

Eirik Halvorsen Wik

Activity profiles and fatigue in elite female and male team handball:

Individual and team characteristics

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Preface

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Abstract

Handball matches place diverse physical demands on players, which over the course of games may result in fatigue and decreased activity levels. However, studies are limited, and activity profiles are often obtained using video recordings, although this instrument may not be sensitive for capturing short-lasting handball-specific movements. The purpose of this master thesis is therefore to examine activity profiles and fatigue development, for teams and individual players of both genders, using modern microtechnology devices.

A microtechnology device (Catapult OptimEye S5) was worn by elite players in a female national team (6 matches, n = 55 samples), and a male national recruit team (3 matches, n = 36 samples), during international tournament matches. Activity profiles were examined on a team- and individual player level, with special regards to possible fatigue development during games. Analyses were performed for Player Load™, accelerations, decelerations, and changes of direction (CoD), as well as high- and moderate-intensity efforts combined (HMI) and low-intensity efforts (LI), all relative to playing time.

High initial intensities were observed for teams and individual players, with declines over the course of games, and with subsequent periods of playing time. In the final period of play, results were inconsistent, with mean values decreasing or increasing, compared to the previous period of play. HMI were preserved or increased towards the end of second halves for teams, while LI were preserved or decreased. Decreases in activity levels were observed after the most intense periods of the game for individual players.

Declines in activity levels may be indicative of temporal and transient fatigue during handball games, for teams and individual players. Pacing strategies may affect activity profiles, possibly causing the observed increases in activity in the final period of play, although underlying mechanisms and situational factors were not accounted for in this study.

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1. Introduction

Knowledge of physical and technical demands of handball is required in order to identify talents and develop position-specific training programs for each individual athlete (Karcher & Buchheit, 2014). Knowledge of match demands will also help in weighing physical training against other training, and prioritizing different physical attributes in training and testing, to make this more optimized and time-efficient (Michalsik, Aagaard, & Madsen, 2013; Povoas et al., 2012).

Research on handball is limited and methodologically complicated compared to other team sports, such as soccer, rugby, and Australian football (Karcher & Buchheit, 2014; Michalsik et al., 2013; Povoas et al., 2012). Furthermore, the majority of literature concerning fatigue in handball involves male teams and athletes. Energy-demanding high-intense actions are not well captured with previous methods, as they are performed in tight spaces, and are therefore probably underestimated in earlier studies (Karcher & Buchheit, 2014; Povoas et al., 2012). To the author's knowledge there are currently no studies of Player Load™, or related measurements of player loading, in handball games. Consequently, research on handball match demands and activity profiles in relation to fatigue is required in order to gain a deeper understanding of the sport and dynamics of matches.

Knowledge from studies of activity profiles can be transferred into practice, in sense of interchanges, rotation strategies, and physical training. Although this requires careful interpretation of results, taking methodological issues into consideration, it may potentially ensure maximal utilization of each individual athlete's physical capacity, and the total capacity of the team. Rotation strategies and recovery are especially important during tournaments, where matches often are played on consecutive days, and coaches need to give players time to recover, but at the same time win games (Ronglan, Raastad, & Borgesen, 2006). It is still important to recognize that physical attributes are only one part of the complex game of handball, and to consider the variation in demands within and between games, which is likely influenced by tactics, opposition, and situation. Technical and tactical skills are arguably of superior importance, however, a physical base will nonetheless be required to execute these skills at the highest possible level.

Purpose of the study

Based on shortcomings in the available literature, the purpose of this thesis was to examine activity profiles of female and male elite handball matches, using new microtechnology devices which are better suited for detection of handball-specific micro movements than traditional methods. Specifically, fatigue development, indicated by temporal or transient changes in physical activity, was of interest, both on a team and individual player level. Findings from this study may have implications for team training and management, and will supplement existing literature on activity profiles and fatigue development in handball games.

Research questions

- 1) Are team activity levels and intensity profiles maintained throughout matches?
- 2) Do individual players experience transient fatigue after intense periods of play?
- 3) Do consecutive periods of play affect individual player activity?

2. Theory

2.1 *The game of handball*

Handball, or team handball, is an Olympic summer sport, which is played across the world, but is especially popular in the European countries. There are several male and female professional leagues, and the International Handball Federation (IHF) includes more than 190 national member federations (IHF, 2014). The male 2014 European Handball Championship was broadcasted in 175 countries (Infront Sports & Media, 2014), underlining the extent and popularity of the game.

A game of handball is played between two teams of seven players, including one goalkeeper, on a 20x40 meter indoor court, and the two halves of 30 minutes effective playing time are separated by a ten minute half-time break (IHF, 2005). Rules allow for unlimited interchanges (IHF, 2005), and from 2012, each team has the right to three team time-outs during a match, with a maximum of two in the same half (Norwegian Handball Federation, 2012). Absolute duration of halves and games can vary with stoppages and time-outs, and studies have reported absolute game times of 73-79 minutes for male matches (Michalsik et al., 2013; Povoas et al., 2012), and 71 minutes for female matches (Michalsik, Aagaard, & Madsen, 2015). Additionally, the second half of female matches was reported to be significantly longer than the first half by Michalsik et al. (2013), while halves in male matches showed no difference in the study by Michalsik et al. (2015).

During a game, depending on possession of the ball, teams will alter between defensive and attacking phases. On average, possession changes every 22-36 seconds, and attacks can be classified as counter-attacks or build-up attacks (Karcher & Buchheit, 2014). The majority of time ($88 \pm 6\%$) in possession is spent on build-up attacks (Karcher & Buchheit, 2014), and while most players play both in offense and defense, some are highly specialized defenders or attackers who interchange for each wave of attacking and defending. A team will consist of players in specialized positions, usually with goalkeepers, wings, backs, and pivots as the gross positional categories.

2.2 Physical demands of handball

There are many similarities between handball and other team sports, such as soccer, Australian football, and the rugby codes (league, union, and sevens), when it comes to player demands. These are all complex sports where both individual and team skills and attributes are required, including tactical, technical, physical, psychological, and social aspects (Michalsik et al., 2013; Ronglan et al., 2006; Wagner, Finkenzeller, Wurth, & von Duvillard, 2014). The importance of each demand may vary with playing level, position, team tactics, and with offensive and defensive phases (Karcher & Buchheit, 2014; Michalsik et al., 2013; Povoas et al., 2012), and as a result of this complexity, physical attributes are not as fundamental and obvious as in many individual sports. A variety of physical demands, potentially determining handball performance, have been mentioned in previous research, including aerobic and anaerobic capacity, ability to perform repeated high-intensity actions and changes of direction (CoD), anthropometry, coordination, strength, stability, flexibility, sprinting, accelerating, decelerating, and jumping (Karcher & Buchheit, 2014; Manchado, Tortosa-Martinez, Vila, Ferragut, & Platen, 2013; Michalsik et al., 2013; Povoas et al., 2012; Wagner et al., 2014). The range of demands highlights the multifaceted nature of physical performance in handball, and the challenge of quantifying these demands in a conforming manner.

2.2.1 Match demands

Activity profiling of handball games has provided a way of quantifying physical performance, and increased insight into match demands. Although studies are limited, it seems male players cover distances of around 3.6-4.4 km (Michalsik et al., 2013; Povoas et al., 2014b; Povoas et al., 2012), while female players cover around 2.9-4.0 km (Manchado et al., 2013; Michalsik, Madsen, & Aagaard, 2014), with mean speeds during male matches around 3.2-6.4 km·h⁻¹ (Karcher & Buchheit, 2014; Michalsik et al., 2013), and female matches around 4.2-5.3 km·h⁻¹ (Manchado et al., 2013; Michalsik et al., 2014). This is lower than in other team sports, possibly as a result of smaller pitch size, fewer players, or different tactical organization (Karcher & Buchheit, 2014). Variations between studies may be due to within- and between-game variations, inconsequent inclusion criteria, or differences in motion analyses. For example, while some authors require a specific amount of field time to be considered a whole-game player (Michalsik et al., 2014; Michalsik et al., 2013), others exclude substitutions and time-outs (Chelly et al., 2011), or do not specify inclusion criteria at all (Povoas et al., 2014a; Povoas et al., 2012). Furthermore, definitions of high-intensity activity have in some studies

included fast running, sprinting, and sideways high-intensity movement (Povoas et al., 2014a; Povoas et al., 2012), while others have defined this as only fast running and sprinting (Michalsik et al., 2014; Michalsik et al., 2013).

Accelerations, decelerations, and CoD occur frequently in handball, and require a significant amount of energy and muscular effort, as they are eccentric-related actions (Howatson & Milak, 2009; Karcher & Buchheit, 2014; Michalsik et al., 2013; Osgnach, Poser, Bernardini, Rinaldo, & di Prampero, 2010; Povoas et al., 2012), not only during high-intense work periods, but every time they are performed (Michalsik et al., 2013; Osgnach et al., 2010; Povoas et al., 2012). This may lead to an underestimation of demands when using traditional time-motion methods based on speed zones (Osgnach et al., 2010; Povoas et al., 2012), which was highlighted in a soccer study by Osgnach et al. (2010), who found that while only 18% of distance was covered in high-speed categories, 42% of the total energy was spent at high-power output. In handball games, Povoas et al. (2012) found that the most frequent high-demanding actions were CoD and stops, which accounted for 60% of all playing actions, and male players across different positions have been reported to perform 19.1-38.2 stops and 18.4-37.9 CoD during games (Povoas et al., 2014b; Povoas et al., 2012). Accelerations are rarely reported, although one study found that female players changed acceleration category (four positive and four negative categories) 191 times per minute (Manchado et al., 2013).

High-intensity activity is of special interest when analyzing activity profiles, as these actions are often crucial to match outcome, require speed, strength, and large amounts of energy, and might cause neuromuscular fatigue (Karcher & Buchheit, 2014). Male players have been reported to cover 7.9-23.2% of total distance and 1.7-4.3% of time in high-intensity movement categories (Michalsik et al., 2013; Povoas et al., 2014b; Povoas et al., 2012), while female players in one study were found to cover 3.3% of total distance and 0.8% of effective time in high-intensity categories (Michalsik et al., 2014). Although high-intensity efforts are expected to be performed regularly during matches, they are often performed in tight spaces on a small court (Karcher & Buchheit, 2014), restricting high absolute velocities, and therefore also recordings as high-intensity activity, when using locomotor categories. Consequently, previous methods may not have been sensitive enough to detect efforts demanding maximal or near maximal effort from the athlete. Differences in definitions of high-intensity activity complicate the interpretation of these findings further.

Some players may be involved in a greater amount and more intense contacts and duels, and perform technical actions, like shots and passes, more often, depending on tactical roles, position, and attacking or defending phases (Karcher & Buchheit, 2014). In male matches, defensive play has been shown to place higher demands in terms of high-intensity work and sideways movement, and also requires higher mean speeds (Michalsik et al., 2013; Povoas et al., 2012). On the other hand, mean speed was found to be similar for attacking and defending in female matches (Michalsik et al., 2014). Additionally, wing players performed more high-intensity work than backs and pivots in both genders (Michalsik et al., 2014; Michalsik et al., 2013; Povoas et al., 2014b), with inconclusive results for total distance, mean speed, and high-demanding actions.

2.2.2 Intermittent work and metabolic demands in handball

Game duration, as well as heart rate (HR) monitoring and estimations of oxygen uptake (VO_2) during games, indicates the need for aerobic energy production during matches (Karcher & Buchheit, 2014; Povoas et al., 2014a). Average HR of 70-87% and peak HR of 93-98% of individual maximal HR (HR_{max}) during games have been reported in both genders (Cunniffe, Fallan, Yau, Evans, & Cardinale, 2015; Kruger, Pilat, Uckert, Frech, & Mooren, 2014; Manchado et al., 2013; Povoas et al., 2014a, 2014b; Povoas et al., 2012), while mean VO_2 has been estimated from HR-measurements to be 79.4% of maximal VO_2 (VO_{2max}) for female players (Michalsik et al., 2014). High aerobic capacity, measured as VO_{2max} , has also been closely linked to running performance in female handball players (Manchado et al., 2013). Additionally, high-intensity actions require high anaerobic energy production and utilization of muscle glycogen, which is supported by average and peak values of blood lactate during games of 3.6 mM and 8.0 mM respectively (Povoas et al., 2014a), although this probably only represents the activity preceding the sample collection, and an accumulation in the blood, rather than the actual glycolytic activity in the muscles (Bangsbo, Iaia, & Krustup, 2007).

Mean values of HR and blood lactate do not fully describe the dynamic work environment of team sport athletes (Glaister, 2005). With repeated bouts of high-intensity work, interspersed with rest periods, handball is considered a physically demanding intermittent team sport (Michalsik et al., 2013), which places a different physiological load on players than continuous exercise (Marin et al., 2011). Studies on work:rest ratios have confirmed the intermittent pattern of handball games, with changes in activity every 2.1-5.9 seconds for male, female, and adolescent male players (Chelly et al., 2011; Michalsik et al., 2014;

Michalsik et al., 2013; Povoas et al., 2012), and changes between high- and low-intensity movement every 55 seconds for male players (Povoas et al., 2012). Work:rest ratios also imply that a good repeated sprint ability probably is beneficial for handball players to minimize fatigue during games (Povoas et al., 2012).

Spencer, Bishop, Dawson, and Goodman (2005) and Glaister (2005) reviewed metabolic responses to repeated sprint work, with the former emphasizing sprints of short-duration, as observed in team sports. Both reviews concluded that during single sprints, intramuscular adenosine triphosphate (ATP) stores are utilized, but largely preserved through buffering from phosphocreatine (PCr) degradation, and also anaerobic glycolysis, explaining only partly depleted PCr stores. Aerobic metabolism plays a smaller part in single short sprints, and Spencer et al. (2005) estimated that this system only delivers 3% of the energy contributing to a 3-second sprint, while PCr can account for 55%, anaerobic glycolysis for 32%, and cellular ATP stores for 10%. Regeneration of ATP from adenosine diphosphate may also occur during intense periods of work (Glaister, 2005).

Responses to repeated sprints are different compared to single sprints, and are influenced by sprint duration, sprint number, and recovery between sprints (Spencer et al., 2005). Both review articles suggested that the relative contribution from aerobic metabolism is increased with increased duration and number of bouts, countering a decreased contribution from anaerobic glycolysis. The increased contribution from aerobic processes may be caused by slow VO_2 on-kinetics, making this a slow-starting process, and allows for restoration of homeostasis (recovery of myoglobin, PCr, lactate, and inorganic phosphate) in low-intensity recovery periods when it is activated (Glaister, 2005). A reduced contribution from anaerobic glycolysis is likely attributed to changes in the metabolic environment, with suggested inhibition from depleted glycogen stores, reduced pH, or inhibition of phosphofructokinase by accumulation of cytosolic citrate (Glaister, 2005). Both reviews also suggested that reduced contribution from PCr is related to decreased performance with multiple sprints. With a half-time for PCr resynthesis of 21-57 seconds, many recovery periods between sprints will be too short for full restoration in team sports (Spencer et al., 2005). Resynthesis of PCr is complex, and is possibly dependent on oxygen- and ATP-availability, magnitude of depletion, recovery mode, and pH (Glaister, 2005; Spencer et al., 2005). Other metabolic and physiological factors contributing to energy and force production may also be involved in fatiguing of

repeated sprint ability, making this a complicated phenomenon which is difficult to study (Glaister, 2005; Spencer et al., 2005).

2.3 Methods for analyzing physical performance and fatigue

Different methods are used to quantify movement patterns, intensity, and exercise load in team sport training and competition, including on-field and off-field measures of external and internal demands. External demands are used to describe an athletes training stimuli (Scott, Lockie, Knight, Clark, & Janse de Jonge, 2013), and can be quantified by time-motion analyses, using video recording or wearable global positioning system (GPS) devices, or with wearable microtechnology devices. Internal demands are used to describe an athletes physiological response to a given external stimuli (Scott et al., 2013), and can be quantified with HR monitoring, blood samples of metabolites and hormones, ratings of perceived exertion, or a combination of these (Scott et al., 2013). The use of devices for physical activity profiling is in some sports already common practice, and in several Australian sports leagues, coaches and sports scientists can make use of this information in real time, also during competition (Sullivan et al., 2014a). This provides a way of clearly quantifying real-time physical performance for a large number of players, in situations where coaches may be more concerned with tactical decisions.

2.3.1 Time-motion analysis

Time-motion analyses have been the favored tool for activity profiling and research on fatigue in team sports the last decade, either by individual player video recording, multiple-camera computerized tracking, or GPS. However, variation in methods used for time-motion analysis makes it difficult to compare absolute results across studies and systems (Randers et al., 2010). Video recordings of individual players have been analyzed with hand notational systems, or with digitalized tracking. Even though these methods can provide useful information on match demands in various sports, they require experienced investigators, are time-consuming, and reliability is questionable, especially when estimating sprint activity with notational systems (Roberts, Trewartha, & Stokes, 2006). Multiple-camera semiautomatic- or automatic computerized tracking systems have made tracking of several players simultaneously possible, and has lead to greater objectivity and more comprehensive analyses, through increased resolution and decreased reliance on experienced operators (Randers et al., 2010). Also, the developments in GPS-tracking have allowed for real-time information on physical performance (Cummins, Orr, O'Connor, & West, 2013; Spencer et

al., 2005), where early studies used sampling frequencies of 1 Hz and 5 Hz. Recent studies use 10 Hz, which is suggested to be sufficient to measure both constant velocity, acceleration and deceleration, at least during straight-line running (Varley, Fairweather, & Aughey, 2012). On the other hand, Buchheit et al. (2014) still found very large variations in measures with 15 Hz GPS, particularly in accelerations and decelerations, and advise practitioners to take care when comparing data from different models and units. At the same time, these results can also be questioned, as some GPS-systems claim to use 15 Hz, but in reality use a lower resolution and extrapolate to 15 Hz, using accelerometer data (R. J. Johnston, Watsford, Kelly, Pine, & Spurrs, 2014). 15 Hz units have also been reported to have lower interunit reliability and validity compared 10 Hz units, although both proved to measure movement demands better than 1 Hz and 5 Hz units (R. J. Johnston et al., 2014).

