General introduction
CHAPTER 1

Training load and its relation to fitness and injury

Coaches and other practitioners try to improve athlete's performance by means of training. From a physiological point of view, Banister argued in his fitness-fatigue model that a training stimulus will cause both short-term fatigue and a longer lasting fitness due to positive adaptations, ideally resulting in a net improvement in (physical) performance (Banister, Calvert, Savage, & Bach, 1975). However, when successive training stimuli are planned with insufficient rest, and positive adaptations cannot take place, there might be an increased risk of non-functional overreaching, illness and/or injury (Halson, 2014). Studies have indeed shown that high training loads are related to higher injury occurrence (e.g. Gabbett, 2004; Rogalski, Dawson, Heasman, & Gabbett, 2013). However, high training loads can most likely also be protective against injuries (Gabbett & Domrow, 2005; Hulin, Gabbett, Lawson, Caputi, & Sampson, 2016). It is therefore conceptualized that there would be a theoretical U-shaped relationship between workload and injury risk (Gabbett, 2016), with high injury risk at either low or high workloads (e.g. Cross, Williams, Trewartha, Kemp, & Stokes, 2015; Dennis, Farhart, Goumas, & Orchard, 2003). Besides low or high absolute workloads, also a rapid increase in workload could increase the risk of injuries (Cross et al., 2015; Hulin et al., 2016; Rogalski et al., 2013). Altogether, to safely improve the fitness of athletes, especially on an elite level where overall loads are usually high and performance margins are small, training loads should be managed adequately. Monitoring and quantifying training load can aid in this load management process.

Internal and external load

Training load can be partitioned in internal and external training load (Halson, 2014). External training load is the output of physical activities by the athlete, whereas internal training load is usually defined as the athlete's (acute) physiological response to this external training load (Impellizzeri, Rampinini, Coutts, Sassi, & Marcora, 2004). Internal load can be described objectively by the athlete's heart rate, blood lactate, and oxygen consumption or subjectively by ratings of perceived exertion (RPE) (Borresen & Lambert, 2009).

Heart rate measures describe the athletes’ cardiovascular load and can provide useful information about training intensity (Dellal et al., 2012). However, it has been argued that for intermittent team sports, with multiple (non-steady state) high-intensity and short-duration activities, heart rate is not a valid internal load marker (Casamichana & Castellano, 2015; Foster et al., 2001). The same accounts for blood lactate and oxygen consumption, which both are also impractical to measure on a daily basis during team sport activity (Osgnach, Poser, Bernardini, Rinaldo, & di Prampero, 2010). Therefore, ratings of perceived exertion (RPE), often multiplied with training duration as session-RPE (Foster et al., 2001; Impellizzeri et al., 2004), have been widely used to provide an overall internal training load marker of team sport athletes (e.g. Algroy, Hetlelid, Seiler, & Stray Pedersen, 2011; Jeong, Reilly, Morton, Bae, & Drust, 2011; Malone et al., 2015; Ritchie, Hopkins, Buchheit, Cordy, & Bartlett, 2016; Wrigley, Drust, Stratton, Scott, & Gregson, 2012). However, although these non-invasive session-RPE scores are useful as a general
indicator of workload, they do not provide information about the (locomotor) activities that lead to this perceived exertion score. For example, the same session-RPE score of 90 arbitrary units can be obtained by 30 min of constant pace running (rated as moderate exertion, RPE = 3) or by 10 min of sprint bouts (rated as nearly maximum exertion, RPE = 9). Therefore, from a training prescription perspective, it seems useful to also quantify external load (Ingebrigtsen, Dalen, Hjelde, Drust, & Wisloff, 2015).

