THE ROLE OF ACELERATION RELATED VARIABLES FOR HAMSTRING MUSCLE (RE-) INJURY PREVENTION IN ELITE ASSOCIATION FOOTBALL

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Abstract

Hamstring muscle injuries constitute a major concern in football and a major challenge for physiotherapists working in this sport, being an injury with long absence from playing and training. Although clinical strategies to rehabilitate these injuries and clinical injury risk assessments have been explored over the years, a broader comprehension of how variables regarding running performance may in some form relate to hamstring injury risk has been missing for clinical professionals. Together with this, its incidence has been increasing despite many preventive efforts, which reveals a necessity for developing risk assessment methods to better inform preventive strategies. The key involvement of hamstring muscles during accelerations and decelerations during football running actions justifies research into acceleration related observations. Therefore, the aims of the current programme of research were to develop new laboratorial and load monitoring strategies related to acceleration actions, by exploring biomechanical factors from a physiotherapist perspective. Additionally, implementing assessments and exposing some key limitations of these assessments in professional clubs is also described throughout the experimental studies of this thesis (chapters 3 and 5).

For the purposes of this thesis, force development variables were analysed in chapter 3, during maximal accelerations on a non-motorised treadmill, and comparisons between professional players with and without previous injuries were performed. Results from this study revealed no differences between groups during both maximal acceleration and steady state of a maximal sprint effort.

A second approach regarding risk analysis and acceleration variables considered the mechanical load based on trunk-mounted accelerometry used in outfield training, as

detailed in chapter 5 of the present thesis. In this study mechanical load expressed by PlayerLoad^{TM}, an accelerometer-derived variable aimed to express the rate of change in acceleration, was collected for the training sessions during three weeks previous to a hamstring injury event, in English Premier League clubs, using matched healthy controls. Although the results did not show significant differences between experimental and control group, this exploratory method may constitute a promising method to assess hamstring injury risk.

Reliability and validity of the acceleration related variables were addressed first for each of the two experimental studies detailed in chapter 3 and 5. For this purpose, a pilot study on reliability of force collection using a non-motorised treadmill was performed to test the experimental protocol with results showing good overall reliability. For the PlayerLoad^{TM}, a laboratorial study detailed in chapter 4 using a laboratorial overground soccer simulation protocol was adopted and convergent validity with subjects´ anthropometrics together with reliability analysis of four isolated football actions (jogging, side cut, stride and sprint) was performed. Results of this study revealed no association between PlayerLoad^{TM} and the subjects height or body mass and also an overall good reliability for the four actions analysed.

In summary, the research presented in this thesis helped better understand the current value and limitations of screening and monitoring acceleration related variables in the context of hamstring (re-)injury prevention in professional football, introducing to the clinical field a different perspective of addressing hamstring behaviour during acceleration actions, and its hypothetical relation with hamstring injury.

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List of abbreviations

AU – Arbitrary units

EMG – Electromyography

EPL – English Premier League

CG – Control group

CV – Coefficient of variation

GPS – Global Positioning System

HIG – Hamstring injury group

ICC – Intra correlation coefficient

LOA – Limits of agreement

MD – Match day

mSAFT ^{90} – Modified overground match simulation protocol

NMT – Non-motorised treadmill

PL – PlayerLoad™

SAFT ^{90} – Overground match simulation protocol

Chapter 1

General Introduction

Force development during running actions in football – where do hamstrings stand?

1.1 Introduction

Association football is a worldwide sport with around 38 million registered association football players (Kunz, 2007). Due to the tactical and technical evolution of the game, football has become more physically challenging for practitioners over the years. The repercussions of the game´s physical demands are reflected in the high number of injuries observed in this sport, particular the ones referent to lower limbs (Ekstrand, Hagglund, & Walden, 2011; Hagglund, Walden, & Ekstrand, 2013). Injuries not only translate into time away from training and competing (Hagglund, Walden, & Ekstrand, 2013), but often represent significant economic constraints to clubs and society (Hawkins, Hulse, Wilkinson, Hodson, & Gibson, 2001). From all the injuries observed in football, hamstring injuries have been gathering the attention of medical, sports science, and coaching professionals, due to high incidence and recurrence rates (Ekstrand, Walden, & Hagglund, 2016), together with extensive absence time from training and competition (Ekstrand, Hagglund, & Walden, 2011; Ekstrand, Hagglund, & Walden, 2011a; Woods, Hawkins, Maltby, Hulse, Thomas, & Hodson, 2004; Opar, Williams, & Shield, 2012).

Particularly for the clinical staff around professional football teams, the rehabilitation and prevention of primary hamstings injuries and recurrent injuries is somehow challenging. One of the reasons for the difficulty in addressing this injury might be related with the general approach regarding (re)injury risk, often based on orthopaedic clinical tests of flexibility and stength whilst lying on a therapeutic bed, or self-reported symptoms by the players during the daily work at the clubs. Together with this, research evidence has been supporting the development and implementation of prevention strategies for hamstring injuries over recent years (Croisier, Ganteaume, Binet, Genty, & Ferret, 2008; Arnason, Andersen, Holme, Engebretsen, & Bahr, 2008; Petersen, Thorborg, Nielsen, Jorgensen, & Holmich, 2011; van der Horst, Smits, Petersen, Goedhart, & Backx, 2015), yet without hamstring injury rates decreasing (Ekstrand & Gillquist, 1983; Ekstrand, Hagglund, & Walden, 2011). In fact, a recent epidemiological study from Ekstrand et al. (2016) performed in 36 professional football clubs across Europe has shown that between 2001 and 2014 there was a 4% annual increase in hamstring injuries occurring during training.

One possible reason for which prevention strategies may have failed so far in preventing and decreasing hamstring injury might be the ecological validity of contemporary assessment strategies. A division of concepts between performance variables and clinical signs, in which self-reported symptoms by the player are included, may have limited power in predicting these injuries. Therefore often physiotherapists at the clubs and the medical staff in general, may be too much looking to variables associated with clinical behaviour and ignoring the running related actions from these muscles. The latter may ultimately help identify important baseline deficits after injury. Similarly, running related loads on the musculoskeletal system during daily training may also contribute to hamstring failure and consequent injury. Nonetheless, risk assessment strategies in general seem to have been more directed to isolated variables and less to the phenomenon surrounding the behaviour of these muscles whilst running.

Hamstrings muscles have a role in running activities in football, being recruited in several stages of the gait cycle during running (Yu, Queen, Abbey, Liu, Moorman, & Garrett, 2008; Novacheck, 1998; Schache, Dorn, Blanch, & Brown, 2012; Thelen, Chumanov, Hoerth, & Best, 2005) and are known to contribute to a player´s capacity to accelerate, especially during high speed actions when developing high horizontal forces (Morin, Gimenez, Edouard, & Arnal, 2015). Whilst this has been shown by research, risk assessment and intervention strategies in professional football seem to have been focused on assessing modifiable variables also suggested by research such as strength (Fousekis, Tsepis, Poulmedis, Athanasopoulos, & Vagenas, 2011; Opar, Williams, Timmins, Hickey, Duhig, & Shield, 2015; Croisier, Ganteaume, Binet, Genty, & Ferret, 2008), flexibility (Engebretsen, Myklebust, Holme, Engebretsen, & Bahr, 2010; Fouseki, Tsepis, Poulmedis, Athanasopoulos, & Vagenas, 2011; Arnason, Sigurdsson, Gudmundsson, Holme, Engebretsen, & Bahr, 2004; Witvrouw, Danneels, & Asselman, 2003), motor control (Cameron, Adams, & Maher, 2003), or jumping performance (Arnason, Sigurdsson, Gudmundsson, Holme, Engebretsen, & Bahr, 2004; Henderson, Barnes, & Portas, 2010). Limited attention has been paid to the assessment of acceleration-related variables during actual running efforts, which could be better to help express function or dysfunction of the hamstrings during football practice. An analysis of these acceleration-related variables can be performed through a number of ways, considering for example horizontal force development during the course of these actions, or the meaningfulness of the acceleration loads associated with them resulting from repeated daily professional football training. Introducing this knowledge to professional football physiotherapy or clinical care in this sport may improve the perspective and provide broader information to the existing clinical setup surrounding these injury assessments.

The development of treadmills with capability to determine horizontal forces during different acceleration levels (Morin, Gimenez, Edouard, & Arnal, 2015; Brughelli, Cronin, Mendiguchia, & Kinsella, 2010), together with the wearing of trunk-mounted accelerometers which became a common practice in professional football (Cummins, Orr, O’Connor, & West, 2013), offers a new window of opportunity for hamstring injury risk assessment in football. As a football physiotherapist, embracing these assessments and monitoring strategies might be a valuable addition to current practices, not only due to their potential for injury prevention purposes but also as, for example, future application as part of the rehabilitation markers for a safer return to training and competition after an injury. For example, non-motorized treadmill (NMT) running tests in Australian Rules football players have identified deficits in horizontal force development in limbs with previously injured hamstring muscles during a submaximal acceleration effort (Brughelli, Cronin, Mendiguchia, & Kinsella, 2010). If these findings are consistent even when the methodology is being implemented in an elite football club context, then this could represent a functional focus to be improved and normalized throughout the course of rehabilitation, as well as be an important return to train and play marker adopted by physiotherapists after a hamstring injury. Additionally, from a different perspective, Ehrmann et al. (2015) associated a decrease in an acceleration-related measure collected from a tri-axial accelerometer with an increased injury incidence in football players. Although his study was not specifically designed around hamstring injuries in football, this finding in particular showed the importance that outfield related acceleration loads have in relation to football injuries. To explore this topic from a physiotherapist perspective, adopting a variable resulting from trunk mounted accelerometry represents an opportunity to look in to the challenges imposed on these muscles from actual training sessions. That is, instead of isolating the hamstring in orthopaedic or laboratorial strength tests, or even treadmill force development actions, it may be of additional value to look to the general rate of change in acceleration. This is implemented whilst hypothesising that if the hamstrings have a significant contribution to the change in rate of force development associated to PL scores, this variable may be adopted for injury hamstring injury prediction purposes, which ultimately complements the clinical and laboratorial approach that clinicians normally adopt regarding these injuries.

