Epilogue
Monitoring training and match load with automated tracking systems has become common practice in elite team sports and may be a useful aid in achieving adequate load management. The aim of this thesis was to determine whether electronic tracking technology (i.e. LPM) could provide accurate measures of more recently emphasized external load variables (i.e. acceleration, deceleration and estimated metabolic power) and to what extent these variables could provide additional insight into the training practices and fitness of elite football players. This epilogue first provides a brief summary of the previous research chapters, followed by the main conclusions. Next, some important limitations and practical implications of the presented results will be discussed. Finally directions for future research will be identified.
Summary

Measuring accelerations and decelerations during football

In intermittent field-based team sports, players often accelerate and decelerate (Dalen, 2016 (Dalen et al., 2016; Wehbe et al., 2014), which is both mechanically (Greig et al., 2006) and metabolically (Buglione & di Prampero, 2013; Osgnach et al., 2010) demanding. Automated tracking systems typically provide time-motion data of whole body movements, which may be used to estimate the external load of players. Compared to commonly used measures such as total distance covered and distance ran in speed zones, measures of acceleration and deceleration could complement these measures and likely improve the quantification of external load in football (Polglaze et al., 2016; Varley & Aughey, 2013). However, while GPS and video-based tracking systems are capable of measuring players’ distance covered and average speed in linear low speed courses, these systems usually show lower accuracy for non-linear courses at higher speeds (e.g. Rawstorn et al., 2014). Although LPM systems potentially show higher accuracy on distance and speed measures (Frencken et al., 2010; Ogris et al., 2012) than GPS and video-based tracking systems, the accuracy of (maximal) accelerations and decelerations in dynamic locomotor conditions was unknown before the present research. Therefore, the first study (Chapter 2) was conducted to examine the accuracy of the Inmotio LPM system in measuring relevant time-motion variables, including average and peak acceleration and deceleration, during various football-specific movements (including straight line running, and 90 and 180° change of direction) at low, medium and maximal intensity. Results indicated that the Inmotio LPM system has good accuracy for measuring distance, average speed and peak speed, even in maximal intensity football-specific exercises. Furthermore, LPM accuracy was acceptable for most measurements of average acceleration and deceleration, but limited for peak acceleration and deceleration. Moreover, the accuracy of the LPM system proved to depend both on movement type and intensity.

Metabolic power of accelerated and decelerated running

Playing football requires players to continuously accelerate, decelerate and change direction which is energetically more demanding than running at constant speed (Buglione & di Prampero, 2013). The second study (Chapter 3) determined this extra energy cost of accelerated and decelerated running by comparing aerobic continuous 10-m shuttle running with constant pace running at average speeds ranging from 7.5–10.0 km·h⁻¹. It was found that 10-m shuttle running required around 30–50% more energy than constant running for the investigated speed range and that this difference increased linearly with increasing speed. In football practice an algorithm originally developed by di Prampero et al. (2005) is often used to estimate energy cost from time-motion data (Osgnach et al., 2010). We therefore also attempted to validate...
this algorithm measuring LPM time-motion data and oxygen consumption for both constant and shuttle running. Results showed that for constant running, estimated energy cost was 6–11% higher than measured energy cost. In contrast, for shuttle running, estimated energy cost was significantly lower (-13 to -16%) than measured energy cost. This means that di Prampero’s approach in combination with LPM time-motion data partly accounts for, but still underestimates, the extra energy needed for accelerations and decelerations compared to estimating energy cost of running based solely on distance ran.

Training load of elite football

To date, limited information is available regarding the periodization practices of elite football players, especially with regard to external load variables. However, because both too low and too high training load, as well as rapid increases in load, have been associated with higher injury risk (Gabbett, 2016), it seems useful to accurately quantify training and match load. Therefore, the study presented in Chapter 4 charted the external and internal in-season training load in a professional Dutch Eredivisie football team, including acceleration and metabolic variables. Training load of typical training days, categorized as days before match day (MD minus), was also compared against whole match values measured using the same LPM system. Training load declined as match day approached (MD-4 > MD-3 > MD-2 > MD-1). Relative to match values (100%), training values for running (52–20% on four to one days before the match) and high-speed running (38–15%) were lower than for total distance (67–35%), while all were considerably lower than match values. On average, medium and high accelerations and decelerations during training were more similar to match values (90–39%), particularly during training sessions four days before the match. Because the acceleration and deceleration values deviated from the more commonly used variables based on distance and speed, it was concluded that measures of acceleration and deceleration indeed complement these more commonly used variables. It was also investigated whether training sessions of the nonstarters one day after the match was at least similar compared to regular training sessions of starters and nonstarters, since this training session is intended to compensate for the missed match. Unexpectedly, training load during the nonstarters training was lower than during regular training sessions on MD-4, while it was lower for several high-intensity variables on MD-3 and MD-2. During weeks with a single match, estimated cumulative weekly load was lower for nonstarters than starters for most variables. Weekly load of the nonstarters was up to about 30% less for running, high-speed running and time spent above 90% of maximal heart rate. Therefore, it was concluded that nonstarters are potentially under-loaded compared to starters, particularly with regard to running at higher speeds.
Fitness testing by playing football