As previously mentioned, time-motion analyses based on time spent in speed zones may lack sensitivity to capture short energy-demanding actions (Karcher & Buchheit, 2014; Roberts et al., 2006). Osgnach et al. (2010) also suggest measuring load in terms of video-based speed is far from optimal, as the metabolic demands of a given speed can differ, depending on the acceleration. Additionally, variations in classification of speed zones and definitions of sprinting make comparisons between studies challenging (Cummins et al., 2013; Dellaserra, Gao, & Ransdell, 2014). GPS measurements also have obvious limitations in indoor sports, such as handball (Dellaserra et al., 2014). Still, Karcher and Buchheit (2014) state that data from these technologies can be useful for gathering knowledge on handball match demands. Also, although large between-system differences were found in terms of absolute measures, a comparison of different video- and GPS-based time-motion methods showed that different systems could detect similar declines in physical performance over a soccer game, allowing for investigation of game-induced fatigue with all systems (Randers et al., 2010).

2.3.2 Physical and physiological tests

In addition to activity profiling, measures of physical performance or physiological response to activity are used to indicate fatigue, most often by comparing results obtained during or after matches to pre-game baseline values. Performance tests can include measures of sprinting, repeated sprinting, jumping, intermittent endurance, and strength, sometimes complemented with more detailed measures of muscle activity or power development, in order to investigate the mechanisms behind performance decrements. Physiological tests often measure metabolic or hormonal responses through HR monitoring, blood samples, or muscle

biopsies, and in some cases, subjective measures of exertion, wellness or muscle soreness are included in research.

2.3.3 Microtechnology and Player Load™

The introduction of microsensors with accelerometers, gyroscopes, and magnetometers has allowed for more detailed quantification of sports specific actions and external load. Using specially developed algorithms, these devices can measure micro movements that would not be captured as precisely using time-motion analysis. Due to large parts of team sports consisting of non-running based work (e.g. jumping, turning, CoD, and tackles), the Australian Institute of Sport and Catapult Sports developed Player Load™ as a measure of physical performance and exertion based on changes in acceleration (Catapult Sports, 2013a), which could potentially be highly relevant for measuring physical performance in handball. For running based sports, accumulated Player Load™ is strongly correlated with distance covered, due to the vertical accelerations generated by forces from heel strike (Catapult Sports, 2013a; Polglaze, Dawson, Hiscock, & Peeling, 2014). For example, Polglaze et al. (2014) and Gallo, Cormack, Gabbett, Williams, and Lorenzen (2014) show a strong ($r = 0.868$) and nearly perfect ($r = 0.97$) correlation between total Player Load™ and total distance in field hockey and Australian Football, while Polglaze et al. (2014) also found a moderate relationship ($r = 0.49$) between Player Load™·min⁻¹ and relative distance (m·min⁻¹). Furthermore, studies conclude that Player Load™ can be used as an alternative measure when GPS is not available (Boyd, Ball, & Aughey, 2013; Polglaze et al., 2014).

Studies using Player Load™ have found that data from microtechnology devices produced by Catapult Sports can discriminate between playing levels (Boyd et al., 2013), playing positions (Boyd et al., 2013; Gabbett, Jenkins, & Abernethy, 2012; Jones, West, Crewther, Cook, & Kilduff, 2015; Polley, Cormack, Gabbett, & Polglaze, 2015), periods of a game (Cormack, Smith, Mooney, Young, & O'Brien, 2014; Jones et al., 2015; Polley et al., 2015), training and competition (Boyd et al., 2013; Gabbett et al., 2012; Montgomery, Pyne, & Minahan, 2010), and is related to technical skills (Sullivan et al., 2014b). It is also found that Player Load™ may be a practical measure to quantify external training load (Gallo et al., 2014; Scott et al., 2013), and may be an indicator of muscle damage (Young, Hepner, & Robbins, 2012). Player Load™·min⁻¹ has also been validated as a useful measure of intensity for Australian football (Mooney, Cormack, O'Brien B, Morgan, & McGuigan, 2013), and Jones et al. (2015) support the use of Player Load™ along with other measures of intensity to monitor performance and

fatigue during match preparation and play. In addition, accelerometers from different manufacturers have shown usefulness to detect fatigue, overtraining, injury, and demands of competition and training (Cummins et al., 2013).

In some frequent-contact team sports, like handball, Player Load™ and other output data from microsensors are particularly useful (Karcher & Buchheit, 2014; Varley, Gabbett, & Aughey, 2013). Devices are also applicable to indoor sports (Montgomery et al., 2010), and require minimal involvement during data collection making them highly relevant for handball. Output data can also be monitored in real-time, and analyses are far less time-consuming than traditional methods. Even though there are several benefits of using microtechnology, and research from other sports show promising results for the use of these, this is a relatively new field of research, and a stronger base of literature is therefore required. Until now, most studies have looked at male players, and no research has been completed to confirm the validity or reliability of algorithms, originally developed for rugby league, for handball-specific movements and match play. Devices and software are also costly, and currently most sports do not permit use in competition, making it hard to compare and combine exercise load from training and matches (Dellaserra et al., 2014). Furthermore, not all athletes may feel comfortable with wearing the vest and device in important matches and training sessions.

2.4 *Fatigue and match activity profiles in handball*

Fatigue and pacing are common themes in team sports research, and newer technology has provided an improved insight into the potential mechanisms of acute fatigue, which again has led to a deeper understanding of physical performance in team sports (Waldron & Highton, 2014). Glaister (2005) defines fatigue during multiple sprint work as a “progressive decline in power output”, whereas Waldron and Highton (2014) define fatigue in a high-intensity intermittent team sport setting as “the eventual reduction in performance compared with baseline values”. Fatigue is therefore characterized by a task-dependent decline in performance, which in team sports can be identified as distance covered or intensity at which an athlete is working, across halves, periods, or temporarily in matches (Waldron & Highton, 2014). One method of examining fatigue is a temporal analysis, where fatigue is examined over the course of a match, either based on pre- and post-game tests, or comparisons between periods or halves of games. Another method is a transient analysis, where the activity in the most intense periods, and in subsequent periods, are analyzed.

2.4.1 Indications of fatigue in activity profiles

Only a few studies of fatigue have been conducted using time-motion analysis in handball, and all of these have used individual video recordings to measure activity (Table 1).

Table 1 Overview of previous time-motion studies of fatigue in handball, using video recordings.

Study	Gender	Level	Matches	Samples
Michalsik et al. (2014)	Female	Danish League	46 League matches	83
Povoas et al. (2014a)	Male	Portuguese League	10 League matches	40
Michalsik et al. (2013)	Male	Danish League	62 League matches	82
Povoas et al. (2012)	Male	Portuguese League	10 League matches	30
Chelly et al. (2011)	Male adolescent	Top-division	6 Training matches	96

A consistent finding in all of the studies was overall decreases in high-intensity activity in the second half, compared to the first, although Povoas et al. (2012) only found this for defending and not for attacking play. Michalsik et al. (2014) and Michalsik et al. (2013) found significant differences and tendencies to decreased mean speed in the second half, but no differences in total distance between halves, while Chelly et al. (2011) found a decline in total distance in the second half. Low-intensity activity was increased in the second half in the study by Michalsik et al. (2014), while Chelly et al. (2011) found more walking and less jogging in the second half. In the studies by Povoas et al. (2012) and Povoas et al. (2014a), there were fewer stops, CoD, and one-on-one situations, as well as increased time between activity changes in the second half. Compared to the first half, mean HR and time spent in $>80\%$ of HR_{max} was also lower. In regard to periods of the game, Povoas et al. (2012) found the most high-intensity running in the first five minutes of the game, and the least in the first five minutes of the second half. Similarly, Michalsik et al. (2013) found that players covered more total and high-intensity distance in the first five minutes of the first half than in the first five minutes of the second half, higher total distance in the first ten minutes than in the last ten minutes of the first half, but higher total distance in the last five minutes of the second half than in the last five minutes of the first half. Collectively, these findings may indicate development of fatigue during and towards the end of handball games (Chelly et al., 2011; Michalsik et al., 2014; Michalsik et al., 2013; Povoas et al., 2014a; Povoas et al., 2012).

2.4.2 Indications of fatigue in physical and physiological tests

Other studies of fatigue in handball, not using time-motion analysis have shown changes in physiological and performance parameters caused by handball games. Sprint performance has been reported to decrease post-match in female (Ronglan et al., 2006) and male players (Chatzinikolaou et al., 2014; Povoas et al., 2014a), and also after intense periods of the second half (Povoas et al., 2014a). Decreased post-game jumping ability in male players was reported by Thorlund, Michalsik, Madsen, and Aagaard (2008) and Povoas et al. (2014a), and 24 hours post-game by Chatzinikolaou et al. (2014). Thorlund et al. (2008) additionally found decreased rate of force development, maximal voluntary contraction (MVC), and neuromuscular activity in both jumping and isometric strength tests post-game, which is supported by findings of decreased upper and lower body strength 24 hours post-game in Chatzinikolaou et al. (2014). Furthermore, declines in the YoYo-IR2 endurance test and agility, as well as increases in perceived muscle soreness, markers of muscle damage, oxidative stress, and inflammatory responses, have been reported after handball games (Chatzinikolaou et al., 2014; Marin et al., 2011), although repeated sprinting ability remained unchanged after intense periods in both halves and after games in Povoas et al. (2014a).

2.5 Fatigue and activity profiles in other team sports

Although there is a growing body of literature on fatigue in team sports, only a few studies have used microtechnology and Player Load™, while the majority have been conducted with GPS- or video-based time-motion analysis. Video-based studies are especially common in soccer, as federation rules do not allow for the use of microsensors in official games, as opposed to Australian football and the rugby codes, where these are allowed. As previously mentioned, inclusion criteria and definitions of speed- and acceleration zones vary between studies, and sports differ in playing time, dynamics, field size, players, and rules, limiting comparisons and the validity for handball.

2.5.1 Between-half differences

The most basic indicator of fatigue, and one commonly reported, is declines in activity from the first to the second half of matches. This has been reported for Player Load™·min⁻¹ in rugby union (Jones et al., 2015) and netball, although only statistically lower for lower-level centers (midfielders) (Cormack et al., 2014). Non-significant decreases were also reported in Australian football (Mooney, Cormack, O'Brien, & Coutts, 2013). Absolute distance (m) has been reported to decrease in the second half in soccer (Bradley, Di Mascio, Peart, Olsen, &

Sheldon, 2010; Bradley & Noakes, 2013; Bradley et al., 2009; Carling & Dupont, 2011; Mohr, Krustup, Andersson, Kirkendal, & Bangsbo, 2008; Mohr, Krustup, & Bangsbo, 2003; Rampinini, Coutts, Castagna, Sassi, & Impellizzeri, 2007; Rampinini, Impellizzeri, Castagna, Coutts, & Wisloff, 2009), along with non-significant decreases in soccer (Di Salvo et al., 2007) and rugby union (Roberts, Trewartha, Higgitt, El-Abd, & Stokes, 2008). Similarly, relative distance ($\text{m}\cdot\text{min}^{-1}$) was reported to decrease in Australian football (Mooney et al., 2013; Varley et al., 2013), rugby sevens (Higham, Pyne, Anson, & Eddy, 2012), and soccer (Varley et al., 2013), along with non-significant decreases in Australian football (Aughey, 2010).

Sub-categories are often collapsed in order to examine high- and low-intensity activity, as high-intensity actions could be crucial for match outcome and fatigue. Second half decreases in high-intensity activity are reported in soccer (Bradley & Noakes, 2013; Carling & Dupont, 2011; Di Salvo, Gregson, Atkinson, Tordoff, & Drust, 2009; Mohr et al., 2008; Mohr et al., 2003; Rampinini et al., 2009), Australian football (Varley et al., 2013), rugby league (Varley et al., 2013), together with non-significant decreases in rugby union (Jones et al., 2015; Roberts et al., 2008), Australian football (Mooney et al., 2013), and soccer (Varley et al., 2013). Bradley et al. (2009) reported significant declines for all positions except for attackers, while Rampinini et al. (2007) found declines only for players with high values of high-intensity activity in the first half, and not for players with lower values. This is similar to other findings from soccer and Australian football (Bradley & Noakes, 2013; Coutts, Quinn, Hocking, Castagna, & Rampinini, 2010). In contrast, Akenhead, Hayes, Thompson, and French (2013) reported that there was a non-significant increase in high-speed running and sprint distance in soccer. Fewer studies examine low-intensity activity as a category, where second half values are decreased in studies of soccer (Mohr et al., 2008; Mohr et al., 2003; Varley et al., 2013) and Australian football (Mooney et al., 2013; Varley et al., 2013), while low-speed movement was non-significantly lower in rugby union (Jones et al., 2015). On the other hand, Di Salvo et al. (2007) reported that soccer players covered more distance in the lowest movement category ($0\text{-}11 \text{ km}\cdot\text{h}^{-1}$) in the second half, and values were unchanged in rugby league (Varley et al., 2013).

2.5.2 Temporal changes through quarters and periods

Researchers frequently divide games into shorter periods, or quarters where this is natural, in order to more accurately describe changes in activity throughout matches. Declines in activity

measures, relative to playing time, are reported across periods of five to 15 minutes in soccer (Bradley & Noakes, 2013), rugby union (Jones et al., 2015), netball (Cormack et al., 2014), lacrosse (Polley et al., 2015), Australian football (Mooney et al., 2013; Aughey, 2010), and rugby league (Sykes, Twist, Nicholas, & Lamb, 2011; Waldron, Highton, Daniels, & Twist, 2013). Absolute or high-intensity distance also decreased through periods of ten to 15 minutes in soccer (Bradley et al., 2009; Carling & Dupont, 2011; Mohr et al., 2008; Mohr et al., 2003), rugby league (Kempton, Sirotic, & Coutts, 2015) and rugby union (Roberts et al., 2008).

A common observation is elevated activity levels in the opening phases of matches or halves, compared to other periods. This was found for values relative to playing time in soccer (Bradley & Noakes, 2013), rugby union (Jones et al., 2015), rugby league (Sykes et al., 2011; Waldron et al., 2013), Australian football (Mooney et al., 2013; Aughey, 2010), lacrosse (Polley et al., 2015), and for lower-level centers in netball (Cormack et al., 2014). Absolute or high-intensity distance in the first period was also reported as the highest in rugby league (Kempton et al., 2015), rugby union (Roberts et al., 2008), and soccer (Bradley et al., 2009; Mohr et al., 2008; Mohr et al., 2003).

The final stage of the game is especially interesting in regard to fatigue. Compared to the previous period, the final five to 15 minutes of a match are reported to decrease, although non-statistical, in relative and absolute activity measures, for some positions in netball (Cormack et al., 2014) and lacrosse (Polley et al., 2015), and for players in Australian football (Mooney et al., 2013; Aughey, 2010), rugby league (Waldron et al., 2013), rugby union (Roberts et al., 2008), and soccer (Bradley et al., 2009; Carling & Dupont, 2011; Mohr et al., 2008; Mohr et al., 2003). On the other hand, studies have reported non-statistical increases in the final five to 15 minutes, compared to the previous periods, for some positions in lacrosse (Polley et al., 2015) and netball (Cormack et al., 2014), and for players in rugby union (Jones et al., 2015), rugby league (Kempton et al., 2015), and soccer (Bradley et al., 2010; Bradley & Noakes, 2013). Sykes et al. (2011) reported that for rugby league players, the relative low-intensity distance increased, while the relative overall and high-intensity distance decreased in the final period compared to the previous, although not significantly. The chosen time-intervals analyzed may be the cause of differences between studies, as 5-minute periods would be more sensitive to changes than 15-minute periods.

2.5.3 Accelerations and decelerations

Studies on acceleration and deceleration profiles in team sports are limited. Using microsensors, Jones et al. (2015) reported declines in rugby union across all magnitudes of acceleration and deceleration, with the first 10-minute periods of the halves as the highest. The final stage was non-significantly higher than the previous period for all accelerations and decelerations, except high decelerations, which was non-significantly lower. Polley et al. (2015) found varied results across positions in lacrosse, although all positions experienced declines in decelerations, and attackers and midfielders had declined values of acceleration. The first quarter was the highest across all positions for moderate accelerations and decelerations, while high accelerations were highest in the first period for midfielders and attackers. The last period also varied, with moderate accelerations and decelerations for midfielders and high accelerations for attackers increasing, and all other values decreasing compared to the previous period, although not all were statistically different. With GPS, acceleration and deceleration values have decreased between halves across a range of team sports (Akenhead et al., 2013; Higham et al., 2012; Varley et al., 2013). When analyzed in 15-minute periods, the same pattern as previously described has been observed, with the highest value in the first 15 minutes, declines across periods, and non-significant declines in the final 15 minutes compared to the previous period (Akenhead et al., 2013; Aughey, 2010).

2.5.4 Transient fatigue

Team sport athletes do not only develop fatigue over the time course of a match, but also during short periods within games. This is often referred to as temporary or transient fatigue, and is indicated by reductions in performance below the match average after the most intense periods of a game. Usually, 5-minute periods are analyzed, as this seems to account for situational variables occurring randomly during games (Waldron & Highton, 2014). When Akenhead et al. (2013) examined accelerations and decelerations with GPS in soccer, high accelerations and high decelerations were lower than the match average in the 5-minute period following their respective peak, but values were restored to average values ten minutes post-peak. A similar development, five and ten minutes after a peak, was also observed by Bradley and Noakes (2013), but with high-intense running distance. Several other studies have also found decreases 5-minute post peak compared to match average of high-intensity or high-speed running distance in soccer and rugby league (Bradley et al., 2010; Bradley et al., 2009; Carling & Dupont, 2011; Di Mascio & Bradley, 2013; Kempton et al., 2015; Mohr et al., 2008; Mohr et al., 2003).