However, despite these technological developments which elite football clubs regularly have at their disposal, the adoption of these instruments, methodologies and variables requires further efforts to justify their meaningfulness, validity and reliability when applied to a practical context. Whilst it may in the field be perceived as the ultimate state of the art or as the most recent research for clinicians in football according which to expand their approach on hamstring injuries in football, its interpretation still remains largely unknown.

1.2 Aim and objectives of the research

Considering the limited and conflicting evidence on current hamstring injury risk assessment methods, the overall aim of this doctoral study was to further the knowledge about the association that acceleration-related variables may have on hamstring injury risk. By exploring this association from a clinical practitioner, it was also an opportunity to introduce biomechanics in the form of novel or recent assessment methods and tools in the clinical field of hamstring injury management. In order to do so, assessment strategies with high ecological validity and applicability in a professional football setting were implemented.

The first objective was to assess force generating asymmetries during sprinting after a hamstring injury, and that in a professional club setup. The protocol involved maximal acceleration efforts and a maintained sprint intended to expose potential dysfunction in the hamstring horizontal force generation capability that could justify the high recurrence rates observed in this population.

The second objective was to evaluate construct validity and reliability of PL a commonly used acceleration-based variable to monitor mechanical load in a field context.

The third and final objective was to evaluate whether PL measured during training sessions can help reveal hamstring injury risk.

Chapter 2

Literature review

2.1 Hamstrings injuries in football.

Hamstring injuries remain a topic of great concern in professional football. First, due to its high prevalence, it represents 16.8% to 25.7% of all injuries registered per season during the latest 13 years according to the follow-up epidemiological study from Ekstrand et al. (2016) involving 36 European professional teams. Second, the extensive absence time from field due to complex rehabilitation calls for attention (Opar, Williams, & Shield, 2012). In fact severe hamstring injuries, correspondent to absence periods from training superior to 28 days, happen more frequently than any other type of injury (Ekstrand, Hagglund, & Walden, 2011; Ekstrand, Hagglund, & Walden, 2011a; Woods, Hawkins, Maltby, Hulse, Thomas, & Hodson, 2004). A third reason for great concern is that these injuries present a recurrence rate of 13-16 %, which despite not increasing over the past seasons typically results in even greater durations of rehabilitation compared to that from the first injury episode (Ekstrand, Walden, & Hagglund, 2016; Ekstrand, Hagglund, & Walden, 2011a; Woods, Hawkins, Maltby, Hulse, Thomas, & Hodson, 2004). All this means that on average a football team will present throughout the season five hamstring injuries at a rate of 0.43-0.51 injuries/1000 training hours and 3.70-4.77 injuries/1000 hours of game (Ekstrand & Gillquist, 1983; Orchard & Seward, 2002; Ekstrand, Hagglund, Walden, 2011; Woods, Hawkins, Maltby, Hulse, Thomas, & Hodson, 2004; Ekstrand, Walden, & Hagglund, 2016). Fourth and finally, those teams that have an increased fixture congestion and therefore less recovery days between games during the competitive season, show a higher incidence of hamstring injuries (among others) when there were four or less days between league games when compared to periods of six or more days (Bengtsson, Ekstrand, & Hagglund, 2013).

For these reasons, hamstring injuries are associated with athletic a considerable burden for the clubs, being often associated with loss of player availability for training and competing (Ekstrand, Walden, & Hagglund, 2016) and representing (together with other injuries) financial losses for the clubs (Woods, Hawkins, Hulse, & Hodson, 2002; Junge, Lamprecht, Stamm, Hasler, Bizzini, & Tschopp et al. 2011). This makes it imperative to increase the knowledge about injury-related factors to allow the implementation of better prevention strategies.

2.2 Running actions in football. Hamstring muscle contribution and injury mechanisms.

Typical actions from football are usually performed as brief activity bouts in a straight line or multidirectional, involving ball disputing or dribbling actions whilst tactical or positional battles take place, and with periods of recovery between these efforts that are variable in duration (Bradley, Sheldon, Wooster, Olsen, Boanas, & Krustrup, 2009). Acceleration and deceleration efforts constitute around 18% of the distance covered of various intensities per game, and contribute to a total running distance of approximately 10-12 km (Akenhead, Hayes, Thompson, & French, 2013). These distances are covered at different speed zones during a football match often classified in low to moderate intensity running (0–14.4 km/h), high-intensity running (>14.4 km/h) and very high intensity running (> 19.8 km.h^{-1}). Regardless of this division in speed zones, the hamstrings are a muscle group with a high level of involvement and demand during all running actions, with this being particularly increased during actions involving high and very high intensity running (Thelen, Chumanov, Hoerth, & Best, 2005). This assumes particular relevance after the study of Barnes et al. (2014) showed that at a professional level, the game has been presenting an increasingly physical demand throughout the recent years, demonstrated by a 30-35% increase of actions involving very high intensity activities from 2006-07 to 2012-13 in the English Premier League (EPL). Hypothetically this fact alone may justify the necessity of matching weekly training intensities to the match-play demands by increasing training loads, in order to reverse a current trend of increased rate of hamstring injuries sustained during matches (Ekstrand, Walden, & Hagglund, 2016).

The mechanism of hamstring injury dictates the intrinsic relation these muscles have with running, especially at high speeds, with the majority of hamstring injuries occurring during running and sprinting in particular (Gabbe, Finch, Bennell, & Wajswelner, 2005). It will be the development of horizontal forces by the hamstrings during acceleration actions that will determine the effectiveness of the player in achieving max speeds during sprinting efforts (Morin, Gimenez, Edouard, & Arnal, 2015). Simultaneously, these muscles will work under eccentric lengthening to decelerate the lower limb during running (Schache, Dorn, Blanch, & Brown, 2012). As the player performs high-speed running or sprinting actions the increase in stride frequency, the main strategy to increase speed, is expected to result in increased lengthening velocities of the muscle-tendon complex as well as additional synergistic actions of muscles like the iliopsoas and the gluteus (Schache, Dorn, Williams, Brown, & Pandy, 2014; Dorn, Schache, & Pandy, 2012). In the late swing stage of the gait cycle a rapid lengthening of all the hamstring muscle portions occurs whilst producing the necessary negative (eccentric) work to decelerate the lower limb at the hip and knee joints (Schache, Dorn, Blanch, & Brown, 2012). As the athlete´s speed increases above 80% of their maximum, a significant increment of this lengthening will occur, with particular emphasis on the additional lengthening the biceps femoris muscle is subject to in comparison with the medial hamstrings. This places the biceps femoris muscle under additional strain (Thelen, Chumanov, Hoerth, & Best, 2005; Schache, Dorn, Wrigley, Brown, & Pandy, 2013), and therefore is believed to be one of the reasons why this muscle injures more often than medial hamstrings.

However, there are conflicting points of view regarding the exact moment at which the muscle failure typically occurs (Orchard, 2011; Chumanov, Schache, Heiderscheit, & Thelen, 2011). On the one hand the late swing phase has been shown as the most stressing moment for the hamstring muscles and the moment where injury occurs (Chumanov, Schache, Heiderscheit, & Thelen, 2011; Schache, Kim, Morgan, & Pandy, 2010; Heiderscheit, Hoerth, Chumanov, Swanson, Thelen, & Thelen, 2005). On the other hand, it has also been advocated that injury can result from the high ground reaction forces during the early stance phase (Orchard, 2011). Effectively, the fact that the hamstrings have been shown to be involved in other stages of the gait cycle apart from the stance phase, contribute to a belief that the injury moment will not occur exclusively during the late swing phase.

The synergistic actions of the hamstrings with other propelling muscles (Schache, Dorn, Williams, Brown, & Pandy, 2014; Dorn, Schache, & Pandy, 2012), together with the evidence showing its role in developing acceleration forces (Morin, Gimenez, Edouard, & Arnal, 2015) has been supported by research, in which the hamstrings have been shown to contribute to other phases of the gait cycle, like throughout the stance phase (Schache, Dorn, Wrigley, Brown, & Pandy, 2013). This involvement of the hamstrings muscles in other phases throughout the gait cycle include its concentric contraction to contribute to the hip extension moment during initial to middle stance phase (Novacheck, 1998), or an eccentric recruitment during the late stance phase (Yu, Queen, Abbey, Liu, Moorman, & Garrett, 2008). For example, Sun et al. (2015) used three-dimensional kinematics to model the sprint efforts of eight male elite sprinters and observed a relation between the ground reaction force direction, passing anteriorly to the knee and hip joints at the early stance phase, and the eccentric torque developed by the hamstrings. Despite this proven recruitment of the hamstrings during the stance phase perhaps the slower contraction velocities at which these occur have led to lesser focus on these phases in the context of injury mechanisms.

The complexity of the hamstring muscle contribution during running actions at different speeds goes beyond the non-uniform contraction dynamics in each stage of the gait cycle, with contradictory research findings relative to neuromuscular recruitment between its different portions. Similar to findings regarding hamstring muscle kinetics, speed increases will implicate electromyography (EMG) magnitude increases from medial and lateral hamstrings portions. However, whereas authors like Schache et al. (2013) did not find significant differences in neuromuscular recruitment between medial and lateral hamstrings across a wide range of moderate to sprint running speeds, others like Higashara et al. (2010) did. The latter authors showed different synchronizations between the semitendinosus and biceps femoris muscles when speed reached 95% of the individual's maximum. Together with these findings semitendinosus seemed to display higher activity during the middle swing phase than biceps femoris at higher speeds, while no differences were registered for the late swing phase between the two muscles in terms of EMG magnitude.