Additional (maximal) fitness tests are usually not employed during the competitive season since they reduce training time and increase already existing fatigue. Since standardized small-sided games (SSGs) are often employed as part of training sessions, it would be of considerable practical value if SSGs could be used to monitor the fitness of football players. Therefore, the final study of this thesis (Chapter 5) evaluated whether locomotor performance during a standardized 6-a-side SSG, commonly done to concomitantly improve football-specific fitness and technical skills, could serve as fitness indicator at the same time. First, locomotor performance (i.e. external load) during the 6-a-side SSG was compared between groups varying in fitness and skill level, namely: professional male senior and junior, professional female senior, and male amateur players. Furthermore, the 6-a-side SSG was related to a frequently used intermittent anaerobic ‘football-specific’ endurance test (i.e. Yo-Yo IR2). Finally, with the amateur players the 6-a-side SSG was tested for reliability for several external load variables. Results indicated that amateur players had lower values than professional senior players on almost all investigated external load variables while women had lower high-intensity external load variables than all other subgroups. Nevertheless, the women showed the highest relative heart rate and perceived the 6-a-side SSG as harder than the other groups. Total distance covered during the 6-a-side SSG was only moderately correlated to Yo-Yo IR2 distance ($r = 0.45$), while the correlation with Yo-Yo IR2 distance improved for estimated metabolic power ($r = 0.60$) and distance above high-intensity thresholds of speed, acceleration and metabolic power ($r = 0.59–0.70$). Intraclass correlation coefficient was 0.84 for total distance, but lower for all other time-motion variables (0.74–0.78). Besides, although total distance covered and average metabolic power during the 6-a-side SSG showed good reproducibility (coefficient of variation = 4%), coefficient of variation was higher for all high-intensity time-motion variables (8–14%). Overall, it was concluded that locomotor performance, during a standardized 6-a-side SSG, operationalized in several external load variables, does not provide a valid and reliable fitness indicator for individual football players. Additionally, results indicated that there might be a ceiling effect for achieving high-intensities during small-sided game play for very fit and skilled players.

Main conclusions

In sum, this thesis aimed to determine whether electronic tracking technology (i.e. LPM) could provide accurate measures of more recently emphasized external load variables (i.e. acceleration, deceleration and estimated metabolic power) and to what extent these variables could provide additional insight into the training practices and fitness of elite football players. Chapter 2 showed that the Inmotio LPM system has acceptable accuracy for measuring average acceleration and deceleration, even in maximal intensity football-specific exercises.
However, LPM accuracy was limited for peak acceleration and deceleration. Furthermore, *Chapter 3* made clear that di Prampero’s metabolic approach used with LPM time-motion data underestimates the true metabolic cost of aerobic shuttle running. *Chapter 4* illustrated that during training measures of acceleration and deceleration provide new information compared to more commonly used variables based on distance and speed. Moreover, *Chapter 5* indicated that locomotor performance during a standardized 6-a-side SSG, operationalized in several external load variables including measures of acceleration and metabolic power, does not provide a valid and reliable fitness indicator for individual football players. Finally, based on the results of *Chapter 4* and *Chapter 5* it is of yet unclear whether measures of estimated metabolic power currently provide much additional value beyond measures based on distance, speed and acceleration.

**Practical implications, limitations of the present research, and directions for future research**

*Accuracy of automated tracking systems*

Accurate and reliable measurement of time-motion variables is an essential first step towards more detailed time-motion analysis. While in recent years the accuracy of GPS systems has improved, mainly due to an with increased sampling frequency (Rampinini *et al.*, 2015; Varley *et al.*, 2012), GPS accuracy is still limited for tracking dynamic and high speed activities (Portas *et al.*, 2010; Rampinini *et al.*, 2015). Nevertheless, in recent years researchers have begun to include GPS-derived acceleration and deceleration measures to quantify team-sport activities (e.g. Akenhead *et al.*, 2016; Akenhead *et al.*, 2013; Arruda *et al.*, 2015; Aughey, 2011; Davies *et al.*, 2013; Gaudino, Alberti, *et al.*, 2014; Hodgson *et al.*, 2014; Russell *et al.*, 2016; Varley & Aughey, 2013). However, the relatively few studies that assessed the accuracy of GPS for measuring accelerations and decelerations reported limited accuracy and reliability, especially for intense accelerations from a standing start (Akenhead *et al.*, 2014; Buchheit, Allen, *et al.*, 2014). Therefore, future studies should further address the accuracy of more advanced GPS-systems (e.g. 15-Hz) for measurement of acceleration and deceleration measures in more challenging conditions (i.e. full multidirectional accelerations).