2.5.5 Physical and physiological indicators of fatigue

Physical and physiological tests have also indicated fatigue after team sport competition. Decreases in sprinting ability, strength variables, jump heights, and endurance performance have been reported following soccer matches (Andersson et al., 2008; Krstrup et al., 2006; Krstrup, Zebis, Jensen, & Mohr, 2010; Rampinini et al., 2011), along with indicators of muscle damage (Andersson et al., 2008) and low intramuscular glycogen stores (Krstrup et al., 2006). Decreased strength and jumping performance, and indicators of muscle damage have also been reported after rugby league (McLellan, Lovell, & Gass, 2011), although repeated jumping performance was unchanged after Australian football matches in one study (Duffield, Coutts, & Quinn, 2009).

2.6 Suggested mechanisms of fatigue in intermittent sports

Mechanisms of acute fatigue development are usually classified by origin as either central or peripheral, and likely, team sport fatigue is the result of a combination of these factors, depending on the type of work performed (Waldron & Highton, 2014). Peripheral fatigue has been defined as "fatigue produced by changes at or distal to the neuromuscular junction" (Gandevia, 2001), and "comprises biochemical changes within the metabolic milieu of the working muscle leading to an attenuated response to neural excitation" (Amann, 2011). Many peripheral factors have been suggested to impact fatigue development, although combined results from team sport studies are often inconclusive. Mechanisms mentioned to possibly affect development of fatigue include elevated levels of lactate, accumulation of hydrogen ions, inorganic phosphate, or potassium ions (K^+), depletion of PCr stores, loss of purine nucleotides, lower glucose levels, glycogen depletion, dehydration, hypothermia, damage to force-producing and -transmitting structures, alterations in the excitation-contraction coupling, and impairment of the stretch-shortening cycle (Andersson et al., 2008; Bangsbo et al., 2007; Glaister, 2005; Mohr, Krstrup, & Bangsbo, 2005; Rampinini et al., 2011; Reilly, Drust, & Clarke, 2008; Spencer et al., 2005; Waldron & Highton, 2014). A common conclusion is that mechanisms behind temporal fatigue experienced towards the end of matches are different from the mechanisms causing transient fatigue after high-intense periods (Bangsbo et al., 2007; Mohr et al., 2005; Reilly et al., 2008).

As handball games are almost exclusively played indoors, in a controlled climatic environment, dehydration and hyperthermia can probably be ruled out as major causes of temporal fatigue, as this is most likely only occurring in hot environments in team sports

(Mohr et al., 2005; Povoas et al., 2014a). Blood glucose levels are also found to be maintained throughout games, and are probably not low enough to affect performance in soccer and handball (Krustrup et al., 2006; Povoas et al., 2014a). The most likely candidate mechanism for this type of fatigue is therefore depletion of glycogen stores in individual muscle fibers as found by Krustrup et al. (2006), although research is limited in a handball setting. This could potentially impair maximal effort in single and repeated sprints towards the end of matches, and glycogen loading and resynthesis strategies are therefore suggested to be beneficial for minimizing performance decrements (Spencer et al., 2005). On the other hand, Glaister (2005) did not consider this a major limiting factor for maintaining ATP levels during multiple sprints, and it may therefore be of greater concern in a tournament situation, where several games are often played with limited recovery periods.

It does not seem that accumulation of lactate or hydrogen ions from anaerobic energy production is casually linked to transient fatigue (Bangsbo et al., 2007; Mohr et al., 2005; Reilly et al., 2008), and although Glaister (2005) propose accumulation of inorganic phosphate from PCr breakdown as a cause of fatigue in multiple sprint work, Bangsbo et al. (2007) suggest this is not a major cause in team sport settings. The same can be said for depletion of PCr stores, where Mohr et al. (2005) and Bangsbo et al. (2007) do not consider this as critical and a major factor in team sports, although levels may be low in individual fibers. On the other hand, Glaister (2005) and Spencer et al. (2005) relate PCr degradation and resynthesis to reduced repeated sprint performance. For transient fatigue, an accumulation of interstitial K^+ is still recognized as a likely candidate mechanism, although team sport research is limited (Bangsbo et al., 2007; Glaister, 2005; Mohr et al., 2005; Reilly et al., 2008). This would affect performance by causing an electrical disturbance in the muscle cell, interrupting the membrane potential and consequently force production (Bangsbo et al., 2007; Mohr et al., 2005).

Central fatigue has been defined as "a progressive reduction in voluntary activation of muscle during exercise" (Gandevia, 2001), and involves "a failure of the CNS [central nervous system] to "drive" the motor neurons, i.e., a reduction in central motor drive" (Amann, 2011). Post-game strength tests in soccer have shown that there may be an alteration in neural drive after a game, and that the highest central fatigue was observed in players with the highest drop in MVC and sprint performance (Rampinini et al., 2011). The authors could not determine the origin of the central fatigue, but suggest that it may originate from the spinal or

supraspinal level, possibly due to biochemical changes. They also concluded that a decreased MVC post-game is more attributed to central than peripheral factors. Similarly, Thorlund et al. (2008) found decreased neuromuscular activity during strength tests after a handball game, and suggested alterations in motor unit recruitment or firing frequency were reasonable mechanisms behind this decline.

2.7 Central control and pacing strategies in team sports

With more comprehensive analyses and a deeper understanding of team sport physical performance, the concept of pacing has received increasing attention, which "in team sport should be considered as the *distribution of energy resources* that optimize match-running performance" (Waldron & Highton, 2014). Researchers struggle to find a clear and consistent mechanism causing declines in team sport performance, and Edwards and Noakes (2009) therefore suggest the existence of a complex central metabolic "control" system, consciously and subconsciously regulating exercise intensity. This system would ensure no maximal utilization, and consequent failure, of any physiological system, and thus there would not be one single system to "blame" for fatigue observed in team sports. In short, the authors explain this "control" system as the central nervous system setting a subconscious exercise level based on previous experience, knowledge of duration, and afferent sensations (e.g. energy stores and temperature) from peripheral systems. Subconscious and conscious systems thereafter dynamically regulate effort and intensity based on peripheral feedback. They support the existence of this system with the fact that several studies do not find critically low levels of dehydration, core temperatures, or metabolite concentrations. Therefore, declines in these levels are more likely to provoke a reaction in the brain leading to reduced effort, than to cause a catastrophic failure.

Central control of effort and intensity is often associated with the concept of pacing, which has been indicated by higher work rates in substitute players compared to whole-match players in several team sports (Black & Gabbett, 2014; Bradley & Noakes, 2013; Carling, Espie, Le Gall, Bloomfield, & Jullien, 2010; Higham et al., 2012; Mohr et al., 2003). Knowledge of duration of small-sided games (Gabbett, Walker, & Walker, 2015) and repeated sprints (Billaut, Bishop, Schaerz, & Noakes, 2011) has been reported to alter exercise intensity, further supporting this theory. Also, high work rates in the opening periods or in the first half can affect work performed in subsequent periods, with players performing

lower levels of work maintaining intensity (Bradley & Noakes, 2013; Coutts et al., 2010; Rampinini et al., 2007).

Edwards and Noakes (2009) summarize observations and suggestions of pacing in a model, accounting for strategies adopted by players at different stages of a match. They suggest an individual self-regulated pacing strategy is set prior to a match, based on experience, game duration, and current physiological status. This "meta" pacing strategy aims to ensure that players complete the full duration of the match, having worked at intense, but sustainable levels. At half-time, status is re-evaluated and a new "meso" pacing strategy is set, which is probably lower due to depletion of energy stores and accumulation of metabolites. The mean of the "meso" strategies of each half, is likely close to the "meta" strategy. Within each half, physical performance is dynamically regulated in "micro" plans, which regulate intensity taking into account very intense periods threatening peripheral homeostasis, and ensure "meso" and "meta" plans are not compromised.

Waldron and Highton (2014) reviewed observations of match activity profiles in different team sports, and found that these are characterized by different pacing profiles, influenced by limitations in interchanges. The most common profile across sports for whole-match players is a "slow-positive" profile, where intensity progressively declines throughout the match. When a player is introduced as a substitute for the first time, a "one-bout, all-out" profile is often observed, with a high initial work rate. If a player is allowed to return for a second interchange bout after a recovery period, a "second-bout reserve" profile is likely seen, with a low initial work rate, and an "end-spurt" (increased work rate towards the end). With unlimited interchanges, a "one-bout, all-out" profile is most likely adopted, due to the unknown duration of bouts.

Some authors have also looked into how players pace their on-field work, and suggest players attempt to preserve capacity for high-intensity actions by reducing low- and medium-intensity work (Cormack, Mooney, Morgan, & McGuigan, 2013; Di Salvo et al., 2007; Duffield et al., 2009; Granatelli et al., 2014; R. D. Johnston, Gabbett, & Jenkins, 2015; Mooney, Cormack, O'Brien, & Coutts, 2013), or by increasing low-intensity recovery between repeated high-intensity efforts and sprints (Gabbett, Wiig, & Spencer, 2013). However, the opposite was reported in Australian football, where high-intensity work and maximal accelerations declined while low-intensity work was preserved through quarters (Aughey, 2010).

2.8 Summary

In summary, previous studies have shown that handball matches place diverse physical demands on players, varying with player position and phases of the game. Although mean intensities and total distances are lower than in other team sports, and a large amount of time and distance is spent at low- and moderate-intensity, short-lasting energy demanding movements, such as accelerations, stops, CoD, and one-on-one situations, make the sport highly physically demanding. The intermittent nature of the game, underlined by studies of work:rest ratios, results in a different physiological and metabolic response than continuous work, requiring high levels of both anaerobic and aerobic energy production.

Partly due to limitations of measuring indoor sports, only video-based time-motion analyses have been conducted in handball. These have indicated declines in movement variables across halves and periods, specifically in high-intensity activity. Commonly, the highest intensity is found in the first periods of the match, with declines throughout the match. Together with findings of decreased physical performance and markers of muscle damage and inflammatory response, this is indicative of match-induced fatigue.

Studies of fatigue development in other team sports have used both single- and multiple-camera video-based analyses, GPS, and microtechnology in order to detect temporal and transient changes in activity. Collectively, it appears absolute and relative measures of activity are decreased between halves and over periods. As reported in handball studies, and studies of other team sports using Player Load™, the first period of play is generally the highest. Furthermore, the final period is often the least intense, although some studies have reported non-significant increases in the final period of play. Transient fatigue is often apparent as declines below the match average after high-intense periods.

The exact mechanisms behind decreased activity remain uncertain, although accumulation of interstitial K^+ and PCr degradation may be involved transient fatigue and decreased repeated sprint ability, and glycogen depletion may be involved in temporal fatigue. Changes in activity patterns may also be the result of a complex central “control” system, regulating exercise intensity based on previous experience, physiological “status”, and perceived duration of the match.

3. Method

3.1 Study design and experimental approach

The present thesis is an observational study, where a microtechnology device (Catapult OptimEye S5) was used to obtain match data and describe possible indicators of fatigue in six female and three male elite international handball matches. The matches were played during the first half of the 2014/2015 competitive season. Data storage was approved by the Norwegian Social Science Data Service.

3.2 Subjects

Subjects were highly trained elite female and male handball players, representing the female Norwegian national team and male Norwegian national recruit team. Players on both teams competed in elite handball leagues across Europe, and the female team went on to win the European Championships, a few months after the observed matches. Due to the current restrictions from the IHF regarding the use of microtechnology devices in official championship tournaments, data was collected in friendly matches and four-nation tournaments. Players participated voluntarily, and could at any time withdraw from data collections.

The female team wore devices in two friendly matches against Hungarian club teams and six Golden League tournament matches. The friendly matches were excluded from further analyses due to differences in match characteristics, opposition, importance, and preparation compared to the Golden League matches. The Golden League tournament is a series of three four-nation tournaments over one season, which was started on the initiative from the Norwegian, Danish, and French handball federations. These three federations host one tournament each per season, where the three respective national teams are accompanied by one invited national team (L'Equipe, 2013). The two Golden League tournaments in this study were held seven weeks apart, and during each tournament the team played three matches in four days. The teams competing were all considered as world class. The male team played three B-tournament matches over three consecutive days, against two similar recruit teams and one lower level national team. All games were considered to be played against teams of a similar level.

A maximum of 15 players could be analyzed for each game, due to a restricted number of devices and players involved in each game. From the six Golden League matches 14 different female outfield players were analyzed, each represented 2-6 times (mean \pm standard deviation (SD) = 4.0 ± 1.7), resulting in a total of 55 female match data samples (31 backs, 14 wings, and 10 pivots). From the three B-tournament matches, 13 individual male outfield players were analyzed, each represented 2-3 times (2.8 ± 0.4), resulting in a total of 36 male match data samples (16 backs, 12 wings, and 8 pivots).

3.3 *Catapult OptimEye S5 and Inertial Movement Analysis*

The OptimEye S5 (Catapult Sports, Australia), is an electronic device with an inertial measurement unit (IMU), approximately 9.6 cm tall, 5.2 cm wide, and 1.3 cm thick, weighing 66.8 g, used for measurement of movement, forces, and orientation. The device includes a built-in 100 Hz tri-axial accelerometer (± 2 -12g) and 200-2000 degrees·second⁻¹ gyroscope, as well as a 100 Hz magnetometer (Catapult Sports, 2014), which essentially is an electronic compass (Gabbett, 2013). This technology allows for high frequency detection of unit orientation and direction, combining information about acceleration, deceleration, rotation, and impact forces in an “Inertial Movement Analysis” (IMA), without connection to GPS, and is therefore also applicable to indoor sports.

3.3.1 Inertial Movement Analysis (IMA)

Raw accelerometer and gyroscope data are used in an IMA, where unit orientation, athlete movement, and acceleration of gravity is adjusted for. By creating a non-gravity vector, output accelerations represent real accelerations (Figure 1). This is made possible by an advanced Kalman filter, and allows for detection of sports-specific micro movements, expressed in the IMA output report (Catapult Sports, 2013b).

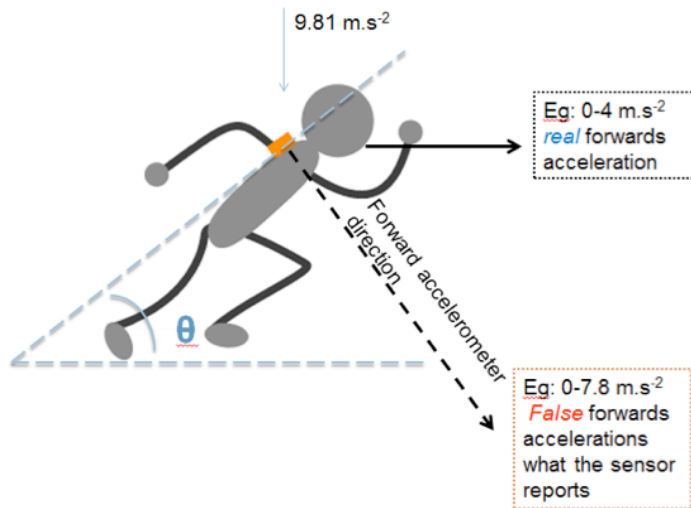


Figure 1 "Illustrates an example of the effect gravity plays in acceleration data interpretation. This display shows a theoretical "real" forwards acceleration trace against the "false" trace reported in non-IMA situation." (Catapult Sports, 2013b)¹.

3.3.2 Accelerations, decelerations, and CoD

In order to discriminate between different game-specific movements, the Catapult OptimEye S5 calculates the magnitude and direction of each effort for the IMA analysis. The result is output data where efforts are categorized as accelerations, left CoD, right CoD, or decelerations, and further into low, medium, or high magnitudes (Catapult Sports, 2013b). Other features of the OptimEye S5 include detection of jumps and tackles, HR monitoring, and ball tracking, but due to uncertain validity and reliability of these for handball matches, they were not analyzed in this study.

To calculate the magnitude of an effort, the start and end point is detected in the acceleration curves, and the area under the curve for the anterior-posterior and mediolateral accelerations is summarized. This sum is then used in the final calculation of magnitude, and is reported as a change in velocity. For accelerations, decelerations, and CoD, efforts were categorized into low, medium, and high based on preset velocity band settings from the manufacturer. Low-intensity efforts were defined as efforts between $1.5\text{-}2.5\text{ m}\cdot\text{s}^{-1}$, medium-intensity as efforts between $2.5\text{-}3.5\text{ m}\cdot\text{s}^{-1}$, and high-intensity as efforts $>3.5\text{ m}\cdot\text{s}^{-1}$. With these categories, the aim is that free running is excluded from the IMA analysis (Catapult Sports, 2013b).

¹ From *Sprint Help - Inertial Movement Analysis (IMA)* (p. 11), by Catapult Sports, 2013. Reprinted with permission.

The direction of an effort is determined by dividing the direction of applied force into four main categories based on an initial twelve 30° directional segments. Taking orientation of the unit into account before and during the effort, it is either defined as an acceleration (-45° to 45°), right CoD (45° to 135°), deceleration (135° to -135°), or left CoD (-135° to -45°) (Figure 2). As a result, a CoD using the right foot is in most cases registered as a left CoD in the IMA output and vice versa (Catapult Sports, 2013b). An important recognition is that a so-called "acceleration" in the IMA output data may not represent what a coach or trainer usually would define as a true running acceleration, but rather represents a short effort of whole body acceleration. As it is the position of the unit, and therefore the superior part of the upper body, that is used for defining directions, body position will also affect which efforts are classified as accelerations, decelerations, or CoD.

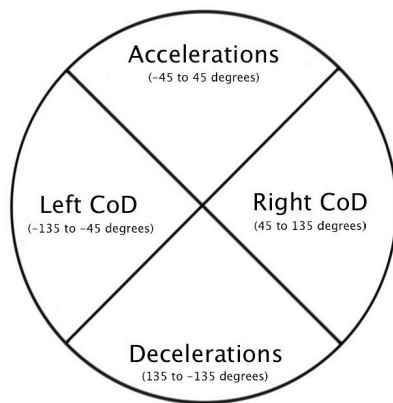


Figure 2 Graphic display of the segments used to categorize efforts into of accelerations, decelerations, CoD to the left, or CoD to the right, simplified from Catapult Sports (2013b).