**Development of tracking technology**

Compared to individual sports, it is particularly difficult in team sports to control external loads due to the unpredictability of the game and a high number of individual players. The development of contemporary tracking technologies have made it possible for professional clubs to easily monitor external load variables during both training and matches (Buchheit, Allen, et al., 2014). In (association) football, video-based tracking systems are often used for matches, while global positioning systems (GPS) are commonly used during training. While video-based and GPS systems are accurate for measurement of distance and average speed in linear courses at relatively low speeds, the accuracy of these systems decreases with higher speeds and (short) non-linear courses (e.g. Edgecomb & Norton, 2006; Portas, Harley, Barnes, & Rush, 2010; Rawstorn, Maddison, Ali, Foskett, & Gant, 2014). Partly because of this, the most used external load variables to date are total distance covered and distance ran in different speed zones (Polglaze, Dawson, & Peeling, 2016). However, accelerations and decelerations often occur in football (Dalen, Ingebrigtsen, Ettema, Havard, & Wisløff, 2016; Wehbe, Hartwig, & Duncan, 2014) and are both mechanically (Greig, McNaughton, & Lovell, 2006) and metabolically demanding (Buglione & di Prampero, 2013; Osgnach et al., 2010). The more recently introduced electronic tracking systems, such as the local position measurement (LPM) system (Frencken, Lemmink, & Delleman, 2010), are potentially more accurate in tracking these accelerations and decelerations and therefore have the potential to improve external load quantification.

**Metabolic power estimations**

Due to the aforementioned developments in tracking technologies, the instantaneous speed and acceleration of players can be easily determined. Around a decade ago, di Prampero et al. (2005) introduced an approach that has made it possible to estimate metabolic power from this instantaneous speed and acceleration. They suggested that accelerated running on flat terrain is biomechanically equivalent to running uphill at a constant speed. Based on previous studies (Minetti, Moia, Roi, Susta, & Ferretti, 2002) that investigated the energy cost of running uphill and downhill they presented an algorithm that estimates the metabolic power and therewith energy cost of accelerated running. The approach has been used in combination with video-based tracking (Osgnach et al, 2010) and GPS tracking (Gaudino et al., 2013) to estimate the energy expenditure of players during matches and training, respectively.
The idea that energy cost can be estimated from time-motion data is appealing because, as mentioned, direct assessments of energy cost are currently methodologically and practically impossible in team sports. Energy expenditure is potentially a better and more valid indicator of overall workload than currently used methods such as training duration, total distance covered and session-RPE. As such it may be a useful variable to investigate, for example, dose-response (Akubat, Barrett, & Abt, 2014) and workload-injury relationships (Gabbett, 2016). However, the validity of the metabolic power approach remains to be fully established.

Time-motion analysis in professional football

When it comes to time-motion analysis in football, and specifically external load, detailed information is available with regard to matches in various competitions (Sarmento et al., 2014). External load (i.e. locomotor performance) variables during matches have been found to positively correlate with aerobic intermittent fitness tests (e.g. Buchheit, Mendez-Villanueva, Simpson, & Bourdon, 2010; Castagna, Manzi, Impellizzeri, Weston, & Barbero Alvarez, 2010; Krustrup et al., 2003). Additionally, many studies (e.g. Carling & Dupont, 2011; Mohr, Krustrup, & Bangsbo, 2003; Rampinini, Impellizzeri, Castagna, Coutts, & Wisloff, 2009) have found a decrease in locomotor performance at the end of the match, which has been typically attributed to fatigue. However, various factors other than fatigue can influence locomotor performance during match play, such as score line, tactics, opposition and player position (Carling, 2013). Therefore, it might be difficult to define maximal ‘performance’ in team sports (Halson, 2014), since achieving high locomotor activity is not a goal per se during matches. Nevertheless, the fitness of players is regarded important, and it might be that, although players can show equal external loads during matches, fitter players exercise on a lower percentage of their maximal intensity. If so, fitter players would fatigue less and an increased fitness of players would mitigate the decrease in performance accuracy usually seen with fatigue (Rampinini et al., 2008; Rampinini et al., 2009).