The Inmotio LPM system seems to have greater accuracy and reliability compared to GPS (Buchheit, Allen, *et al.*, 2014) and video-based systems (Buchheit, Allen, *et al.*, 2014; Siegle *et al.*, 2013), and provides very accurate data of distance and speed measures, as well as sufficiently accurate data regarding average acceleration and deceleration to be of use for at least some purposes (*Chapter 2*). However, also LPM currently seems not capable of accurate measurements of peak acceleration and deceleration. Therefore, the usefulness of peak acceleration, as provided routinely by automated tracking systems has been questioned (Buchheit, Allen, *et al.*, 2014). It
seems more useful to quantify the distance covered or, preferably to facilitate interpretation, the number of accelerations and decelerations above a certain threshold. Moreover, since for standing starts accuracy of acceleration measures is the least accurate, care should also be taken to track sprint time of short (5–30m) sprints with the LPM system. When high accuracy of sprint timing is needed timing gates are preferred.

Currently an increasing number of automated tracking systems are becoming commercially available. Therefore, it might be due time to agree on a standard validation protocol. 3D-motion capture systems (e.g. VICON) seem the gold standard against which automated tracking technology can be compared during dynamic football-specific activity. An alternative could be laser technology, which also comprises 3D-systems. A validation protocol should include multi-directional runs on maximal intensity to fully quantify the possibilities (and limitations) of these tracking systems. This would aid both researchers and practitioners in club settings in selecting the best system for their specific purposes. Ideally, all tracking systems should also be tested for ecological validity of measuring certain key external load variables during football, which was not done in the study presented in Chapter 2. However, measuring full pitch sizes with a gold standard will remain problematic with current techniques.

**Using automated tracking systems in football training and match**

Choosing a tracking system for training and match purposes is a matter of budget and needs. Video-based systems can be used in a flexible manner in stadiums and provide both physical and tactical information (e.g. Frencken, Poel, Visscher, & Lemmink, 2012), but are less suitable for recording training sessions. GPS is also flexible, and can be used for both training and matches, but is potentially less reliable in stadium environments. Moreover, GPS data may not be accurate enough to detect the positions of players relative to each other, which is essential for tactical analysis. LPM systems are usually (semi)-permanent installations; they are currently the most accurate systems, can be used indoor (i.e. stadiums) and can also provide accurate relative positions for tactical purposes.

As far as I know, the study described in *Chapter 4* was the first to compare training load with match load of the same players by using the same tracking system. Ideally, instead of friendly matches, official matches should be used to quantify the reference match load. Recently, just before the start of the 2015–2016 season, FIFA allowed the use of wearable tracking technology during matches. As a result, it became possible to collect the same external and internal load measures during training and matches. Ideally, the same tracking system is used for training and match play, but when more systems are used interchangeably, correction factors could be determined and applied (Buchheit, Allen, *et al.*, 2014). In all likelihood, however, such correction factors need to be re-established each time software updates and ‘improved’ (i.e. different) versions of a system are implemented (Buchheit, Al Haddad, *et al.*, 2014). These changes usually affect high-intensity variables, especially accelerations, the most.
Metabolic power estimations

Since direct assessment of metabolic power during football is impossible, indirect estimation of metabolic power based on time-motion data seems an appealing alternative. Time-motion data could provide a better indicator of overall workload than estimates based on total distance covered (Polglaze et al., 2016) or session-RPE. However, the results presented in Chapter 3 showed that the algorithm originally developed by di Prampero and colleagues (2005) still underestimates the actual energy cost of aerobic (10-m) shuttle running, even when used in combination with reasonably accurate LPM time-motion data. This underestimation of energy cost would probably be even larger and less reliable when GPS time-motion data is used, especially for high-intensity activities (Rampinini et al., 2015) and activities involving ball contact (Buchheit et al., 2015). Although this underestimation of energy cost could decrease partly with more accurate tracking systems (and therewith more accurate measurements of instantaneous speed and acceleration), the underestimation is most likely due in large part to limitations of the approach as explained in the original article (Di Prampero et al., 2005). As a consequence, the use of current metabolic power estimations in football has recently become a topic of debate (Buchheit et al., 2015; Osgnach et al., 2016). At present, the added value of estimated metabolic power to other external load measures during football is unclear. For example, Chapter 4 showed that during whole training sessions estimated energy expenditure of players correlated almost perfectly with total distance covered \((r = 0.99)\). Taken together, it seems fair to conclude that, although estimated metabolic power may complement more commonly used time-motion variables for some purposes, care should be taken when using it in practice, especially when comparing athletes and different types of activities.