3.3.3 Calculation of Player Load™

The Player Load™ formula is an accelerometer-based measurement of external physical loading of team sport athletes, originally developed for rugby league, but also previously used in studies on soccer, Australian football, lacrosse, basketball, and field hockey. Player Load™ is defined as "instantaneous rate of change of acceleration divided by a scaling factor" (Catapult Sports, 2013a), and "is expressed as the square root of the sum of the squared instantaneous rate of change in acceleration in each of the three vectors (X, Y and Z axis) and divided by 100" (Boyd, Ball, & Aughey, 2011). The scaling factor is included to make the numbers easier to work with (Catapult Sports, 2013a). Accumulated or total Player Load™ is therefore a measure of total external load, comparable to total distance in time-motion studies, while Player Load™·min⁻¹ is a measure of intensity, at a certain time or in a given period. The equation for calculating Player Load™ is described below:

$$PlayerLoad^{TM} = \sqrt{\frac{(a_{y1} - a_{y-1})^2 + (a_{x1} - a_{x-1})^2 + (a_{z1} - a_{z-1})^2}{100}}$$

a_y = forward acceleration

a_x = sideways acceleration

a_z = vertical acceleration

3.4 Experimental procedures

To ensure a minimal effect on match performance, all athletes were familiarized with data collection procedures in training sessions prior to games. Apart from players wearing the device during matches, the study did not intervene with any other aspects of the normal training or match preparation. Factors which could potentially influence match fatigue (e.g. nutrition, prior training, or injuries) were not controlled for, and players therefore prepared for the matches as they normally would. To limit the effect of between-device differences, players, as far as possible, used the same unit during the different games, with some exceptions due to alterations in squad composition.

3.4.1 Match data collection

The devices were switched on and fitted on each player, under the match jersey in a tight custom made vest from the manufacturer (Figure 3), before their pre-match warm up. The device was placed in a pouch located between the scapulae, to ensure minimal movement of the device, allowing for detection of movement without causing discomfort or affecting the performance of the player. Players confirmed that wearing the device during matches did not affect their performance in any way, yet some female players chose not to wear devices in any matches ($n = 3$), while others chose to only wear it in some matches ($n = 3$). All eligible male players wore devices in all matches.



Figure 3 The OptimEye S5 (left) fitted in the pouch of a custom made vest (right).

During matches, two researchers sat courtside, following signals in the Catapult Sprint software (Version 5.1.4, Catapult Sports, 2014), ensuring that all devices were turned on and functioning properly throughout the match. Information from the devices was transferred to the software using a wireless receiver and a specialized live function in Catapult Sprint. Separate periods were created in Catapult Sprint for the first and second half, and interchanges were made continuously, ensuring that only time spent on the field was included in the analyses. During time-outs, all players were inactivated. As interchanges were frequent and could involve several players, the interchange area was video-recorded and notes were taken if incorrect, or suspected incorrect, interchanges were made in Catapult Sprint. This way, uncertainties and eventual errors in interchanges and substitutions could be double-checked and corrected after the game.

3.5 Data processing, interpretation, and analyses

Match data was downloaded from the devices using Catapult Sprint, and organized into 5-minute and 10-minute periods, as well as halves, to analyze transient and temporal patterns in match activity. Match and IMA output data were exported to Microsoft® Excel® using a custom-built team report in Catapult Sprint. As in most studies of handball match activity, goalkeepers were excluded from all analyses due to differences in match profile compared to outfield players (Karcher & Buchheit, 2014; Michalsik et al., 2013).

3.5.1 Periods and variables

5-minute periods were calculated from the start of each half, and only full 5-minute periods were included in the analyses. This led to exclusion of the final minutes in some matches, due to varying duration of halves. 10-minute periods were calculated by including the first and final ten minutes of each half, as well as the middle ten minutes of the half, originating in the exact middle point of the half. Due to half durations of more than 30 minutes, small parts of the halves, between the first and middle period, and between the middle and final period, were excluded from this analysis.

Variables included in the analyses were duration of halves and periods, field time in the different periods, and IMA values (Player Load™, accelerations, decelerations, and CoD of three magnitudes) for each player. All variables are presented relative to playing time (Player Load™·min⁻¹, accelerations·min⁻¹, decelerations·min⁻¹, CoD·min⁻¹) to allow for comparisons between players with different time on the field.

3.5.2 Analyses of team fatigue

In order to analyze changes in match activity throughout the game for the team, a mean was calculated for players on the field in the given period, based on individual player data, expressed as a percentage of their individual match mean. Only players who were on the field for a minimum of one minute of the given time-period were included. This was chosen to provide an as true as possible representation of match activity on the field, and at the same time exclude outlying data. Analyses on a team level were made for 5- and 10-minute periods.

The analysis of changes in effort intensity was based on the same 10-minute periods as previously described, and the same inclusion criteria of a minimum of one minute field time was used. High- and medium-intensity efforts (HMI) of acceleration, deceleration, and CoD were summarized, and compared to the sum of low-intensity efforts (LI) from the same variables, both presented relative to playing time ($\text{HMI}\cdot\text{min}^{-1}$ and $\text{LI}\cdot\text{min}^{-1}$).

3.5.3 Analyses of player fatigue

For examination of temporal and transient patterns for individual players, 5-minute periods were analyzed, and the inclusion criteria was 60% of field time in the given period. A mean 5-minute average was calculated for every player, based on the periods of the match fulfilling the 60% inclusion criteria. The 5-minute average was used as a baseline measurement for each player for a match, and the different 5-minute periods were expressed as a percentage of this. 60% was considered adequate, as a higher inclusion criteria would exclude many representative match samples, and would also not represent typical playing times in games, which ranges from 32-53 minutes (Karcher & Buchheit, 2014). This is similar to previous studies on fatigue in handball, where Michalsik et al. (2013) used 70% as inclusion criteria for match data and 60% for half data. Furthermore, in Australian football, Sullivan et al. (2014a) and Aughey (2010) used 75% and 70% respectively for match samples, and in rugby league, Waldron et al. (2013) considered 70% to be representative of a whole-match performance, while McLellan et al. (2011) used 75% of each half as the inclusion criteria.

To analyze temporal fatigue on an individual basis, consecutive 5-minute periods fulfilling the inclusion criteria for field time were analyzed for each half. Independent of game time, the first 5-minute period a player completed 60% of, in each half, was considered their first period of play. Subsequent periods fulfilling the criteria were then counted as their second, third, fourth etc. consecutive period of play. Consecutive periods could not cross the half-time

break. This way each player could be represented twice in a game, with one bout in the first- and one in the second half.

In order to analyze transient fatigue, each player's peak 5-minute period, within each IMA-variable, was identified for each match. These were then compared to the preceding (pre-peak) and following (post-peak) 5-minute period, given that these periods also fulfilled the criteria of 60% playing time. As not every player had a pre- or post-peak period, peak values could be different for these two analyses. This approach to analyzing transient fatigue is similar to previous studies on soccer and rugby league players (Akenhead et al., 2013; Bradley & Noakes, 2013; Bradley et al., 2009; Carling & Dupont, 2011; Di Mascio & Bradley, 2013; Kempton et al., 2015; Mohr et al., 2008; Mohr et al., 2003).

3.6 *Validity and reliability*

3.6.1 *Validity of Catapult devices in a handball context*

Before making inferences from results of a test or research project, the validity and reliability of the measurements must be discussed. The validity of a trial or experiment can be explained simply as if the test measures what it is supposed to measure (Laake, Olsen, & Benestad, 2008). In this study the aim was to examine changes in activity pattern for elite teams over the duration of matches, on a team and individual basis, which in turn could potentially lead to decreased overall handball performance. As the study did not examine technical perspectives, the goal was to measure the intensity of physical performance on the field, expressed as Player Load™, accelerations, decelerations, and CoD, relative to playing time. Previous studies have shown that accelerations, decelerations, and CoD are all frequent in handball games (Chapter 2.2.1), and these IMA-variables, along with Player Load™, were therefore considered relevant to include in an analysis of fatigue, as they at least partly represent physical performance in handball. Karcher and Buchheit (2014) also warranted studies of accelerations, CoD, and player loading to complete match demand profiles in handball.

Another aspect of validity is if the device measures what it is supposed to measure, and studies have been conducted to compare the results from Catapult Sports devices and Player Load™ with other instruments and variables. Wundersitz, Gustin, Richter, Robertson, and Netto (2014) examined the validity of a Catapult Sports device with a treadmill test by comparing to motion analysis with a reflector marker. They reported findings supporting the use of devices for in-field monitoring of peak accelerations during walking, jogging, and to a

lesser degree running, but that increased magnitudes of accelerations lead to decreased validity. Correlations between Player Load™ and other indicators of training load have previously been discussed (Chapter 2.3.3).

3.6.2 Reliability of Catapult devices

Reliability of the equipment and data collection is a requirement for good validity, and describes the accuracy of the instrument and the ability to reproduce results (Laake et al., 2008). Boyd et al. (2011) tested static (upright position) and dynamic reliability (0.5 g and 3.0 g) of the Catapult MinimaxX 2.0 device in an hydraulic shaker, and results indicated acceptable within-, and between-device reliability. Within-device coefficients of variation (CV) were 1.01% for the static-, 0.91% for the dynamic 0.5 g test, and 1.05% for the dynamic 3.0 g test. Between-device CV for the same tests were 1.10%, 1.04%, and 1.02%. Between-device reliability for a field test showed a CV of 1.94%, when two devices were taped together and used during nine Australian football matches. The effect of higher Player Load™ values for the distal device was countered by switching the position of devices (proximal and distal) between games.

Another study of reliability, with an incremental treadmill test (Barrett, Midgley, & Lovell, 2014), showed a moderate to high test-retest reliability of Player Load™ and the individual vectors contributing to it (CV: 5.3-14.8, Intraclass Correlation Coefficient: 0.80-0.93). A nearly perfect within-individual correlation between Player Load™ and measurements of HR ($P = 0.98$) and VO_2 ($P = 0.96$) was also found. Their conclusion was that Player Load™ could be recommended as a measurement of external-load exclusively, and that the placement between the scapulae is appropriate for exercise. On the other hand, moderate to large variations in absolute Player Load™ values also suggested caution should be taken when comparing absolute data from different athletes.

Unpublished data (Holme, 2015), in trials using the exact same devices as in the present study, showed no differences in reliability with increasing forces, and supported the combination of high- and medium-intensity efforts. When integrating data from all directions of force (accelerations, decelerations, and CoD), CV (90% confidence limits (CL)) was 2.9 (2.6-3.3) for low-intensity efforts, and 3.9 (3.5-4.5) for high- and medium-intensity combined. In comparison, CV for separate medium- and high-intensity efforts were 5.5 (4.9-6.4) and 5.6 (5.0-6.5) respectively. When combining all magnitudes (low, medium, and high), respective

CV for accelerations, decelerations, right CoD, and left CoD were 8.8 (7.8-10.2), 8.5 (7.5-9.9), 7.0 (6.2-8.1), and 5.3 (4.7-6.1). CV for Player LoadTM·min⁻¹ was 0.9 (0.8-1.0).

3.7 Statistical analyses

Results are presented as mean \pm 90% CL. Differences between periods of the match were calculated by using a customized spreadsheet (Hopkins, 2006) in Microsoft® Excel® 2008 for Mac, version 12.3.6. Magnitude based inferences were used to describe probabilities of single or pooled periods being substantially higher, trivial, or lower than the comparison. Further, qualitative inferences were made, based on the probabilities, with the categories; most unlikely (<0.5%), very unlikely (0.5-5%), unlikely (5-25%), possibly (25-75%), likely (75-95%), very likely (95-99.5%), most likely (>99.5%), or unclear if confidence limits overlapped into both higher or lower, as described by Batterham and Hopkins (2005).

4. Results

4.1 Team activity profiles

4.1.1 Team profiles for 10-minute periods

Values of Player LoadTM·min⁻¹, with differences between periods and halves, analyzed in 10-minute periods, are presented for the female and male matches in Figure 4. Values and differences between periods in the same half, for accelerations·min⁻¹, decelerations·min⁻¹, and CoD·min⁻¹, are presented in Table 2 and 3 for the female and male team respectively.

For the female team, between-half differences for accelerations·min⁻¹ were unclear for all periods (% likelihood of difference being higher/trivial/lower: First: 38/9/53, Middle: 31/11/58, Last: 47/9/44). For decelerations·min⁻¹, the last period was likely higher in the second half (93/2/5), compared to the first, while differences between halves for the first (39/12/49) and middle (89/10/41) period were unclear. For CoD·min⁻¹, the first period was very likely lower (1/1/98) and the last period very likely higher (98/2/1) in the second half, compared to the first, while the between-half difference for the middle period was unclear (50/22/27).

For the male team, differences between halves were unclear for all periods for accelerations·min⁻¹ (First: 9/3/88, Middle: 6/1/93, Last: 21/7/72). Decelerations·min⁻¹ was very likely lower in the second half for the first period (3/1/96), while differences for the middle (7/1/92) and last (25/7/69) period were unclear. For CoD·min⁻¹, the first (0/0/100, most likely) and middle (4/1/94, likely) periods were lower in the second half, while the between-half difference for the last period was unclear (44/12/44).

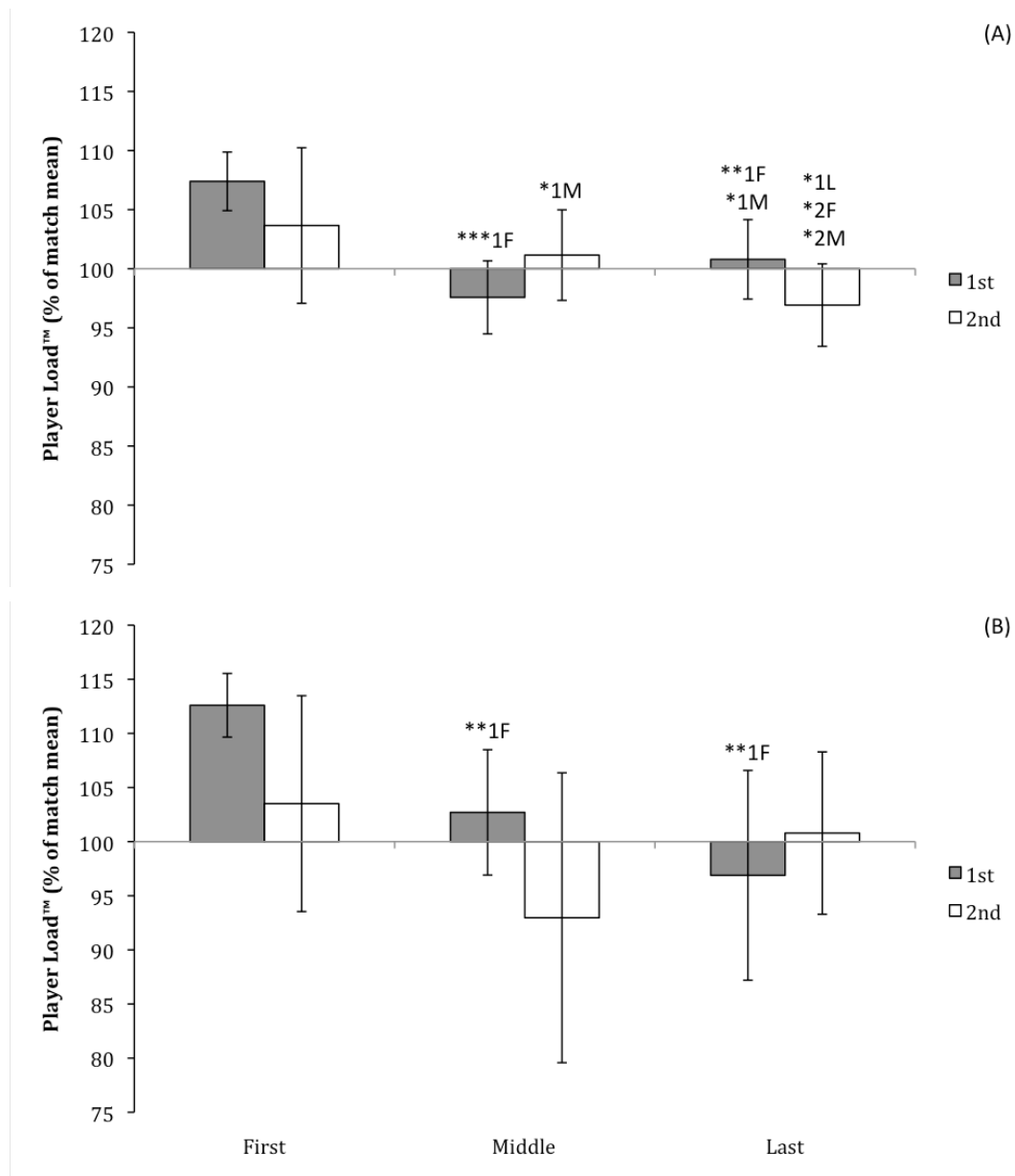


Figure 4 Player Load™·min⁻¹ in 10-minute periods for the female (A) and male (B) matches, presented as percentage of match mean ±90% CL. Differences were either likely (*), very likely (**), or most likely (***). 1F = First half, first period, 1M = First half, middle period, 1L = First half, last period, 2F = Second half, first period, and 2M = Second half, middle period.

Table 2 Percentages of match mean (90% CL) for 10-minute periods in the female matches. % likelihood of differences being higher/trivial/lower.