In football and other team sports, small-sided games (SSGs) are often used during training for conditioning purposes, because they have the advantage to simultaneously train technical, tactical and sport-specific decision making (Davies, Young, Farrow, & Bahnert, 2013). The intensity of SSGs has been deemed sufficient for maintaining and developing aerobic endurance (Hill-Haas, Dawson, Impellizzeri, & Coutts, 2011; Hoff, Wisloff, Engen, Kemi, & Helgerud, 2002; Stolen, Chamari, Castagna, & Wisloff, 2005) as well as to provide a stimulus for more anaerobic acceleration abilities (Ade, Harley, & Bradley, 2014; Hodgson, Akenhead, & Thomas, 2014). Many studies have specified the workload of these SSGs in numerous variations of for example pitch size, number of players and game rules (Halouani, Chtourou, Dellal, Chaouachi, & Chamari, 2014; Hill-Haas et al., 2011).

While the workload of matches and SSGs are well described, limited information is available regarding the training practices of elite football teams, in particular with respect to acceleration and metabolic variables. However, it can be expected that in training sessions accelerations occur relatively often compared to match play, since exercises are played in
smaller areas requiring players to change direction more frequently (Hodgson et al., 2014). Therefore, especially in training, total distance covered and distance ran at high speeds would underestimate the work done by the players (Gaudino et al., 2013). Additionally, training can take up an important part of the total weekly load, for example up to 75% of workload rated by session-RPE in young football players training four times a week (Impellizzeri et al., 2004). Altogether, to better understand training periodization of elite football it could be useful to gain more insight into the relative external load of training sessions compared to matches as well as total weekly loads of training and match combined.

**Aims and outline**

The aim of this thesis is to determine whether electronic tracking technology (i.e. LPM) can provide accurate measures of more recently emphasized external load variables (i.e. acceleration, deceleration and estimated metabolic power) and to what extent these variables can provide additional insight into the training practices and fitness of elite football players.

Studies assessing the validity and reliability of local position measurement (LPM) systems have used methods that were not optimally suitable for the detection of (maximal) accelerations and decelerations in dynamic locomotor conditions and/or did not report on accuracy of acceleration measures. Therefore, Chapter 2 describes the validation of a LPM system for measuring relevant time-motion variables, including average and peak acceleration and deceleration, during various football-specific movements at low, medium and high intensity.

These football-specific movements, which often consist of accelerations, decelerations and changes of direction, are energetically more demanding than constant pace running. To assess the additional energy cost of accelerated and decelerated running Chapter 3 describes an experiment in which the energy cost of shuttle running is compared to that of constant running. Because an algorithm has been developed which in practice is used to estimate energy cost from time-motion data in football, this algorithm will also be validated in combination with LPM time-motion data for both constant running and shuttle running.

In contrast to the detailed information available regarding matches, few studies have described the training practices of elite football players, especially with regard to external load variables. This information can be useful to learn about training periodization of elite football and to gain insight into the relative load of training compared to matches. Therefore, Chapter 4 describes the external and internal in-season training load of typical training days in a professional Dutch Eredivisie football team, including acceleration and metabolic variables. To ease interpretability, training load is expressed relative to match load. Furthermore, nonstarters usually have an extra training session the day after the match to, at least partly, compensate for the missed load during the match. In general, such training for nonstarters aims to have at least a similar load compared to regular training of starters and nonstarters. It will be investigated if
this is indeed the case.

As part of training sessions, small-sided games (SSGs) are frequently employed during the competitive season. It would be of additional practical value if these highly football-specific SSGs could also be used to monitor the fitness of players. This would be especially helpful during the competitive season because in this period there is little time for (maximal) fitness tests. Therefore, Chapter 5 evaluates whether locomotor performance, including acceleration and metabolic variables, during a standardized 6-a-side SSG can serve as fitness indicator. For this purpose the 6-a-side SSG was compared between groups varying in fitness and skill level and related to a frequently used intermittent anaerobic endurance test. Additionally, locomotor performance during this 6-a-side SSG was tested for reliability for several external load variables.

Finally, Chapter 6 (Epilogue) summarizes the previous chapters and highlights the main results and conclusions of the studies. It also discusses some limitations and practical implications of the presented results and identifies directions for future research.