High-intensity activities during football

It is important to note that separate measures of high-intensity speed running and high-intensity accelerations are necessary to accurately describe football activity. For example, Chapter 4 showed that, during training, compared to matches, the relative contribution of accelerations is higher than for running at high speeds. Although the results of Chapter 4 care specific for the elite football team considered and descriptive in nature, this specific information regarding high-intensity training load could also be important in relation to injury. Therefore, it would be interesting to investigate load-injury relationships with different external load variables in football, as has already been done for rugby (Gabbett & Ullah, 2012) and Australian Football (Colby, Dawson, Heasman, Rogalski, & Gabbett, 2014). For intermittent team sports, high-intensity load might be as important, or perhaps even more important, to monitor than more general measures of overall workload (e.g. metabolic power, session-RPE, summed heart rate zones). For example, Chapter 5 showed that high-intensity variables during a standardized SSG were more distinctive between teams of different fitness level than overall workload variables.
Locomotor performance during football

Chapter 5 aimed to link locomotor performance, operationalized in several external load variables, during a standardized football activity (i.e. 6-a-side SSG) to physical fitness (i.e. aerobic/anaerobic endurance capacity). Although SSGs can be better standardized than matches (e.g. continuous play, less position dependent), they still have some limitations that prevent players to reach high locomotor performance. Locomotor performance of players is not a goal per se during SSGs and can therefore be influenced by factors such as player motivation and team tactics (Carling, 2013). Furthermore, there could be a ceiling effect for achieving high exercise intensities for highly fit and skilled players (Hill-Haas et al., 2011), for which indications were also found in Chapter 5. Besides locomotor movements, there are football activities that are not (fully) described by common time-motion analysis, such as duels, tackles, jumps and ball control. Excluding these non-locomotor activities results in underestimation of physical performance during the standardized 6-a-side SSG.

Conditioning nonstarters

Chapter 4 showed that nonstarters might be under-loaded compared to starters. However, it could also be that starters might be over-loaded compared to nonstarters. Research regarding the changes in fitness level of both starters and nonstarters during a football season (Jajtner et al., 2013; Kraemer et al., 2004) is scarce at an elite level, partly due to limited possibilities for fitness testing in the competitive season. Integration of internal and external load (Akubat et al., 2014) during (standardized) football activities may aid to detect those changes in fitness of individual players across the season. Nonetheless, because week-to-week changes in load are probably more predictive for injuries than absolute loads (Gabbett, Hulin, Blanch, & Whiteley, 2016), it seems necessary to adequately prepare nonstarters for sudden starts in subsequent matches. To replicate match-specific load on the post-match days when starters recover, nonstarters could play matches with lower teams from the club, test matches, large sided games during training and/or perform additional conditioning exercises.

Intensity of football training

While Chapter 4 described the training load of elite football training, it would also be useful to quantify the intensity of training sessions. Rather than simply dividing the total training load (e.g. distance) by the total training duration, it could be useful to quantify the density of certain training stimuli. For example, the density of training load variables over a certain time period (e.g. 1−5 min) could be expressed either as a percentage of the maximum match intensity over the same time period or as a percentage of average match intensity. In this manner, one could determine whether and how often during training the load (e.g. number of accelerations, distance at high speed and time above 90% maximum heart rate) of matches is replicated or even exceeded.
Physical demands placed in perspective

Football has become more intense during the past decades (e.g. Bush, Barnes, Archer, Hogg, & Bradley, 2015; Wallace & Norton, 2014). Therefore the physical demands of playing football are much greater than before. It is generally believed that quantification of the physical load aids the planning of training sessions and recovery. Nevertheless, it should be stressed that besides the physical aspects also the mental, technical and tactical qualities of football players determine the football performance. Clearly these latter aspects are greatly underexposed in the current thesis. Ultimately, as the best Dutch football player of all times once put it:

"Als je een speler ziet sprinten is hij te laat vertrokken" (Johan Cruijff).

"If you see a player sprinting, he has started too late" (Johan Cruijff).