		% of match mean (90% CL)	% likelihood vs. first	Qualitative inference	% likelihood vs. middle	Qualitative inference
<i>Accelerations·min⁻¹</i>						
1st	First	106.7 (102.3-111.1)				
	Middle	100.7 (91.7-109.7)	10/7/82	unclear		
	Last	101.2 (94.6-107.9)	7/7/86	unclear	46/14/40	unclear
2nd	First	105.0 (89.8-120.2)				
	Middle	98.3 (88.5-108.1)	21/6/73	unclear		
	Last	101.5 (86.3-116.7)	34/7/59	unclear	60/8/33	unclear
<i>Decelerations·min⁻¹</i>						
1st	First	104.8 (97.6-112.1)				
	Middle	105.6 (92.1-119.1)	49/10/41	unclear		
	Last	92.9 (82.1-103.7)	4/3/94	likely lower	7/3/90	unclear
2nd	First	103.9 (93.2-114.6)				
	Middle	106.4 (98.1-114.7)	58/11/31	unclear		
	Last	108.8 (94.0-123.6)	66/7/27	unclear	57/9/35	unclear
<i>CoD·min⁻¹</i>						
1st	First	113.3 (110.3-116.3)				
	Middle	99.0 (94.3-103.7)	0/0/100	most likely lower		
	Last	92.6 (90.2-95.0)	0/0/100	most likely lower	1/3/96	very likely lower
2nd	First	102.6 (96.0-109.3)				
	Middle	100.1 (95.6-104.6)	20/16/64	unclear		
	Last	100.4 (95.2-105.6)	23/16/61	unclear	42/22/35	unclear

Table 3 Percentages of match mean (90% CL) for 10-minute periods in the male matches. % likelihood of differences being higher/trivial/lower.

		% of match mean (90% CL)	% likelihood vs. first	Qualitative inference	% likelihood vs. middle	Qualitative inference
<i>Accelerations·min⁻¹</i>						
1st	First	117.2 (103.9-130.5)				
	Middle	103.2 (80.4-125.99)	10/3/88	unclear		
	Last	100.2 (95.3-105.1)	3/1/96	very likely lower	33/8/59	unclear
2nd	First	103.6 (82.8-124.4)				
	Middle	84.7 (71.6-97.8)	5/1/94	likely lower		
	Last	94.5 (75.0-114.0)	19/5/77	unclear	83/4/14	unclear
<i>Decelerations·min⁻¹</i>						
1st	First	114.2 (99.9-128.5)				
	Middle	106.1 (98.6-113.6)	10/5/86	unclear		
	Last	107.8 (87.29-128.3)	23/6/71	unclear	54/9/37	unclear
2nd	First	97.8 (88.5-107.1)				
	Middle	85.0 (58.7-111.3)	14/3/83	unclear		
	Last	102.5 (93.5-111.5)	77/9/15	unclear	89/2/10	unclear
<i>CoD·min⁻¹</i>						
1st	First	114.4 (111.1-117.7)				
	Middle	109.6 (99.5-119.7)	13/8/80	unclear		
	Last	99.2 (87.1-111.3)	3/1/96	very likely lower	6/3/91	unclear
2nd	First	100.5 (95.2-105.8)				
	Middle	94.4 (78.3-110.5)	17/6/77	unclear		
	Last	99.2 (85.8-112.6)	34/14/52	unclear	69/8/24	unclear

4.1.2 Team profiles for 5-minute periods

Changes in IMA-variables for players on the field in each 5-minute period of the female and male matches are presented in Figure 5 and 6 respectively.

For the female team, compared to the first half, second half values of Player LoadTM·min⁻¹ were lower for the 10-minute (109.1 ±2.0 vs. 99.3 ±10.4, 5/3/92, likely), 25-minute (108.7 ±5 vs. 98.8 ±5.2, 1/1/98, very likely), and 35-minute period (109.9 ±2.2 vs. 95.6 ±5.7, 0/0/100, most likely). For accelerations·min⁻¹, the 25-minute period was very likely lower than the same period of the first half (115.8 ±10.3 vs. 95.8 ±14.2, 2/1/97). Decelerations·min⁻¹ were very likely higher for the 15-minute (88.3 ±8.86 vs. 112.4 ±9.9, 100/0/0) and 35-minute period (92.6 ±6.2 vs. 108.4 ±10.8, 98/1/1) in the second half compared to the first. Whereas CoD·min⁻¹ in the second half, compared to the first, was very likely lower for the 10-minute (115.4 ±4.8 vs. 93.1 ±14.4, 1/0/99), 25-minute (108.5 ±7.9 vs. 95.4 ±8.7, 2/1/97), and 35-minute period (104.7 ±3.0 vs. 96.8 ±5.3, 1/2/97), it was higher for the 15-minute (100.5 ±5.3 vs. 105.6 ±2.2, 90/6/4, likely) and 20-minute period (93.6 ±4.1 vs. 102.2 ±6.0, 97/2/2, very likely).

For the male team, second half values of Player LoadTM·min⁻¹ were likely lower for the 5-minute (118.4 ±4.2 vs. 103.8 ±14.3, 5/1/94) and 25-minute period (101.1 ±4.8 vs. 93.9 ±7.6, 4/3/93), and very likely lower for the 35-minute period (111.1 ±18.3 vs. 88.0 ±16.3, 3/1/96) compared to the first half. The 5-minute period was very likely lower for accelerations·min⁻¹ (142.2 ±16.4 vs. 107.0 ±24.0, 2/0/98), and most likely lower for decelerations·min⁻¹ (137.8 ±7.7 vs. 100.2 ±13.6, 0/0/100) in the second half. For CoD·min⁻¹, the 5-minute (130.1 ±13.0 vs. 111.3 ±13.7, 3/1/96), 30-minute (97.8 ±5.7 vs. 88.9 ±5.8, 2/1/97), and 35-minute period (111.0 ±12.1 vs. 84.9 ±16.7, 2/0/98) were all very likely lower in the second half.

Differences for each period, compared to all previous periods in the half combined, are fully presented in Appendix I for the female team and in Appendix II for the male team. For the female team, first half differences were both higher, lower, and unclear for $\text{Player Load}^{\text{TM}} \cdot \text{min}^{-1}$, $\text{accelerations} \cdot \text{min}^{-1}$, and $\text{decelerations} \cdot \text{min}^{-1}$. For $\text{CoD} \cdot \text{min}^{-1}$ in the first half, and all IMA-variables in the second half, differences were exclusively lower or unclear. For the male team, first half differences were either lower or unclear for all IMA-variables. This was also true for second half values, with exception of the 20-minute period for $\text{accelerations} \cdot \text{min}^{-1}$, which was higher.

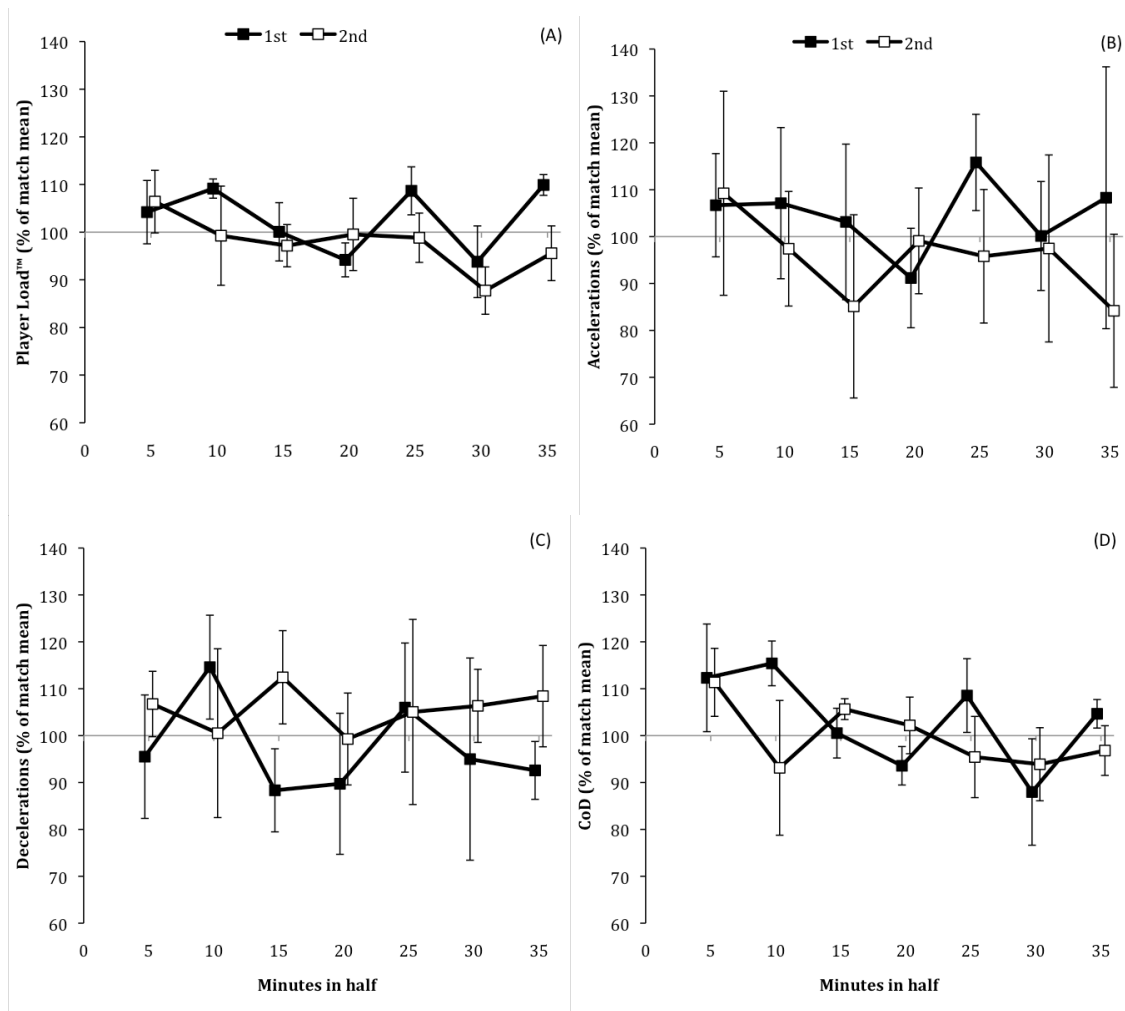


Figure 5 Percentage of match mean $\pm 90\%$ CL for the female matches. $\text{Player Load}^{\text{TM}} \cdot \text{min}^{-1}$ (A), $\text{accelerations} \cdot \text{min}^{-1}$ (B), $\text{decelerations} \cdot \text{min}^{-1}$ (C), and $\text{CoD} \cdot \text{min}^{-1}$ (D). Three first halves and one second half only lasted 30 minutes, and the 35-minute period therefore only represents three and five matches respectively compared to six for the other periods.

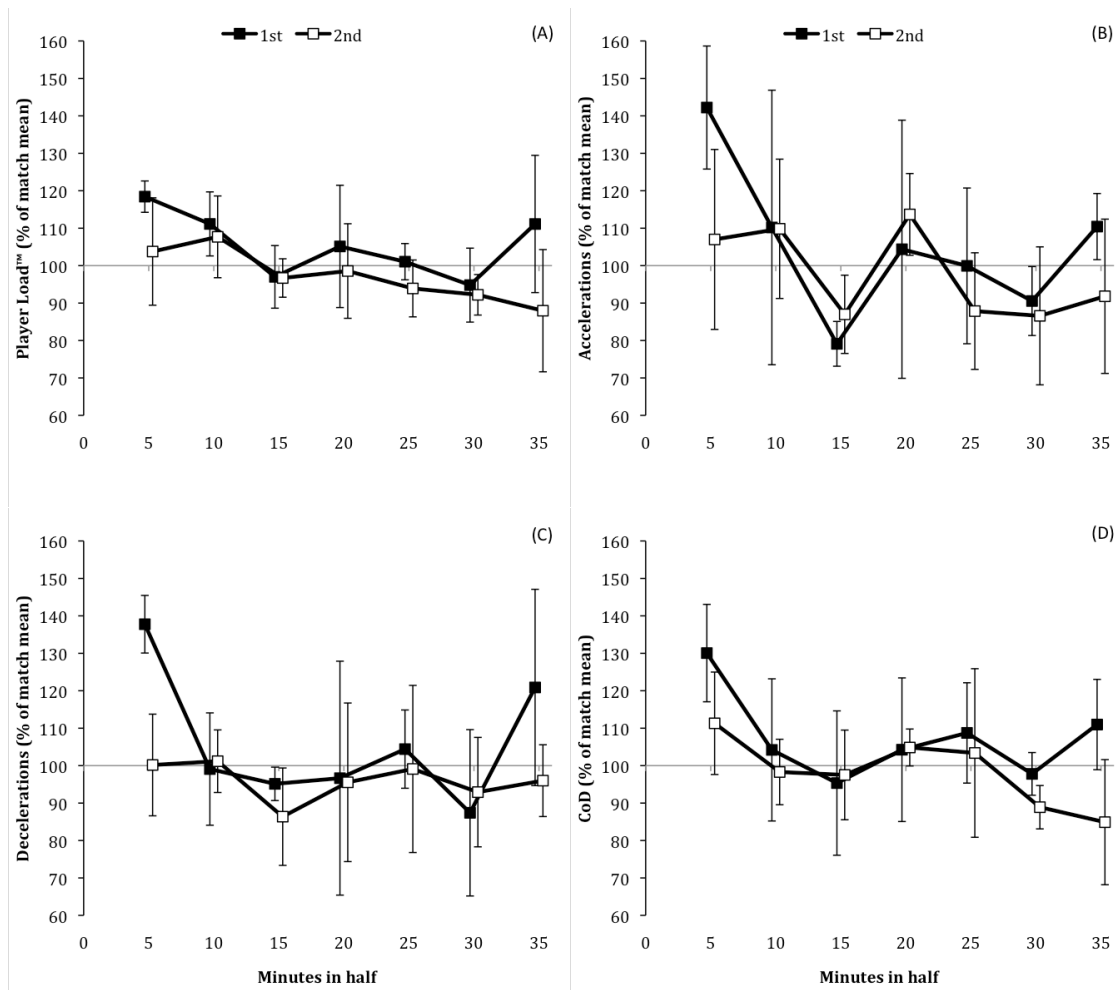


Figure 6 Percentage of match mean $\pm 90\%$ CL for the male matches. Player LoadTM $\cdot\text{min}^{-1}$ (A), accelerations $\cdot\text{min}^{-1}$ (B), decelerations $\cdot\text{min}^{-1}$ (C), and CoD $\cdot\text{min}^{-1}$ (D). One second half lasted 40 minutes, and this 40-minute period was excluded from the analysis.

4.1.3 Team profiles for effort intensity

Number of HMI·min⁻¹ and LI·min⁻¹ for the female and male team are presented in 10-minute periods in Figure 7.

For the female team, between-half differences for HMI·min⁻¹ were trivial for the first (4.8 ±0.2 vs. 4.7 ±0.9, 3/93/4, likely), middle (4.4 ±0.3 vs. 4.4 ±0.6, 1/98/1, very likely), and last period (3.9 ±0.3 vs. 4.5 ±0.4, 7/93/0, likely). For LI·min⁻¹, the second half was possibly lower for the first period (11.5 ±0.5 vs. 10.2 ±1.5, 2/35/64), and possibly higher for the last period (9.2 ±0.6 vs. 10.3 ±0.5, 58/42/0), while the difference between the middle periods was likely trivial (9.9 ±0.5 vs. 10.4 ±0.8, 16/84/1).

For the male team, differences for HMI·min⁻¹ between halves were likely trivial for the first (5.1 ±0.5 vs. 4.5 ±0.5, 0/92/8), middle (4.2 ±0.6 vs. 3.7 ±1.0, 2/86/13), and last period (4.9 ±0.8 vs. 4.7 ±0.2, 3/93/4). For LI·min⁻¹, the second half was likely lower for the first period (12.0 ±0.6 vs. 10.4 ±0.8, 0/8/92), and possibly lower for the middle period (10.6 ±0.7 vs. 9.1 ±1.8, 3/26/71), while the difference was possibly trivial between halves for the last period (10.2 ±0.7 vs. 9.5 ±1.0, 1/74/25).

Differences between periods in each half are presented in full in Appendix III. For the female team, differences were lower or trivial in the first half for both HMI·min⁻¹ and LI·min⁻¹. In the second half, differences were trivial for HMI·min⁻¹ and trivial or unclear for LI·min⁻¹. For the male team, first half differences were trivial for HMI·min⁻¹, and lower or trivial for LI·min⁻¹. However, second half differences were higher or trivial for HMI·min⁻¹, while lower, trivial, or unclear for LI·min⁻¹.