The functional behaviour of the hamstrings during sprint activity suggests that a high degree of coordination between its different portions occurs. Together with this also the capability to resist to eccentric and negative work together with concentric strength development capabilities will have to co-exist in order for the hamstrings to be efficient during running actions as part of football practice. Therefore, and regardless of the prevailing hamstring muscle injury mechanisms during accelerated sprint running in football, fatigue resultant from the constant recruitment of the hamstrings during a match seems to be a predisposing factor and the reason for the increased incidence of hamstring injuries at the end of each playing half (Ekstrand, Hagglund, & Walden, 2011). This fatigue is related with the running demands of the game and ultimately an accumulation of musculoskeletal stresses, leading to a failure in these muscles to maintain their eccentric contraction torques. This phenomenon was observed during half time and at the end of match-play using a treadmill-based match-play simulation protocol (Azidin, Sankey, Drust, Robinson, & Vanrenterghem, 2015; Greig & Siegler, 2009). The inability of the hamstrings to maintain their eccentric force generating capabilities due to fatigue might result from a decrease or delay in myoelectric activity (Timmins, Opar, Williams, Schache, Dear, & Shield, 2014), together with a reduction in muscle glycogen levels (Bangsbo, Mohr, & Krustrup, 2006), resulting in the inability of the muscles to produce fast eccentric strength and making it more prone to injury in these periods.

As previously mentioned in this section, the hamstrings have a major involvement in the late swing and throughout the stance phase of the gait cycle during sprint running. That is, not only are the hamstrings important in decelerating the lower limb during late swing but its neuromuscular activation during this phase also acts as an anticipatory mechanism for developing horizontal forces during ground contact and to accelerating the body forwards (Morin, Gimenez, Edouard, & Arnal, 2015). However, there is currently insufficient information about: 1) the way previous hamstring injury affects acceleration performance during running activities in football, especially the ones involving high speed actions (Morin, Edouard, & Samozino, 2011); 2) the role of whole-body acceleration-related variables resultant from training and competition and their potential to predict injury. These topics seem to be a promising alternative to overcoming the technical limitations of existing research on hamstring injury risk.

2.3 Hamstrings injury risk factors. The value of acceleration-related variables.

The fact that the hamstring muscles are placed under a significant demand and are susceptible to incur injury during football practice has made several researchers try to identify variables that put individuals at increased risk. These risk factors have traditionally been categorized as intrinsic (player´s features) and extrinsic (environmental features) although most reviews on hamstring injuries more often refer to whether the risk factors are modifiable or non-modifiable (see table 1.) (Liu, Garrett, Moorman, & Yu, 2012; van Beijsterveldt, van de Port, Vereijken, & Backx, 2013; Freckleton & Pizzari, 2012; Rogers, 2013). Whilst opinions continue to be divided when it comes to some risk factors such as age, (Gabbe, Bennell, & Finch, 2006; Woods, Hawkins, Maltby, Hulse, Thomas, & Hodson, 2004; Henderson, Barnes, & Portas, 2010; Engebretsen, Myklebust, Holme, Engebretsen, & Bahr, 2010; Hagglund, Walden, & Ekstrand, 2009; Ekstrand, Hagglund, & Walden, 2011) or flexibility (Engebretsen, Myklebust, Holme, Engebretsen, & Bahr, 2010; Fousekis, Tsepis, Poulmedis, Athanasopoulos, & Vagenas, 2011; Arnason, Sigurdsson, Gudmundsson, Holme, Engebretsen, & Bahr, 2004; Witvrouw, Danneels, & Asselman, 2003), there is a general consensus on other risk factors such as ethnicity (Woods, Hawkins, Maltby, Hulse, Thomas, & Hodson, 2004; Verrall, Slavotinek, Barnes, Fon, & Spriggins, 2001), eccentric strength deficits (Fousekis, Tsepis, Poulmedis, Athanasopoulos, & Vagenas, 2011; Opar, Williams, Timmins, Hickey, Duhig, & Shield, 2015; Croisier, Ganteaume, Binet, Genty, & Ferret, 2008), and especially previous injury (Arnason, Sigurdsson, Gudmundsson, Holme, Engebretsen, & Bahr, 2004; Engebretsen, Myklebust, Holme, Engebretsen, & Bahr, 2010; Fousekis, Tsepis, Poulmedis, Athanasopoulos, & Vagenas, 2011; Hagglund, Walden, & Ekstrand, 2013; Gabbe, Bennell, & Finch, 2006; Verrall, Slavotinek, Barnes, Fon, & Spriggins, 2001).

Table 1. Hamstrings injury risk factors addressed in research

	Intrinsic	Extrinsic
Non-Modifiable	Age, ethnicity, previous hamstring injury, previous knee injury, history of pubic osteitis, previous calf strain.	Playing surface
Modifiable	Flexibility, strength imbalances, fatigue, functional measures (e.g. countermovement jump, non-countermovement jump, motor control), low back injury, increased muscle neural tension, poor joint stability.	Insufficient warm-up, training parameters, playing position.

From all modifiable factors eccentric strength deficits or imbalances seem to gather growing evidence regarding its value as predictor of hamstring injuries.

Eccentric strength has been analysed either in an isolated fashion in prospective studies or associated to previous hamstring injury situations. Prospective studies assessing baseline side-to-side deficits in isokinetic eccentric peak torque (Fousekis, Tsepis, Poulmedis, Athanasopoulos, & Vagenas, 2011), low absolute and averaged pre-season and end-season values compared with a control group (Opar, Williams, Timmins, Hickey, Duhig, & Shield, 2015), or non-resolved low strength ratios to the quadriceps antagonist muscle due to low eccentric peak torques (Croisier, Ganteaume, Binet, Genty, & Ferret, 2008) have shown to come with higher risk of sustaining a hamstring injury. From a different perspective, sustaining a hamstring injury seems to affect the muscle capability of producing eccentric strength in various ways. Selective eccentric decreases in peak torque and neuromuscular activation in a lengthened range (Brockett, Morgan, & Proske, 2004; Sole, Milosavljevic, Nicholso, & Sullivan, 2011), together with lower torque development and impulse during eccentric contractions (Opar, Williams, Timmins, Dear, & Shield, 2013) were observed in previously injured hamstrings. However, whilst decreases in eccentric peak torque have been observed in previously strained hamstrings (Lee, Reid, Elliott, & Lloyd, 2009), a study by Opar et al. (2015a) also showed that instead of a unilateral deficit in the injured side, players with a history of unilateral hamstring strains present bilateral deficits if compared with a control group. This raises the question if this deficit is related to a baseline quality of these players that increased their risk of suffering the first episode (as they did), or if it results from an inhibition mechanism from the injury already sustained. Eccentric strength seems, at this moment in time, to be the best way of identifying risk and to modify as part of preventive strategies. However, although eliciting the hamstring muscle function during eccentric contractions appears to have some correlation with its capability of sustaining the volume and intensity of high strain forces during football practice, the current assessment methods might be limited due to their poor ecological value. This may be the reason why some authors evaluating similar assessments (Bennell, Wajswelner, Lew, Schall-Riaucour, Leslie, Plant, et al., 1998) and implementing hamstrings strengthening prevention programs, could not find any correlation with hamstring injury prevention (Gabbe, Branson, & Bennell, 2006). Analysing hamstrings strength normally requires tests using static devices or isokinetic dynamometers, in which the muscles are required to work in positions and speeds of contraction that do not match their usual performance during running actions.

For this reason hamstrings functionality as an injury risk factor has been tested not only by isolating the muscle activity but also through multi-segment tasks aimed to provide power and motor control information. The association between performance on tests replicating multi-segment functional movements and hamstrings injuries has been investigated. A few examples are the countermovement jump (Arnason, Sigurdsson, Gudmundsson, Holme, Engebretsen, & Bahr, 2004; Henderson, Barnes, & Portas, 2010) and standing jump (Arnason, Sigurdsson, Gudmundsson, Holme, Engebretsen, & Bahr, 2004) without showing any association between these test scores and injury risk. Nonetheless, Henderson et al. (2010) found that a 1 cm increase in jump height for a squat jump (without countermovement) increased with 1.47 points the odds of sustaining an injury, and Cameron et al. (2003) described the relationship between poor motor control through active movement discrimination and hamstring injuries. Although information from these tests aims to be reflective of the player's readiness, factors like speed of movement or applied force direction in jump tests fails to replicate the hamstring demands during running activities. It is unlikely that those tests express the ability of these muscles to produce the necessary forces during acceleration and deceleration efforts related with the various types of running efforts observed in football.

The ecological validity could be improved by focusing on their functional role during running actions, i.e. the generation of horizontal forces. For this reason, Brughelli et al. (2010) performed the first study addressing the effect of hamstring injuries on the horizontal force development during sprint running on a NMT at 80% of maximum speed. Their results showed significant side-to-side effects between healthy and previously injured limbs within the injured individual, as well as between the injured individuals compared with a control group, despite players in both groups keeping their speed performances. This testing method based on subjecting the hamstrings to a more equivalent function as observed in their athletic practice, and the extent of asymmetries observed in the results initiated a paradigm shift concerning testing methodologies for hamstring injury risk assessment, as well as return-to-play assessments. However, despite the testing protocol being based on a running effort, the submaximal nature of that effort and the fact that an isolated testing trial was performed may be considered as limitations regarding the hamstrings capacity of repeated sprint performance and injury risk. Also the fact that it was performed in a laboratorial setup with the use of a treadmill and not overground performance reinforces the necessity of improving and complementing this valuable and novel type of evaluations with data provided by outfield assessments.

