skating speed, and average on ice time, while in this study these different match situations were not separated from each other. Brocherie et al. (2018) have also suggested that increased number of player units being used in modern game could explain e.g. lower mean skating distances, but this does not explain the differences between the results of these recent studies this study included. Team tactics may also be reflected in e.g. skating distance and playing time metrics if the sample size (e.g number of matches) is small in the study. Also, the number of periods included to the data affects directly to the given results, when e.g. Lignell et al. (2018) study included an overtime period that increases the skating volumes when only one match is considered. In this study overtime periods were also included, but not reported separately, which can affect the overall results (e.g. mean skating distance, mean playing time per match) and therefore comparison to other studies. Altogether, the evidence seems to indicate that in the long run, as the game evolves, players spend less and less time on ice per shift, which in turn can explain the ability for players to skate at higher intensities when on ice. Or vice versa, players skate and accelerate with so high intensities in modern game that the on-ice time per shift is shorter compared to sport before, with up to 70 - 80 seconds per shift reported (Theoden & Jette 1975, according to Montgomery 1988).

7.3 Strengths and weaknesses of the study

The biggest strength of this study is that it covers skating metrics from the whole ice hockey season consisting total of 372 matches from the total of 146 elite ice hockey players from nine teams. The sample is large and therefore valid enough to represent the level of Liiga as Finnish elite ice hockey league. This allows that the effects of possible differences in tactics and team strengths that may emerge from studies including single or handful of matches (e.g. Brocherie et al. 2018; Lignell et al. 2018; Douglas & Kennedy 2019) can be eliminated. In addition to the size of the data, this study is novel regarding the measurement of the of acceleration and deceleration metrics with ice hockey players in different thresholds in match situations throughout the competitive season. Whereas prior sport specific studies have either looked players in general (Brocherie et al. 2018) or players have been grouped into defensemen and forwards (Lignell et al. 2018; Douglas & Kennedy 2019), in this study players were analyzed in three different groups, with forwards divided separately into centers and wingers. The findings from this study give new and much needed information on players skating load changes during full competitive season as well as playing positional differences at elite level.

It may be seen as a weakness of this study that group sizes were unequal, when the group of wingers were over doubled compared to centers, and defensemen almost doubled compared to centers, respectively, which could possibly affect to the statistical power. Also, playing positional roles were static based on the information from Liiga webpage. There is possibility that especially forwards changed roles within the match and within the season due to injuries and change of tactics, and therefore, it is possible that the mean results reported do not fully reflect the true playing positional roles in the matches. Prior studies (Brocherie et al. 2018) have compared forward skating and backward skating in different intensities, whereas backward skating was not considered in the data of this study, which may have caused some bias especially when looking at defensemen´ skating intensities. The exclusion of playoff series can be seen as a limitation of this study, and therefore the interpretations for full season effects are challenging. This is because the load from playoff series can be considered to be different due to duration of playoff matches which are played until ”sudden death” to settle a tie match if the match is even after three periods. It should also be noted that this study did not specifically consider the results of those players who may have participated in the Euro Hockey Tour and/or Champions Hockey League (ice hockey club tournament for top teams from the first-tier leagues in Europe) during the season, when no matches were played in Liiga series. The additional load that national team and international club tournament matches bring for them, including possible travel load, may have an effect on the total load of those players.

7.4 Practical applications

According to this study ice hockey players seem to lose their ability to do prolonged high-intensity explosive efforts towards the end of the season without affecting in-match performance in different skating velocity ranges. Partial indications of this phenomenon have already been obtained in prior research by looking at the internal load of ice hockey players´ over entire competitive season. Importance of this study is the preciseness of skating load metrics. By looking at only commonly used metrics (e.g. skating distance, playing time or even maximum skating speed), sport specific crucial indicators such as accelerations and decelerations may be left undetected. Through this study the importance of comprehensive monitoring of players performance level is inevitable especially at the professional level. Monitoring different skating variables, emphasize being in high-intensity and maximum performance metrics, it may be possible to deduce the level of the player´s overall fitness state. The more relevant and sport specific variables are being used, the more accurate and optimized training can be achieved. This study also found that players skate at higher intensities but play much shorter shift duration and skate less distance compared to other studies done in the NHL and international level. Aware of this, the physical characteristics of the players may also be developed further to better meet the performance levels required by the Finnish professional ice hockey league.

It was clearly shown that centers and wingers play different tactical role which is reflected via the intensity of skating during each shift. It is worth considering whether this should have effect on playing position specific training, even if the prior research evidence suggests that physical characteristics (Ferland et al. 2021; Sigmund et al. 2016) and absolute match load (Allard et al. 2020) between centers and wingers do not differ. However, by utilizing the gathered data, the training could be fine-tuned accordingly. Therefore, when data suggests that e.g. centers skate at higher intensities than wingers, their playing position specific training should highlight this, through which a possible competitive advantage could be gained.