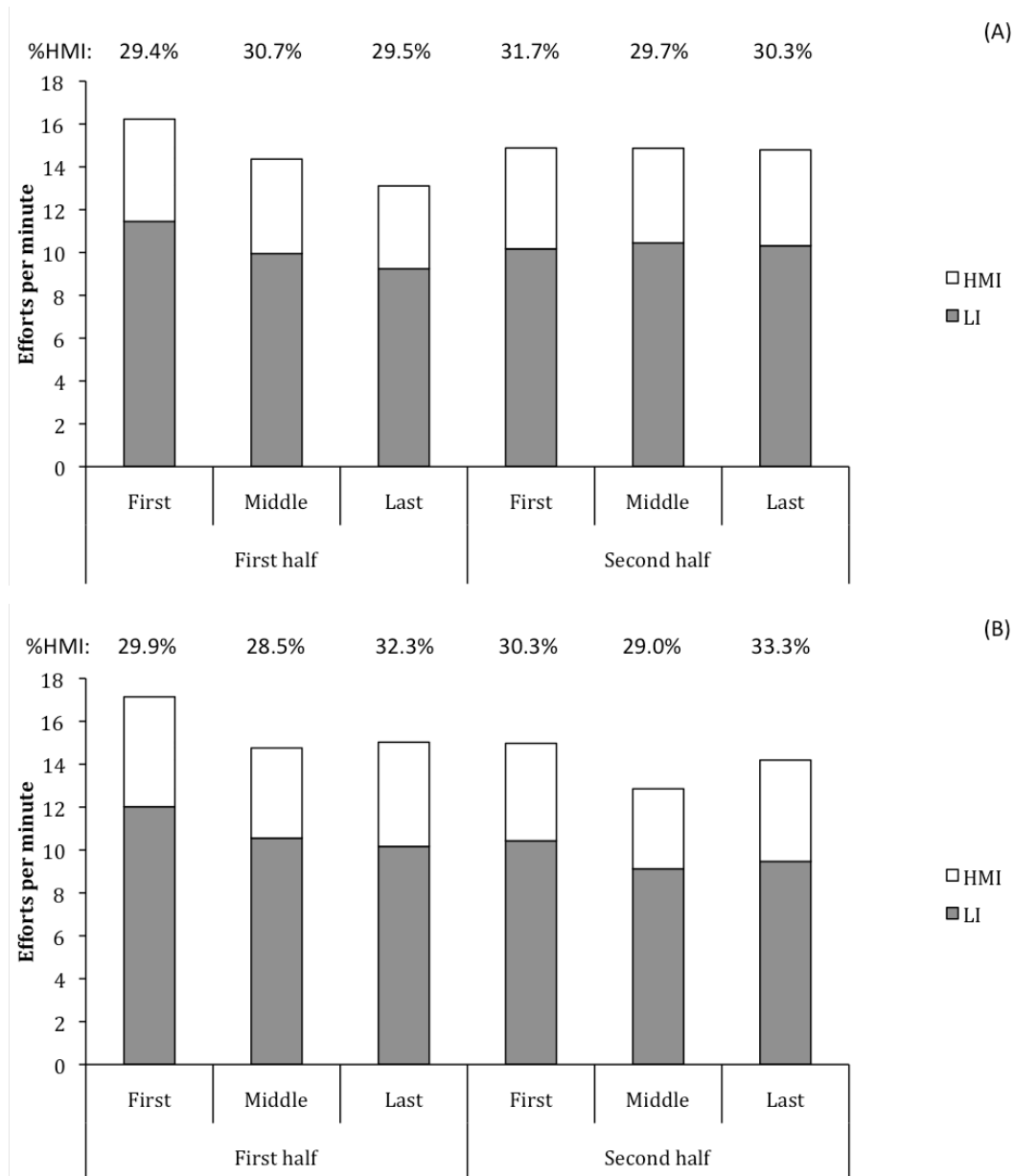


Figure 7 Number of efforts per minute (accelerations, decelerations, and CoD combined), in 10-minute periods for the female (A) and male (B) matches. LI = Low-intensity efforts $\cdot \text{min}^{-1}$ ($1.5\text{-}2.5 \text{ m}\cdot\text{s}^{-1}$), HMI = High- and medium-intensity efforts $\cdot \text{min}^{-1}$ ($>2.5 \text{ m}\cdot\text{s}^{-1}$). %HMI = Percent contribution of HMI to all efforts.

4.2 Activity profiles for individual players

4.2.1 Transient changes in player activity

Peak periods, along with pre- and post-peak values of Player LoadTM·min⁻¹ are presented in Figure 8 for the female and male team, including differences between periods. For both the female and male team, the pre-peak (0/0/100) and post-peak (0/0/100) periods were most likely lower than the respective peak period. Corresponding values and differences for accelerations·min⁻¹, decelerations·min⁻¹, and CoD·min⁻¹ are presented for both female and male players in Table 4. A detailed overview of distribution of peak periods during games is presented in Table 5.

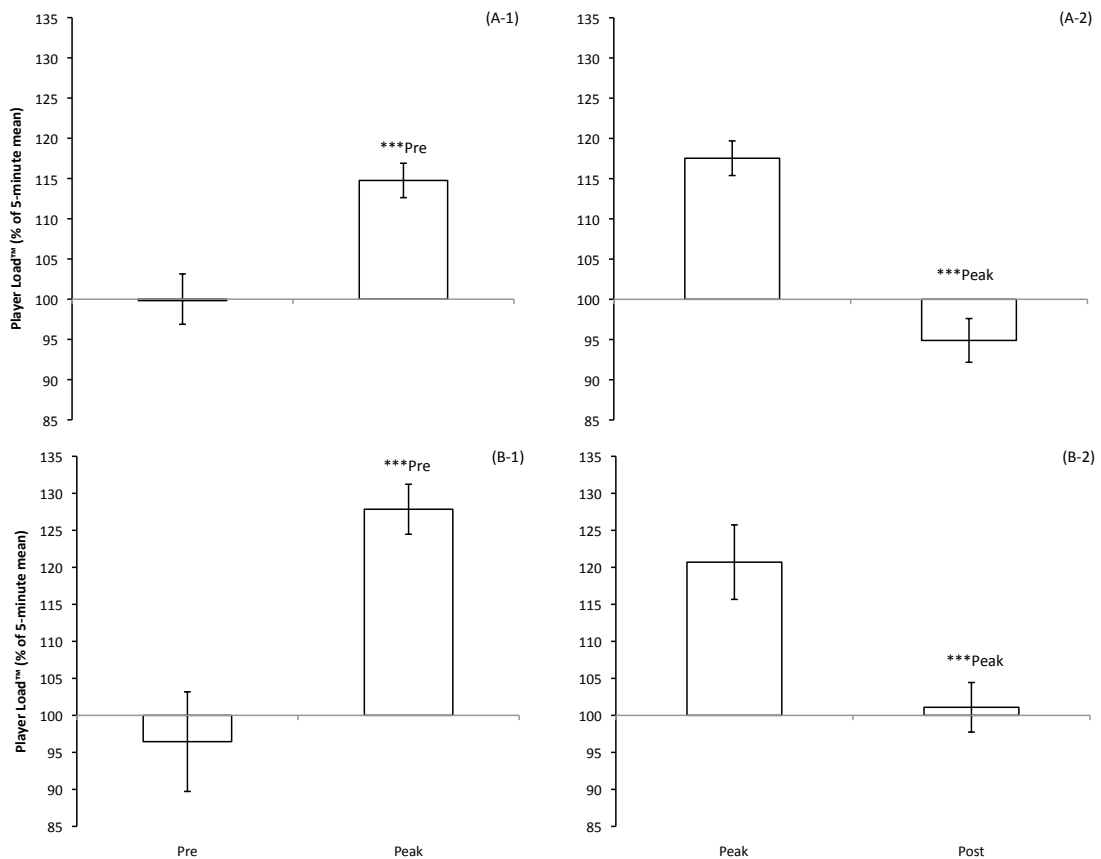


Figure 8 Percentage of 5-minute mean $\pm 90\%$ CL for Player LoadTM·min⁻¹. Female players with a pre-peak (A-1, n = 25) and post-peak period (A-2, n = 33), and male players with a pre-peak (B-1, n = 14) and post-peak period (B-2, n = 17). Differences between periods were most likely (***).

Table 4 Values for 5-minute peak, pre-peak, and post-peak periods of the female (A) and male (B) players for IMA-variables. All peak periods were most likely different (100%) from their respective pre- or post-period.

	5-minute period	n	% of 5-minute mean (90% CL)	% of 5-minute mean (90% CL)
(A)				
<i>Accelerations·min⁻¹</i>	Pre vs. Peak	22	91.1 (82.0-100.2)	143.4 (133.7-153.1)
	Peak vs. Post	34	152.4 (144.6-160.2)	95.0 (87.8-102.2)
<i>Decelerations·min⁻¹</i>	Pre vs. Peak	23	85.0 (75.3-94.7)	153.3 (143.8-162.8)
	Peak vs. Post	29	153.9 (146.3-161.5)	90.1 (82.7-97.5)
<i>CoD·min⁻¹</i>	Pre vs. Peak	19	89.0 (80.7-97.3)	126.8 (122.1-131.5)
	Peak vs. Post	35	127.2 (124.1-130.3)	97.0 (92.1-101.9)
(B)				
<i>Accelerations·min⁻¹</i>	Pre vs. Peak	15	86.2 (75.8-96.6)	180.9 (154.7-207.1)
	Peak vs. Post	18	174.0 (153.0-195.0)	80.7 (70.2-91.2)
<i>Decelerations·min⁻¹</i>	Pre vs. Peak	15	89.8 (77.5-102.1)	162.1 (144.2-180.0)
	Peak vs. Post	19	147.7 (140.3-155.1)	102.1 (92.0-112.2)
<i>CoD·min⁻¹</i>	Pre vs. Peak	15	99.5 (90.8-108.3)	131.4 (124.1-138.7)
	Peak vs. Post	18	133.0 (126.3-139.7)	98.1 (93.4-102.8)

Table 5 Distribution of peak periods for female and male players across IMA-variables. Percentage of peak periods observed in a player's first or final period of play (60% field time), and after a period of rest (pre-game, half-time, or <60% field time) or a period of play (60% field time).

		First	Final	Other	After rest	After play
Female (n = 51)	<i>Player LoadTM·min⁻¹</i>	35%	12%	54%	51%	49%
	<i>Accelerations·min⁻¹</i>	36%	21%	43%	56%	44%
	<i>Decelerations·min⁻¹</i>	24%	28%	48%	55%	45%
	<i>CoD·min⁻¹</i>	42%	11%	47%	63%	37%
	Mean	34%	18%	48%	56%	44%
Male (n = 30)	<i>Player LoadTM·min⁻¹</i>	39%	10%	52%	53%	47%
	<i>Accelerations·min⁻¹</i>	29%	21%	50%	55%	45%
	<i>Decelerations·min⁻¹</i>	36%	15%	48%	55%	45%
	<i>CoD·min⁻¹</i>	42%	23%	35%	50%	50%
	Mean	37%	17%	46%	53%	47%

4.2.2 Changes in player activity with consecutive periods on the field

The effect of several consecutive periods of play on Player LoadTM·min⁻¹ for the female and male players are presented in Figure 9, including differences from all previous periods combined. The corresponding mean values and differences for accelerations·min⁻¹, decelerations·min⁻¹, and CoD·min⁻¹ are presented in Table 6.

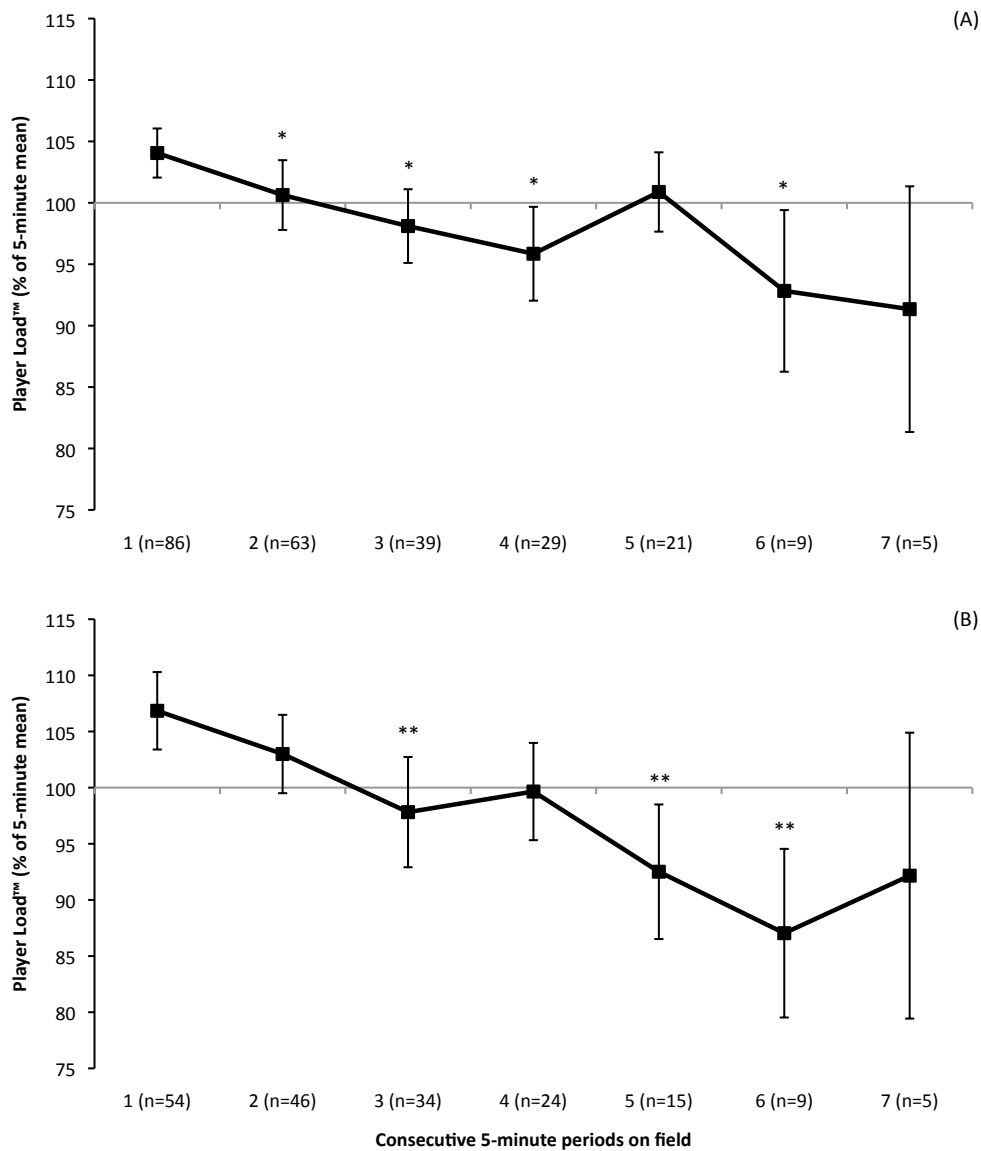


Figure 9 Percentage of 5-minute mean $\pm 90\%$ CL for Player LoadTM·min⁻¹, for female (A) and male (B) players with consecutive 5-minute periods of play. Differences compared to all previous periods combined were likely (*) or very likely (**).

Table 6 Percentage of 5-minute mean (90% CL) in subsequent bouts for female (A) and male (B) players. % likelihood of differences being higher/trivial/lower.

	(A)	% of 5-min mean (90% CL)	% likelihood	Qualitative inference	(B)	% of 5-min mean (90% CL)	% likelihood	Qualitative inference
<i>Accelerations·min⁻¹</i>								
1	104.9	(96.7-113.2)				121.5	(105.6-137.4)	
2	103.2	(96.6-109.8)	34/12/54	unclear		107.7	(95.4-120.0)	11/3/86 unclear
3	91.6	(92.5-100.7)	2/2/96	very likely lower		81.3	(69.4-93.2)	0/0/100 most likely lower
4	94.3	(82.9-105.8)	18/8/74	unclear		101.0	(81.8-120.2)	39/6/55 unclear
5	99.9	(87.7-112.1)	52/10/38	unclear		101.6	(80.6-122.6)	43/6/51 unclear
6	96.1	(84.8-107.5)	29/11/60	unclear		60.2	(32.7-87.7)	1/0/99 very likely lower
7	76.9	(47.6-106.2)	9/2/89	unclear		83.4	(60.0-106.8)	16/4/81 unclear
<i>Decelerations·min⁻¹</i>								
1	104.2	(98.3-110.1)				110.7	(103.0-118.4)	
2	102.4	(95.2-109.6)	31/13/56	unclear		96.9	(88.5-105.3)	2/2/97 very likely lower
3	96.8	(88.7-104.9)	9/7/84	unclear		93.8	(81.7-105.9)	9/5/87 unclear
4	95.8	(86.5-105.1)	15/9/76	unclear		100.6	(86.0-115.2)	46/9/45 unclear
5	100.4	(88.1-112.7)	48/11/41	unclear		97.1	(82.9-111.3)	31/8/61 unclear
6	89.3	(63.9-114.7)	21/4/75	unclear		87.4	(68.7-106.1)	12/4/85 unclear
7	82.4	(69.2-95.6)	3/1/96	very likely lower		105.4	(73.0-137.8)	65/4/30 unclear
<i>CoD·min⁻¹</i>								
1	107.5	(104.4-110.6)				109.7	(104.2-115.2)	
2	98.0	(93.7-102.3)	0/0/100	most likely lower		100.5	(95.6-105.4)	1/2/97 very likely lower
3	101.1	(96.1-106.1)	22/21/58	unclear		92.8	(87.2-98.4)	0/0/100 most likely lower
4	95.1	(90.1-100.1)	1/3/97	very likely lower		96.7	(89.9-103.6)	12/11/78 unclear
5	96.3	(89.1-103.5)	13/11/76	unclear		102.2	(90.9-113.5)	57/11/32 unclear
6	87.1	(75.5-98.7)	3/2/95	likely lower		87.1	(76.2-98.0)	2/2/96 very likely lower
7	88.6	(83.6-93.6)	1/1/99	very likely lower		86.2	(69.7-102.7)	9/3/88 unclear

5. Discussion

The aim of the present study was to examine activity profiles, relating them to possible fatigue development, using modern microsensor technology during male and female elite handball matches. The main findings for team profiles from both genders were high initial intensities, declines throughout matches, and lower values in the second half, across IMA-variables, although decelerations·min⁻¹ for the female team did not follow this pattern. An increase in activity measures was often observed in the final five or ten minutes of a half, compared to the previous period, although this was not consistent in all IMA-variables or halves. No between-half differences were apparent in HMI·min⁻¹ for either gender, although these decreased in the last period of the first half for females, and increased in the final period of the second half for males. Between-half decreases, and declines in LI·min⁻¹ across periods were apparent in the female and male team, although in the final period, these were higher in the second half for females. For individual athletes, analyses of the five minutes post-peak indicated that players experienced lower activity levels after intense periods of play. Furthermore, declines were observed in activity levels of individual players with consecutive periods of playing time.

5.1 Team activity profiles

5.1.1 Team profiles for Player Load™

Player Load™·min⁻¹ showed the least variation, and was the most consistent of the variables measured. It was also the primary measure of match intensity in this study, and therefore the majority of the discussion will concern these analyses.

Initial intensity of halves

An elevated opening intensity was observed in both genders for Player Load™·min⁻¹. This is consistent with previous findings of high initial work rates in handball (Chapter 2.4.1) and a variety of other team sports (Chapter 2.5.2). Michalsik et al. (2013) propose that this is an indication that fatigue may occur already in the first half, at least temporarily for full time players. Findings of greater exercise economy at the start of rugby league matches (Kempton et al., 2015), also suggest that players may experience better physiological conditions for high work loads in the opening phase.