2.4 From the laboratory to the field. Why acceleration load monitoring may be useful for hamstring injury risk in football?

With the advent of monitoring systems in football, and particular trunk-mounted Global Positioning System (GPS), several training and game variables related with physical performance have been monitored in the past years (Dellaserra, Gao, & Ransdell, 2014). The information provided by trunk-mounted monitoring systems can come from the GPS technology as well as from the commonly built-in tri-axial accelerometer. Whilst the GPS based data relative to performance variables like total distance and speed, or distance performed at different speed zones, might be of potential value to express the physiological demands on the cardiovascular and musculoskeletal system, data from the tri-axial accelerometer offers the potential to measure acceleration-based variables. For example, the variable PL, a cumulative measure of rate of change in acceleration (Boyd, Ball, & Aughey , 2011), may provide more directly related information considering the mechanical stresses imposed on the player´s musculoskeletal system. Accelerations and decelerations are known to lead to high forces acting on the musculoskeletal system which need to be absorbed by internal musculoskeletal structures (Bobbert, Schamhardt, & Nick, 1991). These forces result from the process to overcome external environmental forces acting on the player's body, like ground reaction and the gravitational forces, leading to its absorption by the body´s musculoskeletal structures (Hamner & Delp, 2013; Kawamori & Haff, 2004; Wakeling, Tschaner, Nigg, & Stergiou, 2001). With the use of PL a cumulative score of these forces is obtained, and one can understand the mechanical stress that was imposed to the player´s body. Of particular relevance might be how this variable expressing total mechanical load on the body may reflect the stress on the hamstrings muscles. As previously detailed, the hamstring muscles have a significant role during acceleration and deceleration actions during running, and PL variations may well be a predictor of hamstring (re-)injury.

Analysing the accumulation or variation of mechanical load resultant from accelerations and decelerations expressed by PL and its relation with hamstring injury is based on the concepts of exercise adaptation and optimal load. Muscle responses to mechanical loading from exercise involve expected structural and functional adaptations (Wisdom, Delp, & Kuhl, 2015). This refers to the importance of a sufficient amount of stimulus to evoke repair and maintenance of the muscle-tendon complex. A similar process is expected in response to football related loads for muscles such as the hamstrings. Therefore, an optimal level of repetitive load will promote and maintain beneficial adaptations whilst excessive or insufficient load can lead to total failure to function, being this the rationale in the basis of training load monitoring and its relation with injury risk. For example, applying this concept to hamstring injury, Brukner et al. (2014) addressed a recurrent hamstring strain situation in a football player by delivering an overload running program with high intensity content (over 6 $m.s^{-1}$), once it was suspected that a maladaptation to exercise was one of the causes of the recurrence episodes. Whilst the latter is an example of a maladaptation resulting from poor training stimulus, the opposite may also occur. The accumulation of mechanical load associated to football actions imposed to players in a repeated fashion during training and competition during the course of a season (Malone, Di Michele, Morgans, Burgess, Morton, & Drust, 2014) is likely to increase the player´s injury risk.

Addressing the several types of load data provided by portable systems has led to a better understanding of the loads associated with football, allowing to establish positional profiles regarding a number of parameters, such as speed distances in several professional football competitions (Bush, Barnes, Archer, Hogg, & Bradley, 2015; Ingebrigtsen, Dalen, Hjelde, Drust, & Wisloff, 2015; Carling, Le Gall, & Dupont, 2012; Wehbe, Hartwig, & Duncan, 2014). However, so far whilst metabolic validations of this data in football have been done to a certain extent (Osgnach, Poser, Bernardini, Rinaldo, & Di Prampero, 2010; Gaudino, Iaia, Alberti, Hawkins, Strudwick, & Gregson, 2014; Barret, Widgley, Towlson, Garret, Portas, & Lovell, 2016; Gallo, Cormack, Gabbett, Williams, & Lorenzen, 2015), mechanical loads and their relation with injury risk have so far only been addressed by a single study in football (Ehrmann, Duncan, Sindhuase, Franzen, & Greene, 2015). Ehrmann et al. (2015) assessed professional football players during one season for several GPS and accelerometer parameters. Comparison of one- and four-week blocks preceding injury with seasonal averages showed significant associations between increments in game and training intensities (expressed in meters/minute) and injury occurrence. Simultaneously, New Body Load, a measure reflecting accelerometry obtained from the tri-axial accelerometer, was significantly lower for one and four week blocks. These results suggest not only an overloading effect leading to increased injury risk, but also the existence of an optimal load level by which the musculoskeletal system of the players adapts, which in turn provides a protective effect against injury. In order to determine these optimal levels, research around the content and variation of mechanical load will potentially help to distinguish different levels and thresholds where the player´s fitness and performance may implicate high levels of several injury type risks, in which the hamstrings injury comes as one of the most concerning.

A good example of how mechanical load can reflect the stress on the player´s body, although not associating it directly with injury, is expressed in the study from Barrett et al. (2015). These authors have shown the potential of this variable in the form of PL as injury predictor in a football context, by analysing the ratio of PL to total distance during match play in 63 under-21 players for 86 football matches. Findings from their study showed an increased ratio observed in the last 15 minutes of each half caused by a decrease in the total distance covered whilst maintaining the same rate of acceleration (expressed by PL). By showing how players changed their locomotive strategies to allow them to maintain the same acceleration and deceleration efforts, there seems to be an additional explanation for the increased injury occurrence observed in these periods. Results showing how the added mechanical load through a players body influence their ability to maintain a similar load absorption and force development, throughout a football match, reinforce the value of this data in the injury risk analysis context.

The relation between several types of load variables monitored using portable systems and injury, in which accelerometry is included, has also been performed involving team field sports like Australian Rules football and rugby. Although the features of these sports differ from football, their running demands present some similarities in the way it stresses the musculoskeletal system of its players resulting in similar injuries as observed in football. Therefore, also in these contexts the variation of and nature of load variables presented an association with injuries. For example, Colby et al. (2014) compared the accumulated and weekly variations of load referent to several variables performed by professional Australian Rules footballers during the periods of pre- and in-season. In pre-season, players´ three weeks total distance and sprint distance ranges made them more and less prone to sustain an injury during this period, respectively. Whilst during pre-season variables did not directly reflect accelerometry, in-season results showed a significant association between accelerometer derived data and increased injury risk. Also Relative Velocity Change, a GPS-derived variable expressing acceleration, deceleration and direction changes was associated with increased injury risk for variations involving previous to current week in pre-season, and a four week period accumulation load in-season. Another study involving professional rugby players performed by Gabbett et al. (2012) showed how high volumes of distances covered at low running speed below 5 $m.s^{-1}$ had a protective effect against lower limb soft tissue injuries in general, whilst elevated amounts of sprinting showed opposite results.

In summary, the fact is that hamstring injury rates in professional football are increasing over the years despite extensive research efforts on risk factors to inform preventive strategies. There is value in this research, which for example has been showing that eccentric strength deficits have been positively correlated with hamstring injury risk, yet the fact that these tests do not tend to evaluate muscle recruitment in a more ecological fashion such as running tests might, justifies the development of other approaches. The fact that during running actions hamstrings not only participate in deceleration actions but also accelerating the body forward, suggests that there might be an association between the extensive amount of acceleration actions performed during football practice and hamstring injuries. Additionally, previously observed deficits in the ability of hamstrings to generate horizontal forces during acceleration actions in an NMT in a post-injury context reinforced the association between these actions and hamstrings injury. Finally, whilst laboratory based tests may improve the knowledge about hamstring function regarding acceleration capabilities, the role of load monitoring during field training in modern professional football cannot be ignored. Load monitoring strategies have been identified to potentially help identify differences between injured and non-injured players from data prior to the injury.

Overall, the literature suggests that there is potential in the use of acceleration-based variables to try and identify risk of hamstring injury in football, either in sprint running efforts on instrumented treadmills, or from trunk-mounted accelerometry in the field.

Chapter 3

Asymmetry after hamstring injury in English Premier League: issue resolved, or perhaps not?

3.1 Abstract

Hamstring injuries constitute one of the most concerning injuries in EPL football, due to its high primary incidence but also its recurrence. Functional methods assessing hamstring function during high-risk performance tasks such as sprinting are vital to identify potential risk factors. The purpose of this study was to assess horizontal force deficits during maximum sprint running on a NMT in football players with previous history of hamstring strains as a pre-season risk-assessment in a club setting. 17 male football players from one EPL club were divided into 2 groups, experimental (n= 6, age = 24.5 ± 2.3 years) and control (n= 11, age = 21.3 ± 1.2 years), according to history of previous hamstring injury. Participants performed a protocol including a 10 seconds maximum sprint on a NMT. Force deficits during acceleration phase and steady state phases of the sprint were assessed between limbs and between groups. The main outcome measures were horizontal and vertical peak forces during the acceleration phase or steady state. There were no significant differences in peak forces between previously injured and non-injured limbs, or between groups, challenging the ideas around functional force deficits in sprint running as a diagnostic measure of hamstring re-injury risk.

Keywords: *horizontal force, sprint test, non-motorized treadmill*

3.2 Introduction

Hamstring strains are the most common and challenging injuries in professional football (Bloomfield, Polman, & O´Dononghue, 2007). They represent about 12 to 17% of the total moderate and severe injuries (causing absence of 8-28 days and more than 28 days, respectively) in this sport, leading to the highest prolonged absence time from training and competition (Ekstrand, Hagglund, & Walden, 2011; Engebretsen, Myklebust, Holme, Engebretsen, & Bahr, 2010; Hagglund, Walden, & Ekstrand, 2013; Hawkins, Hulse, Wilkinson, Hodson, & Gibson, 2001). Hamstrings also present a high recurrence rate of 12-14% (Woods, Hawkins, Maltby, Hulse, Thomas, & Hodson, 2004; Orchard, 2011), and re-injury on average requires six days longer absence from competition than the initial injury (Cameron, Adams, & Maher, 2003). In fact, previous injury remains to be the strongest available predictor for hamstring injury (Hagglund, Walden, & Ekstrand, 2012; Woods, Hawkins, Maltby, Hulse, Thomas, & Hodson, 2004; Engebretsen, Myklebust, Holme, Engebretsen, & Bahr, 2010; Mendiguchia, Alerton-Geli, & Brughelli, 2011; Prior, Guerin, & Grimmer, 2009).