7.5 Conclusions

This is the first study made which looks professional ice hockey players´ skating load through several different skating variables over an entire competitive season. The objective was to evaluate whether the external load metrics would change towards the end of the season, as the prior research of internal load indicates. According to the results, the overall load from the full competitive season specifically affects the explosive efforts related to prolonged accelerations and decelerations. The number of these high-intensity and maximum efforts lasting over 0.5 seconds during the shifts decreased towards the end of the season. On the contrary, the number of short accelerations and decelerations increased from the first quarter of the season without any actual subsequent recession when measured without time limit in different threshold ranges. Despite the reduction of prolonged explosive efforts, the other skating performance metrics including distance skated or time spent on ice with high-intensity speeds, do not seem to be affected.

The second object of this study was to compare skating loads between different playing positions. Contrary to previous studies, in this study forwards were grouped separately into centers and wingers. Forwards in general, regardless of the playing position, performed more high-intensity and maximal decelerations, skated higher intensities overall, and had higher maximal and mean skating speed per shift compared to defensemen supporting prior research findings. In contrast, defensemen spend more time in lower skating intensities than forwards. Novelty of this study is that forwards are not unanimous group but rather present playing position role differences through high-intensity skating. The role difference is visible despite that the playing time and the distance skated do not differ between forward players. It should be noted that no interaction was observed between different season phases and playing positions regarding changes of skating variables, and thus in sport specific performance, the changes in skating load is not playing position dependent. Results from this study are in line with prior studies (Lignell et al. 2018; Douglas and Kennedy 2019) referring playing positional differences between forwards and defensemen, but what was found was, that players in fact skate slightly higher speeds, spend less time on ice and skate less distance per match than other studies have reported. It should be considered though, that studies are done within different ice hockey leagues, and technologies and skating speed thresholds used differ which may affect the interpretation. The results from this study contribute to the sport of ice hockey by bringing measurable and precise information which should lead to a more value-based training and therefore to most optimized overall performance.

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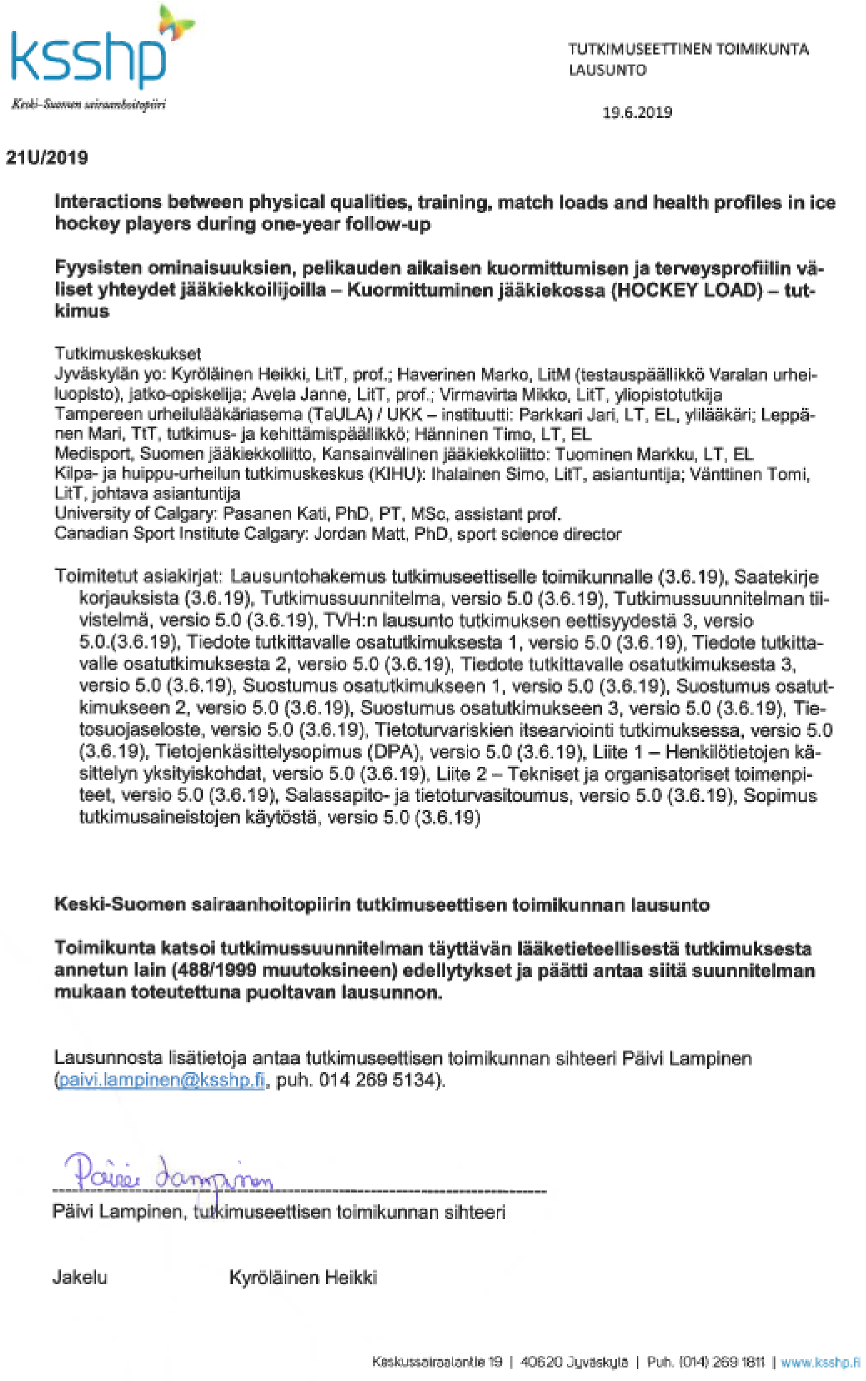
APPENDIX