Akenhead et al. (2013) on the other hand, suggest that the consistent finding of the highest intensities in the first 15 minutes of soccer games could be caused by tactical enforcements by coaches, or by the preceding period of rest after the warm-up, allowing for clearance of metabolites and optimal conditions for force production, along with full energy stores. Other studies have suggested players may be more motivated and aroused in the opening minutes, wanting to get a good start to the game, further contributing to a chaotic and high-intense phase, before the game slows down and finds its rhythm (Akenhead et al., 2013; Bradley & Noakes, 2013; Lovell, Barrett, Portas, & Weston, 2013). From a tactical standpoint, starting the game with a high intensity may be beneficial, as an early lead would put pressure on the opponents throughout the game. This may on the other hand cause players to fatigue earlier, as several studies have found that declines in activity levels are related to high work rates in previous stages of matches (Bradley & Noakes, 2013; Coutts et al., 2010; Rampinini et al., 2007). Intensity may also be down-regulated after an intense opening period in order to maintain the overall pacing strategy for the game, according to the pacing model proposed by Edwards and Noakes (2009).

Findings of longer time of “ball in play” in the opening period of soccer and rugby league games may also suggest players have the opportunity to work more in this period (Carling & Dupont, 2011; Kempton et al., 2015). Kempton et al. (2015) additionally found a higher number of defensive collisions in the opening phase, further supporting the suggestion that physically demanding opening periods are attributed to game dynamics, and not just physical capacity. These suggestions have lead scientists (Bradley & Noakes, 2013; Carling, 2013; Cummins et al., 2013; Lovell et al., 2013) to question studies where researchers have compared later stages of the game with only the first period to detect fatigue, and this is the reason periods were compared to all previous periods in the half combined in the present study.

Also in the second half, Player LoadTM·min⁻¹ was elevated compared to the rest of the half. However, mean values were lower than in the first half, with exception of the first five minutes for the female team. A high opening intensity of the second half is possibly attributed to many of the same factors as in the first half, and a lower starting intensity, compared to the first half, is similar to findings in handball (Michalsik et al., 2013; Povoas et al., 2012) and soccer (Lovell et al., 2013). At the same time, this was only the

case in soccer players with high work rates in the first half in the study by Bradley and Noakes (2013).

Lower intensities in the first minutes of the second half are not surprising when comparing against the first half, as the opening phases of games are characterized by especially elevated intensities. This could also be an indication of fatigue caused by the first half, or could be due to a lack of warm-up after the half time break (Bradley & Noakes, 2013; Michalsik et al., 2013; Povoas et al., 2012). A re-warm-up was reported to preserve muscle temperature and maintain sprint performance in soccer players (Mohr, Krstrup, Nybo, Nielsen, & Bangsbo, 2004), and could therefore also be beneficial for handball players in the starting minutes of the second half. Bradley and Noakes (2013) suggest a lower opening intensity of the second half may be the result of pacing, and a re-evaluation of a “meso” pacing strategy (Chapter 2.7) could therefore cause lower initial intensities in the second half (Edwards & Noakes, 2009). However, authors do not exclude the possibility that high demands during the first half are responsible for performance declines across the whole second half, and not only towards the end.

Declines between and during halves

Findings in both genders of lower intensities in second half periods, compared to the corresponding periods of the first half, can be associated with previous observations of decreased second half activity in handball (Chapter 2.4.1) and Player LoadTM·min⁻¹ in other team sports (Chapter 2.5.1). Declines found within each half in Player LoadTM·min⁻¹ are also in agreement with decreased intensity of handball games (Chapter 2.4.1) and decreased activity measures in other team sports (Chapter 2.5.2), through shorter time-periods.

A decline in Player LoadTM·min⁻¹ across periods or between halves in handball is possibly attributed to physical impairment of players, and consequent inability to work at a desired rate. This is supported by findings of decreased physical performance (Chapter 2.4.2) and suggested changes in muscle structure following handball games (Ronglan et al., 2006). Glycogen depletion of individual muscle fibers has also been shown in players after soccer games (Krstrup et al., 2006), but the relevance for handball is questionable, as game time is shorter than for soccer, lower mean speeds

during games are found (Karcher & Buchheit, 2014), and rules allow for unlimited interchanges and therefore more opportunities for rest in handball. Despite the lack of measurements of potential mechanisms in the present study, previous studies have suggested impairments in physical capacity are associated to lower team activity in handball games (Michalsik et al., 2013; Povoas et al., 2014a; Povoas et al., 2012; Ronglan et al., 2006; Thorlund et al., 2008). Reduced intensity could also be caused by a mismatch between game demands and physical fitness (Cormack et al., 2014; R. D. Johnston et al., 2015), where players may start the game at an intensity which is too high to maintain for a whole match. This is especially relevant in national teams, where players often have less experience with match demands at a higher competition level (Ronglan et al., 2006), and is also in line with the pacing theory, where knowledge of energy demands and previous experience is an important determinant for setting an appropriate pacing strategy (Edwards & Noakes, 2009).

As decrements in physical performance are not consistent across physical attributes and tests after handball games (Povoas et al., 2014a; Ronglan et al., 2006), rotation strategies and interchanges may be sufficient to maintain physical capacity of handball players, and especially for the team as a whole. Other mechanisms, not associated to individual player fatigue could therefore possibly explain declines in team activity. In some cases, the match result could be decided already early in the second half, explaining intensity declines (Michalsik et al., 2013; Mohr et al., 2003). As intensity only dropped in the second half for defensive phases in Povoas et al. (2012), more defensive play could also be causing the observed second half declines in the present study, although this was not specifically examined. However, the mean score difference was 3.0 ± 6.3 in favor of the female team, and 2.3 ± 3.1 in favor of the male team, suggesting even games, and furthermore, goals scored in the first and second halves were similar (Female: 12.5 ± 2.7 vs. 12.2 ± 3.5 , Male: 13.0 ± 6.5 vs. 15.0 ± 8.1). Another possibility is that weaker or less fit players were introduced into the games in the later stages, to try them out, or that coaches were experimenting with new tactics and formations. Although these are possible factors affecting team activity and causing apparent team fatigue, they were not examined in this study. Therefore, these aforementioned factors remain speculative, requiring further examination in future studies.

Final periods of halves

Considering the findings of declines between and during halves in the present study, the logical development would be lower activity levels in the final periods of the game. However, in addition to decreases in the final period, compared to the previous, there were also increases in Player LoadTM·min⁻¹. In line with these observations, findings by Michalsik et al. (2013) indicated increased activity levels in the closing minutes of games. This was suggested by the authors to be a sign of transient fatigue, but also that players may reduce activity during the second half in order to increase tactical and physical performance at the end of the matches. Increased activity levels towards the end of matches could also be caused by increased motivation and coach involvement, similar to what is suggested for the opening phase of matches.

Increases in activity levels may indicate that players were not completely physically exhausted in the final stages, which supports the concept of pacing and the “end spurt” phenomenon, explained in a team sport setting by Waldron and Highton (2014). The observed increases may therefore suggest that pacing strategies are adopted by players and teams, either consciously or subconsciously, on a tactical or physical level. Alternatively, it could be that players on the field towards the end of games were interchanged players, introduced in the later stages. This is supported by the fact that in the six female and three male matches, only five individual player samples from each gender met the inclusion criteria in seven consecutive periods of a half (Figure 9), suggesting a high player turnover. Substitute- or interchange players in team sports generally work more intensely than whole-game players (Chapter 2.7), which may be attributed to fatigued whole-game players, or a different pacing strategy (Black & Gabbett, 2014; Waldron & Highton, 2014). This notion is further supported by findings in Australian football, where a higher amount of interchanges was beneficial for maintaining m·min⁻¹ and high-speed running (Mooney et al., 2013). As such, activity profiles for the team as a whole may not be optimal for detection of player fatigue in a sport with unlimited interchanges, like handball, but will still be a good indication of whole-team physical performance.

5.1.2 Accelerations, decelerations, and CoD

For the male team, accelerations·min⁻¹, decelerations·min⁻¹, and CoD·min⁻¹, followed the same gross patterns as for Player LoadTM·min⁻¹, although variations were greater, resulting in more “unclear” differences. There were some discrepancies in the final periods of halves, when comparing to the previous period, for accelerations·min⁻¹ and decelerations·min⁻¹. One period was also higher than all the previous periods combined for accelerations·min⁻¹, which was not found for Player LoadTM·min⁻¹. Similarly, for the female team, accelerations·min⁻¹ and CoD·min⁻¹ followed largely the same patterns as Player LoadTM·min⁻¹. However, there were exceptions in the final period of each half for both accelerations·min⁻¹ and CoD·min⁻¹, and some values were statistically higher in the second half for CoD·min⁻¹, which was not the case for Player·LoadTM·min⁻¹. Decreases in accelerations and decelerations across periods of games have been observed using microtechnology and GPS in team sports (Chapter 2.5.3). To the authors knowledge, no previous studies have examined fatiguing of accelerations or decelerations in handball, or CoD using microtechnology or GPS specifically in any team sports.

Similarities with profiles for Player LoadTM·min⁻¹ are not unexpected, as the Player LoadTM formula is based on acceleration from three vectors. The discussed mechanisms behind changes in activity profiles for Player LoadTM·min⁻¹, therefore likely also apply to accelerations·min⁻¹, decelerations·min⁻¹, and CoD·min⁻¹. However, researchers have pointed out that fatigue, muscle damage, and recovery is movement specific (Mendez-Villanueva, Hamer, & Bishop, 2007), which may explain variations in results between IMA-variables.

The consequence of fatiguing muscles on deceleration- and CoD-performance may be different from acceleration, as these require high amounts of eccentric force in order to slow down the body (Akenhead et al., 2013). As accelerations, decelerations, and CoD are highly energy demanding (Chapter 2.2.1), and physical performance tests have shown decreased strength, sprinting, and jumping after handball games (Chapter 2.4.2), general declines throughout matches are not unexpected. Akenhead et al. (2013) suggest that reductions in acceleration and decelerations in soccer may partly be explained by homeostatic disturbances within the muscle, while Polley et al. (2015) suggest a general fatigue, higher physiological cost, and variations in match situations may collectively

cause these declines. Thorlund et al. (2008) explain that reductions in force production potentially could impair physical performance towards the end of matches, in form of decreased ability to sprint, side-cut, jump, or accelerate. It therefore seems that reduced neuromuscular power, caused by fatiguing muscles or pacing strategies, are the most likely causes of the observed declines.

Interestingly, a different pattern was observed for decelerations·min⁻¹ for the female team. Between-half differences were either unclear or higher in the second half, compared to the first, and through the second half mean values were increasing, as opposed to decreasing for Player Load™·min⁻¹. Furthermore, the initial period of the game was not elevated, and the final ten minutes also showed the highest value of all periods. It is surprising that decelerations increase in number through the game in the female team, although both (Jones et al., 2015) and (Polley et al., 2015) did find increased decelerations in the final period for some positions and magnitudes. Possibly, movement patterns change when players are fatiguing, leading to an increased number of decelerations, or maybe these are affected differently than the other IMA-variables by game-fatigue, when measuring with a microsensor device. Still, as no physiological or physical measures were examined in the present study, further studies are warranted to confirm these findings, and to explore the underlying mechanisms.

5.1.3 Team profiles of effort intensity

Overall maintained HMI·min⁻¹, with exception of the last ten minutes of the first half for the female team, is contrasting to previous handball literature, where high-intensity activity is consistently lower in the second half (Chapter 2.4.1). This may be due to limitations in time-motion analysis (Chapter 2.3.1), or different definitions of high-intensity activity. Furthermore, previous studies have only compared halves, while the present study compared 10-minute periods, which further complicates comparisons with these results.

In an attempt to find underlying reasons for declines in Player Load™·min⁻¹ in Australian footballers, Cormack et al. (2013) found weaker correlations between the mediolateral (unclear negative differences) and vertical vectors contributing to Player Load™·min⁻¹ and activity profile variables in a fatigued state. Especially, there was a reduced contribution of vertical acceleration to Player Load™·min⁻¹, in a fatigued state.

This was suggested to either be caused by less changes of speed or more running at lower intensities, possibly as part of a pacing strategy, resulting in reduced capacity to generate Player Load™·min⁻¹ when neuromuscular fatigue is present. Other studies have suggested that players, when fatiguing, “sacrifice” non-critical low- and medium-intensity activity and increase low-intensity recovery, in order to pace and maintain high-speed activities which are considered crucial for match outcome (Di Salvo et al., 2007; Duffield et al., 2009; Gabbett et al., 2013; Granatelli et al., 2014; R. D. Johnston et al., 2015; Mooney et al., 2013). This would be in accordance with findings of decreased LI·min⁻¹ and maintained HMI·min⁻¹ in the present study.

5.2 Transient changes in player activity

Findings in the present study suggest players experience declines in IMA-variables following an intense period, causing decreases below the match average, possibly due to fatigue. This is in line with previous studies of transient fatigue in other team sports (Chapter 2.5.4), and also underlines the variations in intensity for individual players during handball matches.

Transient fatigue in handball may be caused by insufficient rest periods in certain periods of the match. The mean time between changes of high- and low-intensity activity was found to be 55 seconds by Povoas et al. (2012), and Povoas et al. (2014a) also found that one third of rest periods between intense runs were under 30 seconds. This could hinder recovery of energy stores and force-production conditions (Povoas et al., 2012), as half-time for PCr resynthesis is suggested to be between 21-57 seconds (Spencer et al., 2005). Studies of mechanisms behind transient fatigue remain inconclusive, although PCr-degradation and K⁺ accumulation may be implicated (Chapter 2.6). Alternatively, Waldron and Highton (2014) suggest transient declines could also be caused by “micro” pacing strategies (Chapter 2.7). If this is the case, periods of lower intensity after peak-periods may be a protective strategy, in order to maintain the overall pacing strategy for the game or half (Edwards & Noakes, 2009). To limit the decreases in activity after intense 5-minute periods, improving anaerobic capacity and repeated sprinting ability may be beneficial (Bradley et al., 2009; Mohr et al., 2008; Povoas et al., 2012).

The fact that all IMA-variables decreased in the post-peak period can be interpreted as an indication of fatigue, but as not all levels were lower than the match average, it could also just be the result of variations in game dynamics and the intermittent nature of team sports (Akenhead et al., 2013). This is supported by mean pre-peak values for all IMA-variables in both genders below, or equal to, the match mean. Furthermore, around one third of peak periods were found in the first period a player was on the field, and the majority of peak periods were completed after a period of rest (Table 5). This could correspond to findings of high initial playing intensity on a team level, as previously discussed, and for subsequent bouts in individual players (Figure 9). Carling and Dupont (2011) also found that the time of “ball in play” was longer in the peak periods of soccer games, suggesting caution should be taken when interpreting transient fatigue, as players would have more opportunities to play than in the other periods. Di Mascio and Bradley (2013) additionally found that recovery time was longer in the five minutes post-peak, which may be caused by similar factors. In rugby league, Kempton et al. (2015) found that time in defensive play was greater in the peak periods, which further suggests situational factors have an effect on analyses of transient fatigue in handball, considering defensive phases have been reported to be more demanding than attacking (Chapter 2.2.1).

5.3 Temporal changes with consecutive bouts of field time

Similar to the team profiles, the highest value for all IMA-variables, in both genders, were found in the first period of play. As discussed, this may be more related to situational variables, rather than to declines in subsequent periods. The fact that the first period in the individual analysis could be at any point of the match, may also suggest that that players are more motivated and active, wanting to make an impact as soon as they are introduced into the match. If players in general play more intensely in their first period of play, which is also supported by the distribution of peak periods, this can be used tactically by coaches, by introducing rested “impact players” in certain periods of the game in order to raise the intensity on the field (Waldron et al., 2013).

The gross patterns for all IMA-variables, for both genders, were declines through subsequent bouts of play, which is in line with the declines discussed for the team profiles. This is likely caused by either fatiguing of neuromuscular systems or pacing strategies. These findings also further strengthen the suggestion that team declines in

activity are partly explained by declines in individual player activity. Interestingly, decelerations·min⁻¹ declined with subsequent periods on the field also for female players, contradicting observations from the team profile. A decrease in individual players is more in line with the expected development, and may suggest that team profiles partly are affected by other factors than fatigue or pacing. Alternatively, the differences between the team and player profiles are related to the small sample of only five female players completing seven consecutive bouts in one half. Overall declines may still suggest that activity is not sustained with longer periods of field time, which may be indicative of match-induced fatigue in players who play large parts of halves without rest periods.

The profiles for both genders are similar to the “slow-positive” pacing profiles of whole-game players in team sports (Chapter 2.7). As Waldron and Highton (2014) point out, the unlimited interchange rule may positively alter pacing strategies, as players know that they can be replaced if they are fatiguing. The general finding across football codes of a “one-bout all-out” strategy for players introduced later in the match (Waldron & Highton, 2014) may also be relevant in the present study, in form of higher means for players playing only a few consecutive periods.

The general finding was a decrease in the final period, compared to the previous, for female players, and an increase for male players, with opposite findings for CoD·min⁻¹ in both genders. The increase in the last period for the male team may be another indication of the “end spurt” phenomenon, which would provide further support to the concept of pacing in handball players. Waldron and Highton (2014) argue that “an increase in running performance must reflect either the full, or at least partial, recovery of a player”, and as such, the results from the individual analysis may back the suggestion that players are not exhausted at the end of games. As previously discussed, situational variables may also explain activity levels, and given the small sample of players completing seven bouts in a half, along with contradicting results for female players, this requires further investigation.

5.4 Limitations of the study

5.4.1 Subjects and matches

The level of the female team was world class, however, the matches analyzed were in four-nation tournaments. Thus, it is possible that team disposition and interchanges may have varied from what would have been done in more significant qualification or championship matches. The fact that the male team was a recruit team and played in an international recruit tournament must also be taken into consideration when generalizing findings from these matches.

Due to the relatively small sample and time-frame of the present study, a position-specific analysis of fatigue was not performed. Even though the analyses on fatigue development in this study were based on individual match-, and 5-minute averages, positional representation could be a source of bias (Michalsik et al., 2013), as different demands between positions indicate possible differences in fatigue development (Karcher & Buchheit, 2014; Povoas et al., 2014a). On the other hand, as the present study was observational, the sample is expected to represent a standard handball match at the respective levels, including players from a variety of positions, and the percent contribution to the sample from each position was similar to a normal line-up.