Considering the high re-injury rates, one of the biggest challenges professional football clubs face today is to prevent re-injury, starting with identifying functional deficiencies that are believed to lead to an increased risk of re-injury. Hamstring strain injury can result in a variety of functional deficiencies, altering aspects such as motor control (Cameron, Adams, & Maher, 2003), activation patterns (Sole, Milosavljevic, Nicholson, & Sullivan, 2012; 2011), isokinetic torque development (Opar, Williams, Timmins, Dear, & Shield, 2013) and load distribution during contraction (Silder, Reeder, & Thelen, 2010). The most common way of addressing any such deficits is by observing asymmetries between the injured limb and the contralateral side. For example, sprint tests on a NMT have revealed that previously injured players can achieve their pre-injured levels of speed, but this whilst employing compensation mechanisms from the non-injured limb (Brughelli, Cronin, Mendiguchia, & Kinsella, 2010). If a treadmill-based sprint test can reveal inter-limb asymmetry in force generation, then this practical test has great potential to support rehabilitation processes that are aimed at preventing hamstring re-injury risk.

The assessment of functional asymmetry in a club context remains a challenge, even at the highest level such as in the EPL. The development of assessment protocols are subject to variations in available equipment, and time constraints on staff and players. This often makes it difficult, if not impossible, to replicate protocols exactly as described in research that may have been conducted in a laboratory context. Support staff in a club is often forced to implement their assessment protocol under the assumption that they are still able to reveal the asymmetries, without having the opportunity to carefully consider the validity. Despite some studies using NMTs and sprint performance, especially in the context of reliability (Hopker, Coleman, Jonathan, & Calbraith, 2009; Hughes, Doherty, Tong, Reilly, & Cable, 2006), there is however a lack of research validating the force output provided by these instruments relative to the forces generated whilst sprinting in a field. However, considering the potential value of assessing functional asymmetry in the prevention of re-injury, the authors therefore identified a need to investigate its robustness when implemented in a club setting.

The purpose of this study was to quantify functional asymmetry in EPL football players with previous history of hamstring strain, in a protocol involving sprinting on an instrumented NMT. Based on previous findings, we hypothesised that individuals with a previous hamstring strain would present functional asymmetry through force generating deficits in the injured limb.

3.3 Methods

3.3.1 Protocol

Experimental trials were conducted as part of pre-season testing. After a familiarisation session, participants performed the protocol including a 10 seconds time period of maximal sprint running on a non-motorised treadmill (NMT; Woodway - Curve Model, Wisconsin, USA – Figure 1.). Following an initial 5 minute warm-up on a cycle ergometer, participants completed a protocol which included 10 seconds of maximum sprinting during which there was an acceleration to achieve maximum speed and maintaining speed during a brief steady state phase in the final seconds of the sprint. Horizontal and vertical forces were captured by force transducers (Anyload 563 YH) located in the treadmill frame supporting the belt, and speed data of the complete protocol were collected at a sampling rate of 200 Hz.

With the foot moving through an arch rather than on a flat surface, the shear forces do not have the same meaning as in a flatbed treadmill. With force transducers built in the supports of the treadmill belt, overall, the forces measured in a horizontal direction represent force generation for propelling the treadmill and vertical forces represent forces to keep the body on average in the same vertical position throughout the trial.

A video recording of each sprint was made at 50 Hz, with inset of the treadmill clock to reliably separate left and right steps in the recorded force profiles.

3.3.2 Data reduction

Two independent phases of the sprint were considered for analysis, the acceleration and the steady state period. The acceleration period included the first step from the beginning of the sprint until the first maximum speed step. During this phase the maximal propulsive horizontal force development was extracted. The steady state period consisted of the first eight steps after maximum speed was performed, including the maximum speed first step. Peak force values for all the steps of each leg prior to reaching maximum speed and in the eight steady state period steps were registered. One would expect that with very short contacts during sprinting it would be very difficult to lengthen contact time, hence peak forces were analysed rather than propulsive impulses.

Comparisons within individual participants (between legs) and between groups were performed for maximal horizontal and vertical peak force generated during acceleration and steady state phases of the sprint, as well as for the average of all peak force values per phase. Force values for each step and the considered period (acceleration and steady state) under analysis were obtained using raw data. In order to identify each step for each phase the vertical force component was used, allowing the identification of the start and end point for each step. These events were then used to identify maximal horizontal force values during contact.

Figure 1. Non-motorized treadmill

Some observations concerning force profiles as seen in Figure 2 deserve some prior technical considerations. The highest horizontal force development occurred in the initial stage of the sprint acceleration, rather than at the time of maximal sprinting. This is expected as horizontal force is related to acceleration rather than velocity. A previous study from Brughelli et al. (2010) using a tethered NMT showed continued high horizontal forces with constant speed running, with force mean scores ranging from 175N to 325N, for the two limbs of the experimental group (previously injured and contralateral respectively). For a similar phase of a sprint action in the current study the mean scores for horizontal force ranged between 67,1 N and 72,4 N, in the dominant and non-dominant side of the control group, respectively. This suggests that their treadmill belt generated substantial resistance during constant speed running, to be overcome by continued propulsion forces of up to 20% of the vertical force generation. Horizontal forces observed with the curved NMT adopted in our study were only about 3% of the vertical forces during constant speed running. This result contradicts the existent literature in which vertical and horizontal forces were analysed using a NMT. A previous study by Brughelli et al (2011) showed that in a maximal sprint effort using a different NMT model mean maximum horizontal forces can represent around 18% of the mean maximum vertical forces during the same period. The latter authors analysed 80% max speed sprint efforts also on a NMT found this relation to range from around 13% in a control group up to 17% in the contralateral limb of subjects with previous history of unilateral hamstring strain (Brughelli, Cronin, Mendiguchia, & Kinsella, 2010).

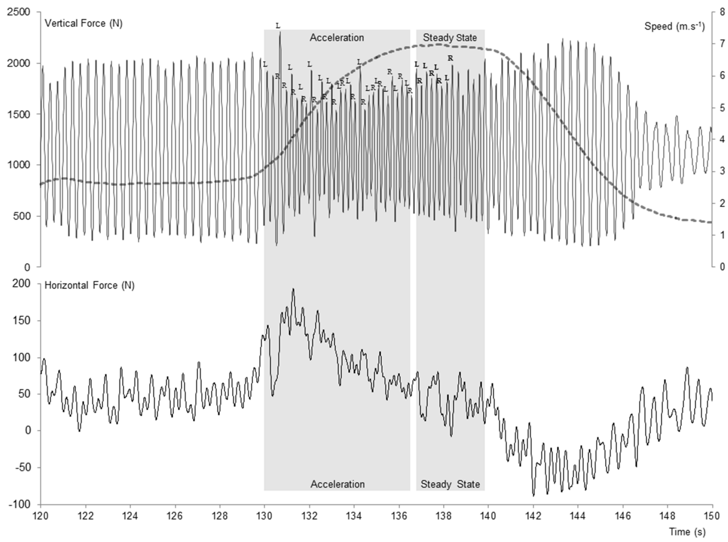

Figure 2: Force profile during acceleration and steady state phases (shading) of a 10 seconds sprint on NMT. Sprint occurs from 130-140 seconds and identification of right (R) and left (L) is shown for the full acceleration phase and for eight steps of the steady state at maximum speed.

3.3.3 Reliability protocol

A separate group of nine male participants performed the protocol three times on separate days (regular recreational athletes, age 29.6 ± 5.3 years; height 178.1 ± 8.3 cm; weight 76.2 ± 9.6 kg). Mauchly's test for sphericity was performed and one-way ANOVA for repeated measures was conducted for general differences among trials. Where a main trial effect was found, Tukey post-hoc comparisons were performed. Intra-class correlation (ICC) was calculated for assessing reliability. Maximum speed values were only significantly lower in the first compared to consecutive two sessions, suggesting that one familiarisation session was sufficient to reach a consistent maximum speed on a NMT. Comparison of outcome measures revealed strong correlations between trial 2 and trial 3 ($r > 0.90$), except for a moderate correlation for Peak Horizontal Forces ($r = 0.62$). Overall, these results supported the use of a single familiarization session before data collection in the experimental protocol. Also, analysing averaged peak values for horizontal force as opposed to analysing only the highest peak value provides more reliable information. No other variables were collected from the subjects as all of them had been cleared to play according to criteria based on regular sports medicine examination but also physical parameters such as strength, flexibility, ability to run, sprint and perform football specific actions.