APPENDIX 1. An approval of the ethical committee of Central Finland Health Care District



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TUTKIMUSEETTINEN TOIMIKUNTA
LAUSUNTO

19.6.2019

21U/2019

Interactions between physical qualities, training, match loads and health profiles in ice hockey players during one-year follow-up

Fyysisten ominaisuuksien, pelikauden aikaisen kuormittumisen ja terveysprofiilin väliset yhteydet jääkiekkoilijoilla – Kuormittuminen jääkiekossa (HOCKEY LOAD) – tutkimus

Tutkimuskeskukset
Jyväskylän yo: Kyröläinen Heikki, LitT, prof.; Haverinen Marko, LitM (testauspäällikkö Varalan urheiluopisto), jatko-opiskelija; Avela Janne, LitT, prof.; Virmavirta Mikko, LitT, yliopistotutkija
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University of Calgary: Pasanen Kati, PhD, PT, MSc, assistant prof.
Canadian Sport Institute Calgary: Jordan Matt, PhD, sport science director

Toimitetut asiakirjat: Lausuntohakemus tutkimuseettiselle toimikunnalle (3.6.19), Saatekirje korjauksista (3.6.19), Tutkimussuunnitelma, versio 5.0 (3.6.19), Tutkimussuunnitelman tiivistelmä, versio 5.0 (3.6.19), TVH:n lausunto tutkimuksen eettisyydestä 3, versio 5.0.(3.6.19), Tiedote tutkittavalle osatutkimuksesta 1, versio 5.0 (3.6.19), Tiedote tutkittavalle osatutkimuksesta 2, versio 5.0 (3.6.19), Tiedote tutkittavalle osatutkimuksesta 3, versio 5.0 (3.6.19), Suostumus osatutkimukseen 1, versio 5.0 (3.6.19), Suostumus osatutkimukseen 2, versio 5.0 (3.6.19), Suostumus osatutkimukseen 3, versio 5.0 (3.6.19), Tietosuojaseloste, versio 5.0 (3.6.19), Tietoturvariskien itsearviointi tutkimuksessa, versio 5.0 (3.6.19), Tietojenkäsittelysopimus (DPA), versio 5.0 (3.6.19), Liite 1 – Henkilötietojen käsittelyn yksityiskohdat, versio 5.0 (3.6.19), Liite 2 – Tekniset ja organisatoriset toimenpiteet, versio 5.0 (3.6.19), Salassapito- ja tietoturvasitoumus, versio 5.0 (3.6.19), Sopimus tutkimusaineistojen käytöstä, versio 5.0 (3.6.19)

Keski-Suomen sairaanhoitopiirin tutkimuseettisen toimikunnan lausunto

Toimikunta katsoi tutkimussuunnitelman täyttävän lääketieteellisestä tutkimuksesta annetun lain (488/1999 muutoksineen) edellytykset ja päätti antaa siitä suunnitelman mukaan toteutettuna puoltavan lausunnon.

Lausunnosta lisätietoja antaa tutkimuseettisen toimikunnan sihteeri Päivi Lampinen (paivi.lampinen@ksshp.fi, puh. 014 269 5134).

Päivi Lampinen
Päivi Lampinen, tutkimuseettisen toimikunnan sihteeri

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