The matches in this study were played in four-nation tournaments, with limited rest between games. A deteriorated physical performance and presence of muscle damage and inflammation has been reported up to 24 hours after handball games (Chatzinikolaou et al., 2014; Marin et al., 2011), suggesting recovery time between matches could have been insufficient. Chatzinikolaou et al. (2014) still argue that their results allow for a new match already a day after the previous, while Ronglan et al. (2006) suggested that even 48 hours was not sufficient for optimal recovery after intense handball play. R. D. Johnston et al. (2015) also found that players pace their effort throughout tournaments, implying that activity profiles may not accurately represent profiles of single games. At the same time, most championships are played with a tight schedule, and during the 2014 European Championship, the Norwegian team played eight games in 15 days, with games every second day. Therefore, further studies of player- and team profiles in intense match schedules may be beneficial for improving load management and performance during tournaments.

5.4.2 Methodological limitations

Results concerning validity and reliability of Catapult Sports' IMUs have not been published in a handball setting. Although unpublished data (Chapter 3.6.2) show promising reliability for IMA-variables in handball, there is still a thin line between efforts characterized as accelerations, CoD, or decelerations, based on the position of the unit when performing them, making classification of effort direction slightly incidental. The velocities defined as high, medium, and low were also preset, not allowing for individual zones, and the lack of consistent speed zones across studies has also been mentioned to limit time-motion and microsensor studies (Dellaserra et al., 2014). In the present study there were no measures of internal load, and a combination with external load would provide a more sensitive measure of demands (Carling, 2013; Dellaserra et al., 2014). There were also no measures of underlying mechanisms of fatigue.

For team analyses, different lengths of halves resulted in the five last minutes not representing the true last five minutes of each game, which potentially could be important, as the present study has shown both increases and decreases compared to the previous period. This has also underlined the importance of analyzing matches in 5-minute periods, as opposed to 10- or 15-minute periods. An improved analysis of intensity of efforts, presented relative to the individual match mean could also be more accurate.

For individual analyses, the inclusion criteria of 60% playing time allows for two minutes of rest within every 5-minute period, possibly countering development of fatigue. Therefore, with a larger sample, a stricter inclusion criteria could be enforced. The analysis of transient fatigue is limited by preset 5-minute periods, which may not capture the true peak five minutes, and an additional analysis of the ten minutes post peak would provide a deeper understanding of fatigue after intense periods. In the temporal analysis, bouts of consecutive periods in the first and second half were combined, which may mask potential between-half differences, especially in the first and last period. Also, players with one to seven periods of playing time were all combined, hiding potential differences in pacing strategies.

5.4.3 Association of physical- to overall performance

A major shortcoming in this study is the lack of performance-related measures, which ultimately makes it difficult to quantify the effect of decreased physical performance on overall handball performance. Physical performance, and small reduction in this, is not vital for match outcome *per se*, as players can compensate with other skills (Carling, 2013; Ronglan et al., 2006). Studies of Australian football have suggested that the ability to get involved in the game is more important than activity levels (R. J. Johnston et al., 2012; Sullivan et al., 2014a), and higher work rates are often reported for less successful, compared to more successful, teams in soccer (Di Salvo et al., 2009; Rampinini et al., 2007; Rampinini et al., 2009). Furthermore, the score line likely affects physical performance and pacing strategies (Black & Gabbett, 2014; Bradley & Noakes, 2013; Sullivan et al., 2014a).

On the other hand, Michalsik et al. (2013) argue that the ability to perform high-intensity work might be the most important factor that differentiates teams of higher and lower levels in handball. This is in line with findings of superior test-results of endurance, upper and lower body strength, sprint and jumping performance, and anaerobic capacity for handball players of a higher compared to lower level (Granados, Izquierdo, Ibanez, Ruesta, & Gorostiaga, 2013; Kruger et al., 2014; Nikolaidis & Ingebrigtsen, 2013). Furthermore, Ronglan et al. (2006) explain that strength is assumed to increase with higher playing levels in handball, and most actions, like shooting, blocking, and tackling require strength and power. As a result, high demands of elite match-play suggest fatigue will hinder chances of performing at the required level.

As there are no definitions of a critically low “intensity-threshold” where fatigue affects performance, this is currently a subjective decision coaches have to make during games. From a coaching perspective, a slightly fatigued top-class player may still be considered a better choice than a fully recovered lower class player, and information on activity profiles are therefore even harder to implement in practice. If there was a defined critical intensity-threshold required for handball players to maintain overall performance, it could allow the coaching staff to make tactical decisions for interchanges based on real-time data on player intensity.

5.5 Practical applications and directions for future studies

5.5.1 Recommendations for handball

Monitoring Player LoadTM during practice and competition is suggested to be beneficial for assessing readiness of players and to detect fatiguing players during matches in other team sports (Jones et al., 2015). As Player LoadTM·min⁻¹ and other IMA-variables could differentiate between periods of matches in the present study, this may have implications for match strategies and tactical decisions also in handball.

Based on the present findings it seems players can not maintain activity levels towards the end of games with subsequent periods of playing time, which may suggest rotating players will improve the activity levels of a team through the match. High initial intensities and the observation of peak periods often occurring in the first period of play, suggest coaches could introduce “fresh” players to manipulate game intensity. This is up to coaches to further interpret, as other factors may be more important to overall performance. As handball players may pace their intensity, coach involvement and reinforcements could affect match intensity, although this was not examined specifically. Although not measured in the study, physical conditioning could also be beneficial, as this could counteract the declines in activity levels towards the end, and also enable players to set a higher starting intensity, which can be maintained throughout games.

5.5.2 Directions for future studies

Position-specific analyses of fatigue, based on individual intensity-zones, combined with measures of underlying mechanisms, should be the focus of future studies in handball. Pacing strategies should receive more attention, for single matches as well as tournaments, including analyses of rotations and interchanges of players and their effect on activity levels. A further validation of microsensor technology in a handball specific environment is also required. Finally, researchers should aim to investigate the impact of declined physical performance on overall handball performance, and include performance and situational variables in analyses, such as time of “ball in play”, involvements with the ball, technical errors, goals scored and conceded, and time spent in offensive and defensive play. This could eventually lead to the finding of critical threshold levels of activity required for optimal handball performance at the top tier.

6. Conclusion

In this study, activity profiles for the IMA-variables Player Load™, accelerations, decelerations, and CoD were examined, relative to playing time, in an elite male and female national handball team, with special regards to fatigue development. Team profiles suggested match intensity was the highest in the opening period of the game, with overall declines in activity during and between halves. In the final period of the game, the findings were inconclusive, as some analyses showed increases, while others showed decreases, compared to the previous period of play. In the female team, a different profile was observed for decelerations, compared to the other IMA-variables, which requires further investigation. Low-intensity efforts declined through the second halves, possibly as a protective mechanism to maintain crucial high- and medium-intensity efforts.

Individual players experienced declines in playing intensity after peak periods, which were often found in the first period on the field, possibly indicative of transient fatigue. This coincided with findings of the highest intensity in the first period of playing time, when consecutive periods of play were analyzed. In this analysis, intensity also declined with subsequent bouts on the field. Intensity in the final period increased or decreased, compared to the previous period, further supporting the possibility that players may have paced their efforts. Situational, game-dependent, factors may have played a part in the observed patterns, and should be included in future studies.

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Abbreviations

ATP	Adenosine triphosphate
CoD	Change(s) of direction
CL	Confidence limits
CV	Coefficient(s) of variation
GPS	Global positioning system
HMI	High- and medium-intensity efforts
HR	Heart rate(s)
HR _{max}	Maximal heart rate
IHF	International Handball Federation
IMA	Inertial Movement Analysis
K ⁺	Potassium ions
LI	Low-intensity efforts
MVC	Maximal voluntary contraction
PCr	Phosphocreatine
SD	Standard deviation
VO ₂	Oxygen uptake
VO _{2 max}	Maximal oxygen uptake

Appendix

- I Differences between 5-minute periods for the female team
- II Differences between 5-minute periods for the male team
- III Differences between 10-minute periods for effort intensity
- IV Approval of image use
- V Approval of data storage

Appendix I - Differences between 5-minute periods for the female team

Differences between periods of the female matches, compared to all previous periods in the half combined.

Min.	1st half		2nd half	
	% likelihood (higher/trivial/lower)	Qualitative inference	% likelihood (higher/trivial/lower)	Qualitative inference
<i>Player LoadTM·min⁻¹</i>				
10	85/8/7	unclear	11/6/83	unclear
15	3/4/93	likely lower	5/7/88	likely lower
20	0/0/100	most likely lower	30/17/54	unclear
25	96/3/1	very likely higher	20/21/59	unclear
30	2/2/96	very likely lower	0/0/100	most likely lower
35	100/0/0	most likely higher	14/17/69	unclear
<i>Accelerations·min⁻¹</i>				
10	48/8/44	unclear	17/4/80	unclear
15	32/7/61	unclear	7/2/91	unclear
20	2/1/96	very likely lower	54/10/36	unclear
25	97/1/2	very likely higher	37/9/54	unclear
30	21/9/71	unclear	47/7/46	unclear
35	61/6/32	unclear	8/3/90	unclear
<i>Decelerations·min⁻¹</i>				
10	97/1/2	very likely higher	24/6/70	unclear
15	1/1/99	very likely lower	86/5/9	unclear
20	12/4/84	unclear	10/6/84	unclear
25	84/5/11	unclear	47/7/45	unclear
30	34/6/60	unclear	54/15/31	unclear
35	5/7/89	likely lower	65/11/24	unclear
<i>CoD·min⁻¹</i>				
10	63/11/27	unclear	2/1/97	very likely lower
15	0/0/99	very likely lower	71/13/16	unclear
20	0/0/100	most likely lower	30/18/52	unclear
25	68/14/19	unclear	6/5/90	unclear
30	1/1/98	very likely lower	4/4/92	likely lower
35	62/28/10	unclear	9/13/78	unclear

Appendix II - Differences between 5-minute periods for the male team

Differences between periods of the male matches, compared to all previous periods in the half combined.

Min.	1st half		2nd half	
	% likelihood higher/trivial/lower	Qualitative inference	% likelihood higher/trivial/lower	Qualitative inference
<i>Player LoadTM·min⁻¹</i>				
10	6/3/90	unclear	67/9/24	unclear
15	1/0/99	very likely lower	2/2/96	very likely lower
20	25/9/66	unclear	18/10/72	unclear
25	1/2/97	very likely lower	3/3/95	likely lower
30	4/1/95	likely lower	1/1/98	very likely lower
35	76/6/18	unclear	9/27/89	unclear
<i>Accelerations·min⁻¹</i>				
10	7/1/92	unclear	57/7/37	unclear
15	0/0/100	most likely lower	1/0/99	very likely lower
20	32/5/64	unclear	96/2/3	very likely higher
25	16/5/79	unclear	3/1/96	very likely lower
30	1/0/99	very likely lower	8/2/91	unclear
35	85/7/8	unclear	20/6/74	unclear
<i>Decelerations·min⁻¹</i>				
10	1/0/99	very likely lower	50/13/37	unclear
15	0/0/100	most likely lower	3/1/96	very likely lower
20	15/3/82	unclear	44/9/47	unclear
25	24/13/64	unclear	60/8/32	unclear
30	6/1/92	unclear	24/10/66	unclear
35	89/2/9	unclear	42/19/40	unclear
<i>CoD·min⁻¹</i>				
10	2/0/97	very likely lower	4/2/94	likely lower
15	3/1/96	very likely lower	10/5/85	unclear
20	22/7/71	unclear	69/18/13	unclear
25	45/13/42	unclear	47/9/44	unclear
30	0/1/99	very likely lower	0/0/100	most likely lower
35	73/10/17	unclear	5/1/93	unclear

Appendix III - Differences between 10-minute periods for effort intensity

Differences in efforts relative to playing time between periods for the female (A) and male (B) matches.
HMI = High- and medium-intensity efforts, LI = Low-intensity efforts. % likelihood of differences being higher/trivial/lower.

		vs. First		vs. Middle	
		% likelihood	Qualitative inference	% likelihood	Qualitative inference
(A)					
<i>HMI·min⁻¹</i>					
1st	Middle	0/99/1	very likely trivial		
	Last	0/0/100	most likely lower	0/97/3	very likely trivial
2nd	Middle	2/87/11	likely trivial		
	Last	2/91/8	likely trivial	2/98/1	very likely trivial
<i>LI·min⁻¹</i>					
1st	Middle	0/8/92	likely lower		
	Last	0/1/100	very likely lower	0/77/23	likely trivial
2nd	Middle	21/71/9	unclear		
	Last	16/74/10	unclear	2/93/5	likely trivial
(B)					
<i>HMI·min⁻¹</i>					
1st	Middle	0/61/39	possibly trivial		
	Last	1/94/5	likely trivial	18/81/1	likely trivial
2nd	Middle	2/65/33	possibly trivial		
	Last	2/97/1	very likely trivial	50/49/1	possibly higher
<i>LI·min⁻¹</i>					
1st	Middle	0/11/89	likely lower		
	Last	0/3/97	very likely lower	1/93/6	likely trivial
2nd	Middle	4/31/65	possibly lower		
	Last	1/52/47	possibly trivial	21/72/8	unclear

Appendix IV - Approval of image use

Hi Eirik

Nice to hear from you and hope everything is going well with your studies.

No problem using the IMA information from the Sprint help manual and referencing it for your research.

Regarding the specifications around the S5 device, I have emailed one of our technicians based in Australia, so will pass on the information once I get a reply.

Kind Regards,
James Malone

Sport Scientist
CATAPULT Sports

A: One Aire Street, Leeds, LS1 4PR
E: james@catapultsports.com
M: +44 7825 166476
S: james.malone23
W: www.catapultsports.com

On Tue, May 19, 2015 at 12:01 AM, Eirik Halvorsen Wik <eirikwik@hotmail.com> wrote:

Hi,

My name is Eirik Halvorsen Wik, and I am currently writing my masters thesis at the Norwegian School of Sport Sciences, handing it in June 1st, with Matt Spencer as my supervisor. My thesis is about fatigue development in team handball players, and we have collected data using the Catapult OptimEye S5.

In order to explain how the IMA-data is calculated I would like to include a figure from page 11 in Catapult's «Sprint Help - Inertial Movement Analysis (IMA)» (October 13). I am therefore asking if this can be approved from Catapult? The source will be properly acknowledged.

I am also having some trouble finding specifications, regarding weight and size (height, width, thickness), of the device, as well as type or brand of the accelerometer, gyroscope and magnetometer. As this would be beneficial for giving a thorough description of the data collection procedure, I was wondering if you could help me with some of these specifications, or point me in the right direction in order to find them?

Sincerely,
Eirik Halvorsen Wik,
Norwegian School of Sport Sciences

Appendix V - Approval of data storage

Norsk samfunnsvitenskapelig datatjeneste AS
NORWEGIAN SOCIAL SCIENCE DATA SERVICES



Harald Hårfagres gate 29
N-5007 Bergen
Norway
Tel: +47-55 58 21 17
Fax: +47-55 58 96 50
nsd@nsd.uib.no
www.nsd.uib.no
Org.nr. 985 321 884

Matthew Spencer
Seksjon for fysisk prestasjonsevne Norges idrettshøgskole
Postboks 4014
0806 OSLO

Vår dato: 02.09.2014

Vår ref: 39602 / 3 / LT

Deres dato:

Deres ref:

TILBAKEMELDING PÅ MELDING OM BEHANDLING AV PERSONOPPLYSNINGER

Vi viser til melding om behandling av personopplysninger, mottatt 28.08.2014. Meldingen gjelder prosjektet:

<i>39602</i>	<i>Arbeidskravsanalyse av håndballspillere på nasjonalt/internasjonalt nivå - fysiske krav og taktiske profiler</i>
<i>Behandlingsansvarlig</i>	<i>Norges idrettshøgskole, ved institusjonens øverste leder</i>
<i>Daglig ansvarlig</i>	<i>Matthew Spencer</i>

Personvernombudet har vurdert prosjektet og finner at behandlingen av personopplysninger er meldepliktig i henhold til personopplysningsloven § 31. Behandlingen tilfredsstiller kravene i personopplysningsloven.

Personvernombudets vurdering forutsetter at prosjektet gjennomføres i tråd med opplysningene gitt i melde skjemaet, korrespondanse med ombudet, ombudets kommentarer samt personopplysningsloven og helseregisterloven med forskrifter. Behandlingen av personopplysninger kan settes i gang.

Det gjøres oppmerksom på at det skal gis ny melding dersom behandlingen endres i forhold til de opplysninger som ligger til grunn for personvernombudets vurdering. Endringsmeldinger gis via et eget skjema, <http://www.nsd.uib.no/personvern/meldeplikt/skjema.html>. Det skal også gis melding etter tre år dersom prosjektet fortsatt pågår. Meldinger skal skje skriftlig til ombudet.

Personvernombudet har lagt ut opplysninger om prosjektet i en offentlig database, <http://pvo.nsd.no/prosjekt>.

Personvernombudet vil ved prosjektets avslutning, 31.12.2018, rette en henvendelse angående status for behandlingen av personopplysninger.

Vennlig hilsen

Katrine Utaaker Segadal

Lis Tenold

Kontaktperson: Lis Tenold tlf: 55 58 33 77

Vedlegg: Prosjektvurdering

Dokumentet er elektronisk produsert og godkjent ved NSDs rutiner for elektronisk godkjenning.

Avdelingskontorer / District Offices

OSLO: NSD, Universitetet i Oslo, Postboks 1055 Blindern, 0316 Oslo. Tel: +47-22 85 52 11. nsd@uio.no
TRONDHEIM: NSD, Norges teknisk-naturvitenskapelige universitet, 7491 Trondheim. Tel: +47-73 59 19 07. kyrre.svarva@svt.ntnu.no
TROMSØ: NSD, SVF, Universitetet i Tromsø, 9037 Tromsø. Tel: +47-77 64 43 36. nsdmaa@sv.uit.no