3.3.4 Participants

For the main study, 17 male professional football players from an EPL club were recruited to this study and allocated to two groups: hamstring injury group (HIG) (n= 6, age 24.5 ± 2.3 years, height 1.79 ± 0.03 m, mass 76.3 ± 2.5 kg) and a control group (CG) (n = 11, age 21.27 ± 1.2 years, height 1.83 ± 0.03 m, mass 82.2 ± 2.8 kg). The difference in group size was related to the hamstring injury history within the team. This was a study within a single club setting aiming to replicate a previously published protocol (Brughelli et al., 2010), conducted during pre-season, and with every player of the team being tested. The two groups were then defined according to the inclusion and exclusion criteria detailed above. There were no significant statistical differences among groups for age, height or weight. Sample characteristics including playing position and foot dominance are expressed in Table

2, along with the severity of the hamstring injury and average absence time from training for the HIG. All subjects from HIG had sustained a sprint related hamstring injury. All participants provided prior written informed consent according to the guidelines of the local ethical committee. For the purpose of this study, hamstring injury was defined as occurring during training or competition, which prevented participation in normal training and/or competition for more than 48 hours, not including the day of injury (Hawkins, Hulse, Wilkinson, Hodson, & Gibson, 2001). Club medical records were consulted to identify more detailed inclusion/exclusion criteria. Inclusion criteria for the HIG were a history of previous hamstring injury in one leg, and occurrence less than two years prior to the study, as in Brughelli et al. (2010). Exclusion criteria were the presence of lower limb or lumbar spine pathology at the time of study; chronic lumbar spine pathology; history of hamstring muscle or lumbar spine surgery (Silder, Reeder, & Thelen, 2010; Sole, Milosavljevic, Nicholson, & Sullivan, 2012) and previous history of bilateral hamstring strain within two years of the study. Together with this, it was important to understand within the players of the team if any particular physical complaint or restrictions, especially the ones relative to chronic degenerative conditions would not refrain the player to perform maximally during the NMT test or dramatically alter their locomotion strategies. The testing protocol was performed during the first days of pre-season, reason why it was also not expected that fatigue might be a confounding variable for test results as the players had not yet started any outfield or indoor physical work.

GPS data from a maximal sprint test in training were consulted to obtain records of overground maximum speed values for each player to compare maximum sprinting speeds achieved on the NMT versus overground, with the purpose of further understanding potential limitations in sprint speed performance on the NMT (GPSports®, Dundalk, Ireland; Catapult Sports®, South Melbourne, Australia).

Table 2. Participant´s playing position, foot dominance and injury profile.

	n	Position			Foot Dominance		Grade of hamstring injury*			Days absent from training due to injury (Mean ± SD)	Number of days since injury when tested (Min; Max)
		Defender	Midfielder	Striker	Right	Left	1	2	3		
HIG (n)	6	3	3	0	2	4	3	3	0	20.3 ± 2.2	141; 518
CG (n)	11	4	6	1	8	3	-	-	-	-	-

*Injury grading system according to O'Donoghue (1962), Peetrons (2002) and Stoller (2007).

3.3.5 Statistical analyses

Statistical procedures were conducted using SPSS (v.20.0, SPSS Inc., Chicago, IL, USA). Outcome variables were maximum speed, maximum peak force, and average of peak forces (horizontal and vertical, acceleration and steady state phase). Normality of data was checked using Shapiro-Wilk tests. Paired comparisons between previously injured versus uninjured leg in the HIG, and between dominant versus non dominant leg in the CG were made using paired student t-tests or Wilcoxon tests. Independent between-group comparisons for maximal and averaged peak force values in HIG versus CG were made using independent student t-tests or Mann-Whitney U tests. Results are presented using mean and standard deviations. The level of significance was set as $p < 0.05$.

3.4 Results

No significant side-to-side differences were observed for any of the force-related variables studied during the acceleration phase of the sprint, despite an effect size ranging from minimal to large was observed (table 3). For the steady state phase of the sprint maximum horizontal force development of non-dominant limb was significantly larger than the dominant limb in the CG ($p = 0.036$) with a large effect size ($d = 1.65$). No significant differences were found for any other variables.

No statistical differences were observed for force values between groups (table 4), also a range of effect sizes from small to large was observed across variables.

Across both groups the maximum speed on NMT was 25.2% lower than the maximum outdoor speed collected from GPS data.

Table 3. HIG and CG force related variables in the Acceleration and Steady State phases of the sprint.

Forces NMT (N)	CG (Mean ± SD)		*p*	*d*	HIG (Mean ± SD)		*p*	*d*
	Dominant side	Non dominant side			Previous injured side	Non-injured side		
Acceleration phase								
Max Horizontal Force (N)	211.0 ± 10.7	198.0 ± 14.4	0.265	1.04	198.0 ± 17.5	195.9 ± 17.2	0.753	0.17
Averaged Horizontal Force (N)	124.8 ± 9.4	124.8 ± 8.2	0.859	0.00	113.3 ± 7.9	115.5 ± 6.5	0.575	0.31
Max Vertical Force (N)	2312.7 ± 76.1	2158.0 ± 78.0	0.059	2.00	2116.1 ± 70.2	2076.4 ± 73.5	0.642	0.56
Averaged Vertical Force (N)	1875.6 ± 108.1	2025.5 ± 115.9	0.790	1.33	1866.8 ± 68.6	1802.0 ± 47.2	0.333	1.11
Steady State phase								
Max Horizontal Force (N)	67.1 ± 2.4	72.4 ± 3.8	**0.036**	1.65	70.2 ± 5.9	71.5 ± 6.5	0.812	0.27
Averaged Horizontal Force (N)	52.5 ± 4.4	54.3 ± 4.6	0.545	2.62	51.2 ± 4.5	51.7 ± 6.2	0.917	0.09
Max Vertical Force (N)	2101.9 ± 96.9	2140.4 ± 94.5	0.436	0.74	2048.6 ± 81.6	1985.1 ± 100.6	0.113	0.70
Averaged Vertical Force (N)	1984.1 ± 96.1	2047.8 ± 85.8	0.080	0.70	1888.5 ± 116.9	1791.5 ±100.1	0.256	0.87

Table 4. Group comparison of force related variables.

	Acceleration Phase				Steady State Phase			
	HIG (Mean ± SD)	CG (Mean ± SD)	*p*	*d*	HIG (Mean ± SD)	CG (Mean ± SD)	*p*	*d*
Max Speed NMT ($m.s^{-1}$)	-	-			6.9 ± 0.2	7.2 ± 0.2	0.526	1.50
Max Speed Outdoor/GPS ($m.s^{-1}$)	-	-			9.7 ± 0.1	9.5 ± 0.3	0.484	1.00
Horizontal Force Peak Right (N)	195.6 ± 16.1	211.8 ± 11.9	0.661	1.16	74.6 ± 7.2	68.1 ± 2.6	0.129	1.33
Horizontal Force Peak Left (N)	198.4 ± 18.5	197.1 ± 13.4	0.141	0.08	67 ± 4.5	71.5 ± 3.8	0.421	1.08
Horizontal Force Averaged Peaks Right (N)	115.4 ± 5.8	124.6 ± 7.8	0.591	0.82	52.3 ± 6.9	52.0 ± 3.6	0.294	0.30
Horizontal Force Averaged Peaks Left (N)	113.4 ± 8.4	125.0 ± 9.7	0.754	1.28	50.5 ± 3.4	54.2 ± 4.9	0.227	0.89
Vertical Force Peak Right (N)	2081.3 ± 63.6	2229.8 ± 72.5	0.088	2.18	2045.8 ± 98.0	2097.1 ± 93.3	0.524	0.54
Vertical Force Peak Left (N)	2111.2 ± 79.7	2203.7 ± 77.1	0.366	1.18	1987.9 ± 94.5	2145.1 ± 98.0	0.262	1.63
Vertical Force Averaged Peaks Right (N)	1832.6 ± 56.8	1906.8 ± 71.9	0.318	1.15	1834.6 ± 131.6	2075.7 ± 155.6	0.488	1.68
Vertical Force Averaged Peaks Left (N)	1836.2 ± 64.2	1966.7 ± 70.7	0.519	1.93	1845.4 ± 85.4	2056.2 ± 88.5	0.400	2.42

3.5 Discussion

The aim of this study was to quantify functional asymmetry in the magnitude of horizontal force development during a maximum sprint running on a NMT, in EPL football players with previous history of hamstring strain. Whilst Brughelli et al. (2010) found that the previously injured limb presented 45.9% lower horizontal force generation than the non-injured limb, and that horizontal force generation in the injured group was significantly reduced compared to a control group, we found no differences in horizontal and vertical maximal force or averaged peak forces measured in the acceleration phase up to the maximum speed step in a 10 seconds sprint effort, as well as in the first eight steps of the steady state phase. We therefore rejected our a priori hypothesis that with the assessment we would reveal functional asymmetries in players with a previous hamstring injury. We will discuss possible explanations for this absence of differences, which may be associated with the population, the equipment, or the protocol.

A first possible explanation for our findings is that our participants, being part of an elite football club, had undergone an intensive rehabilitation program to increase chances of a successful return to football practice as well as to minimize the risk of re-injury occurring. Specifically, eccentric exercises were utilised as is now generally accepted in the therapeutic literature (Arnason, Andersen, Holme, Engebretsen, & Bahr, 2008; Askling, Karlsson, & Thorstensson, 2003; Petersen, Thorborg, Nielsen, Jorgensen, & Holmich, 2011). This rehabilitation routine might have better cancelled out any force deficits post-injury in our study. Also, the average time since injury may have been longer than that in Brughelli et al. (2010), but this cannot be confirmed as this was not reported in their study.

Our rejection of the a priori hypothesis may also be related to the equipment. We used load cells embedded in a curved NMT for assessment of forces, whereas in Brughelli et al. (2010) a Woodway® 3.0 with load cell in a non-elastic tether connected to the subject was used to estimate forces. In our study low horizontal forces were observed during constant speed sprinting as opposed to high forces in the latter study (72.4 N and 324 N respectively). To our knowledge, no studies have been undertaken related to how reliable the measurement of forces is in either of the NMT models despite a few papers addressing reliability and validity in terms of power, speed, gait length and time to fatigue (Highton, Lamb, Twist, & Nicholas, 2012; Lim, & Chia, 2007; Oliver, Armstrong, & Williams, 2007; Tong, Bell, Ball, & Winter, 2001). Our pilot test evaluated test-retest reliability of the force related outcome measures for our NMT model, and identified peak horizontal force generation as a moderate outcome measure, but we currently have no means to compare this to other NMT models. However, we reinforced the rigour of our measurements by using raw data from the force cells not relying on the equipment software to provide the results scores. Despite this procedure the use of two pairs of cells directly embedded on the treadmill surface and its capability to provide an accurate horizontal force measurement might still be questioned and focus of continued research.

Rejection of the a priori hypothesis could be associated with the testing protocol. Horizontal force development is higher during the acceleration phase (figure 2) and has been correlated with performance variables related to acceleration, rather than those related to steady state sprinting (Mendiguchia, Alerton-Geli, & Brughelli, 2011). For that reason it was hypothesised that any injury-related differences in horizontal force performance were more likely to be present in this phase. However results from our study presented no differences and in the study of Brughelli et al. (2010) asymmetries were observed for force development during a steady state sprint. Whilst this may from a mechanical viewpoint be counterintuitive, there remains uncertainty over which phase may well be most meaningful. Sherry and Best (2004) distinguish the moments of injury while running between sprinting and accelerating from a stationary position to full sprint. Whilst 13 of their 24 participants reported injury while sprinting, five reported injury during acceleration. Whilst we also evaluated force development during steady state sprinting, the steady state was a maximum speed effort, as opposed to an 80% effort adopted by Brughelli et al. (2010). Our decision to use a maximal effort was made under the assumption that replicating sport specific demands as involved in football play should consider a maximal and not sub-maximal effort. The maximal effort, in fact, was still considered to impose a limitation as it was found to allow the player to only achieve a progression speed of 75% of what is achieved in an overground sprint, similar to what has been reported in previous work (Morin & Sève, 2011). Equally the absence of an alternative strength assessment to confirm the absence of asymmetry in our study is a limitation to this study.

Overall, our study has challenged the robustness of functional asymmetry assessments in a club environment to identify risk of re-injury. This is an important finding for the practical field, as it in the first place highlights the need to rigorously test whether modifications to an assessment protocol annihilate its capacity to actually reveal deficiencies. We do not believe that our findings undermine the likely role of asymmetry as a re-injury mechanism, with considerable arguments existing that support the importance of horizontal force development in sprint performance.

The clinical importance of establishing protocols such as the one described in this study may improve the battery of clinical and performance tests normally adopted after hamstring rehabilitation, and therefore decrease the likelihood of recurrent injuries. In the case of this study the timing of the evaluation protocol might have been of importance to validate the usefulness of these types of testing protocols. For example, although no differences were observed between our groups of players, anecdotally throughout the season players from the previous injured group did not necessarily sustain more injuries than the control group ones.

Rather, we hope that our findings can generate a critical attitude towards further development and validation of assessment protocols, including the ones that are ultimately implemented in a club setting. Furthermore, future translational research aiming at the validation of equipment in an actual club setting is suggested. This is a considerable challenge for practitioners in a club environment, dealing on the one hand with limitations of the elite environment context, and on the other hand with the continuous emergence of a broad variety of commodity technologies.

3.6 Conclusion

In conclusion, our results challenge the role of functional force deficits as a diagnostic measure of hamstring re-injury risk, and warrant further investigation to establish whether force development asymmetries can be indicative of re-injury risk. It remains uncertain whether horizontal force deficits in a NMT can represent a potential risk factor for hamstring injuries. More importantly though, it has highlighted the scientific challenges that practitioners are faced with in an elite club environment, and that there is a need to validate assessment protocols, even if differences from lab based assessments may at first sight appear to be small.

Additionally, whilst laboratory assessment strategies require further improvement in what concerns the identification of hamstring (re)injury risk, exposing the running action demands over these muscles through analysing acceleration variables within the football training context may still reveal insufficiencies that help identify (re)injury risk. For this reason, physiotherapists and other clinical professionals could consider how outfield acceleration loads relate to the occurrence of hamstring injuries. Progression in this field needs to therefore be complemented with the analysis of the acceleration loads that are imposed daily onto the players´ musculoskeletal systems. For this purpose the technological resources currently present in the sport and accessible to the support staff was considered. Upon examination of the variety of data that is regularly collected in professional EPL clubs, it was revealed that trunk mounted accelerometry may well deliver the data we were looking for. The most commonly used outcome variable from this technique was Player Load (PL), which represents a validated and reliable expression of rate of change in acceleration that could potentially expose meaningful differences between injured and non-injured players regarding the cause of hamstring injuries. However this variable requires further analysis in relation to its validity and reliability for football specific actions. Therefore the next step in this work was to analyse the robustness and validity of PL, and subsequently evaluate training related acceleration loads and its implication on hamstring injuries in professional football.

Chapter 4

Mechanical Player Load TM using trunk mounted accelerometry in Football: Is it a reliable, task- and player-specific observation?

4.1 Abstract

The aim of the present study was to examine reliability and construct convergent validity of PL from trunk mounted accelerometry, expressed as a cumulative measure (PL) and an intensity measure ($PL.min^{-1}$). Fifteen male participants twice performed an overground football match simulation that included four different multidirectional football actions (jog, side cut, stride and sprint) whilst wearing a trunk mounted accelerometer inbuilt in a global positioning system (GPS) unit. Results showed a moderate to high reliability as indicated by the ICC (0.806-0.949) and limits of agreement (LOA). Convergent validity analysis showed considerable between-subject variation (coefficient of variation (CV) range 14.5-24.5%), which was not explained from participant demographics despite a negative association with body height for the stride task. Between-task variations generally showed a moderate correlation between ranking of subjects for PL (0.593-0.764) and $PL.min^{-1}$ (0.282-0.736). It was concluded that monitoring Player Load ® in football multidirectional actions presents moderate to high reliability, that between-participant variability most likely relies on the individual's locomotive skills and not their anthropometrics, and that the intensity of a task expressed by $PL.min^{-1}$ is largely related to the running velocity of the task.

Keywords: *accelerometry, football, validity, reliability.*

4.2 Introduction

Accelerations and decelerations constitute an essential element of football, particularly in sprint actions or short changes of direction such as side cutting or dribbling (Bloomfield, Polman & O´Dononghue, 2007; Varley & Aughey, 2013). The high accelerations and decelerations are known to lead to high forces acting on the musculoskeletal system which in turn need to be absorbed by internal musculoskeletal structures (Bobbert, Schamhardt, & Nick, 1991). It is possible that the magnitude of these forces can directly exceed the body's capacity to absorb their impact and lead to acute tissue damage (e.g. bone fracture, muscle strain, ligament tear), but the excessive exposure to moderate yet repetitive forces can also exceed the body's capacity to recover from small (micro) damage, eventually leading to macro damage (e.g. stress fractures, cartilage degeneration).

Monitoring acceleration and deceleration loads through the use of accelerometers embedded in the commonly used trunk mounted GPS units may help understand the association between the forces due to excessive loading on the football player´s musculoskeletal tissues, and assist in injury risk profiling. This monitoring is based on the impact that the absorption of ground reaction forces may have on the football player´s body (Ehrmann, Duncan, Sindhuase, Franzen, & Greene, 2015; Colby, Dawson, Heasman, Rogalski, & Gabbet, 2014), and whilst showing some promising results from the way accumulated accelerometry based loads per week can relate to injury risk (Colby, Dawson, Heasman, Rogalski, & Gabbett, 2014), a number of unknowns regarding validity and reliability around accelerometry monitoring still remain. To date, accelerations and decelerations have often been expressed using PL, a cumulative measure of rate of change in acceleration (Boyd, Ball, & Aughey, 2011).

The reliability of PL has been addressed in the recent literature. The laboratorial setup from Boyd et al. (2011) used a hydraulic testing machine and showed good reliability for accelerometry data collected in these conditions. Kelly, et al. (2015) also found a good inter and intra-device reliability when assessing raw accelerometer data using a laboratorial setup with mechanical rotation device. Barrett, et al. (2014) investigated an incremental treadmill running protocol with speeds ranging from 7 to 16 $Km.h^{-1}$, showed high test-retest reliability for PL, but between- subject PL scores were subject to individual running style variations. Recently, multi-directional running movements were investigated (Barrett et al. 2016) which adopted a soccer-specific free-running match simulation ($SAFT^{90}$). Their test – retest results suggested high intra-device reliability, an absence of systematic bias, and low CV. Despite this work, there are still some unknowns related to PL reliability. For example, reliability of PL for movements in isolation has not been addressed to date. The analysis involving multidirectional movements from Barrett et al. (2016) considered total cumulative scores and did not isolate efforts such as sprinting, striding or side cutting. Analysing PL reliability of movements in isolation avoids potential bias from contamination of the acceleration signal loads from other movements or gestures when reliability of cumulative PL is analysed. Also, due to the cumulative nature of PL over time, it fails to represent the mechanical intensity of a movement and is unsuitable for distinguishing the impact that different actions have on a player during football. Expressing PL per unit of time ($PL.min^{-1}$) can therefore help indicate the rate of stress to which the player subjects their body for a given time period. By having representative intensity PL values for given movements a more meaningful insight into the mechanical stresses that these movements impose on the body can be gained.

Besides reliability, another issue that still deserves further clarification is the convergent validity of PL, namely, how it is expected to vary between players, for example based on their body sizes. Player characteristics such as body mass influence the development of ground reaction forces (Derrick, Caldwell, & Hamill, 2000; Silder, Besier, & Delp, 2015), yet it is still unknown how PL is affected. For example, if an entire squad were to undergo the same training session, then it is important to know whether PL is expected to be the same or whether it will differ between players based on their body size.

The aim of this study was to improve our understanding of reliability and convergent validity of PL from trunk mounted accelerometry, expressed as a cumulative measure (PL) and as an intensity measure ($PL.min^{-1}$), across different multidirectional football actions. We considered the effects of the intensity level and duration of the action, as well as the subjects´ anthropometrics.

4.3 Methods

4.3.1 Participants

Fifteen male participants (25.8 ± 4.3 years; 1.79 ± 0.10 m; 77.3 ± 10.4 kg) were recruited for this study. All participants were recreational level athletes used to football practice and were free from any injury at the time of the study. Informed consent was obtained prior to participation in the study. The study met the requirements of the Liverpool John Moores University ethics committee and approval was obtained prior to the commencement of the study.

4.3.2 Experimental protocol

An overground match simulation protocol (SAFT ^{90}) was modified from its original distance of 20 meters to 15 meters to fit our indoor laboratory (mSAFT^{90}) (Azidin, Sankey, Drust, Robinson, & Vanrenterghem, 2015). The mSAFT^{90} was designed to be reflective of the multidirectional nature of the specific movements of football, including frequent accelerations and decelerations. The movement intensity and activity performed by the participants whilst completing the overground course was maintained using verbal signals on an audio track, and contact actions such as kicking or tackling were not performed (Lovell, Knapper, & Small, 2008). Course design was based around a shuttle run over a 15 m distance, incorporating four positioned poles for the participants to navigate using multidirectional utility movements (Figure 3). The simulation protocol was altered slightly to account for space limitations in the laboratory. The main change regarding the original simulation protocol relies on the extra 180º turn around point *c* (see figure 3) from which the participant progresses after an intermediate stoppage time in point *d*, before finishing the entire circuit and returning to the original starting point *a*. To ensure that speeds regarding each task were not influenced by the protocol modification, speed cells were placed between point *a* and *b-d.*

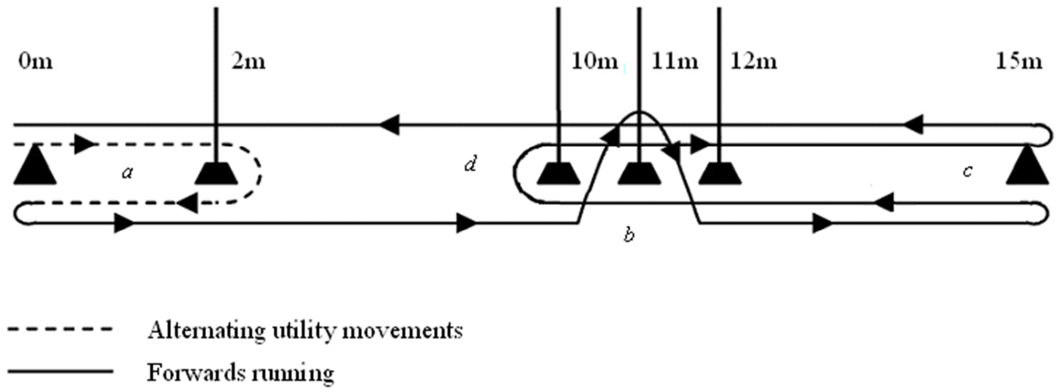

Figure 3. Diagram of the mSAFT^{90} laboratorial field course. Reprinted by permission from Taylor & Francis Publishers (Azidin, Sankey, Drust, Robinson, & Vanrenterghem, 2015), copyright 2015.

All participants first attended a familiarization session including the reproduction of a reduced number of the protocol tasks which were not recorded, followed by two data collection sessions separated by a minimum of three days. Each participant undertook both data collection sessions wearing standardised footwear and following a standardised warm-up involving mobility and stretching activities. For data collection purposes each subject wore a trunk mounted GPS unit (Viper model, Statsports Technologies, USA), which had an in-built tri-axial 100 Hz accelerometer (ADXL 326, Analog Devices, Norwood, USA). A vest was used by each participant in whom the unit was tightly secured in a pouch that was located approximately over the 7th cervical vertebrae, in between the two scapulae. To minimize movement artefacts created by the positioning of the unit in the vest, the tightness of the vest was maximized up to a basic level of comfort and different size vests were adopted according to the subject's chest sizes. The participants completed 45 minutes of the simulation protocol and the middle 15 minutes accelerometry data was used for analysis. This provided sufficient data on each of the observed tasks (see table 5), and minimized variations in outcome measures due to early adaptation with the protocol in the first 15 minutes of the protocol. Also, the interference of fatigue due to prolonged exercise in the performance of the protocol was avoided, as fatigue effects had been observed in the latter stages of each half for this type of simulation protocols (Barret, Widgley, Towlson, Garret, Portas, & Lovell, 2016; Marshall, Lovell, Jeppesen, Andersen, & Siegler, 2014).

4.3.3 Data reduction

Accelerometer data was downloaded in raw format from the manufacturer software (Viper, Statsports Technologies, USA), and a custom Matlab programme (Version R2014a, The MathWorks, Inc., Natick, MA, USA) was used to identify and select data to be included in the analysis. An interactive Graphical User Interface was developed to verify the exact timing of transitions between tasks (see Figure 4). Start and end point identification of each task based on its time measure was adjusted by the same researcher.

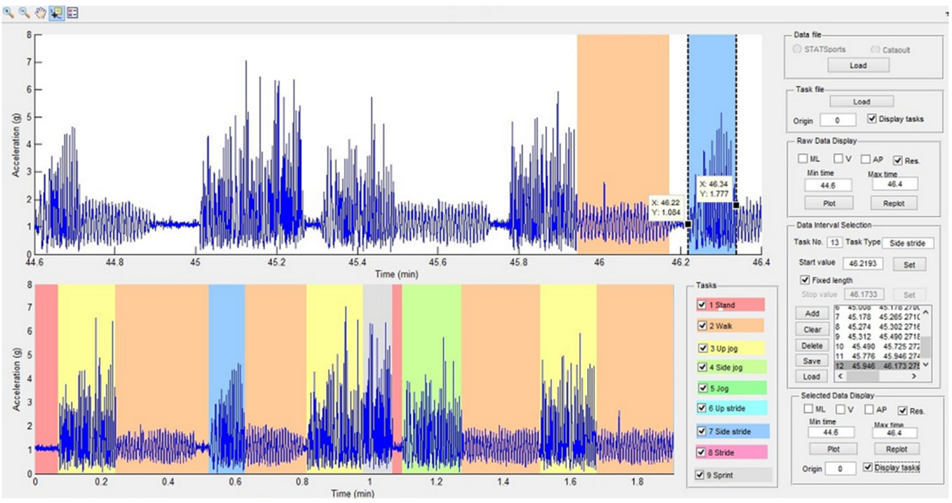

Figure 4. Custom Matlab template.

Due to the contributions of every action present in this protocol to the final cumulative PL score, in the present study data was isolated and analysed for each of four actions: jogging, side cut, stride and sprint (see Table 5).

Table 5. Activities analysed during the 15 minutes mSAFT^{90} profile

Activity type	Total number of activities	Speed ($Km.h^{-1}$)
Total jogging	**29**	10.3
Up jog, zigzag and 180º turn[1]	17	
Side jog, zigzag and 180º turn[1]	12	
Total side cut	**8**	15.0
Up stride and side cut[2]	2	
Side stride and side cut[2]	6	
Total strides[3]	**2**	15.0
Total sprints[4]	**3**	≥ 20.4

Jogging consisted of an initial back and forward or sideways jogging between cones *a* as indicated in Figure 1, straight line jogging followed by zig-zag between poles at *b*, 180º turn at point *c* and short stop at a designated mark *d*, followed by jog and a second 180º turn at *c* and final jog up to the starting point *a*. The side cut task started with a stride back and forward or sideways between cones at *a*, straight line stride and side cut at a designated mark signed in the floor. Stride consisted of a straight line stride after side cut task to initial position *a* with 5 seconds stoppage time in between; and sprint refers to a maximal sprint from the designated mark *d* to the starting position *a* including a 180º turn at *c* following an initial up and side jog up to *d*.

These four tasks implied higher demands of acceleration and deceleration, for which walking and standing periods were excluded from the analysis. By eliminating the contribution of accelerometry data from these two actions in the final PL score and isolating the data from jogging, side cutting, striding and sprinting, one could more accurately analyse the reliability of PL in these tasks. The software calculated PL as the square root of the sum of the instantaneous rate of change in acceleration and deceleration (Boyd, Ball, & Aughey, 2011), as well PL.min^{-1} by dividing PL by the exact time spent executing a task.

4.3.4 Statistical analysis

Within subject reliability analysis was performed first. Mean differences between test and re-test (systematic bias) were analysed using Student´s t-tests for paired samples, with a level of significance set as $p< 0.05$. LOA for absolute reliability were also calculated according to the recommendations of Atkinson and Nevill (1998) and expressed in the form of Bland-Altman plots. Relative reliability to verify consistency of measurements between trials was assessed using two-way random

ICC, in which scores were categorized as high (>0.90), moderate (0.80-0.89), or questionable (<0.80) (Hopkins, 2000).

Trial 2 results were used for the convergent validity analysis. Convergent validity was evaluated through within-subject variation in PL and PL.min^{-1} using CV, followed by Pearson´s association measures to verify the association between accelerometry scores of each task and measures of body mass, height and BMI. Comparisons across all tasks were performed using ANOVA for repeated samples, and Student´s t-tests were used to identify the pairs of tasks for each variable where a statistically significant difference was present.

Spearman´s rank correlations were calculated to verify the consistency of the subjects' ranking of accelerometry scores for each of the four tasks. Scores were categorized as high (>0.90), moderate (0.80-0.89), or questionable (<0.80). All statistical procedures were conducted using Statistical Package for the Social Sciences (SPSS, version 20.0, SPSS Inc., Chicago, IL, USA).

4.4 Results

4.4.1 Reliability analysis

Table 6 expresses results for trial 1 and 2 regarding PL and PL.min^{-1} mSAFT^{90} 15-30 minutes scores. Paired Student´s t-tests showed an isolated small systematic bias for the jogging task when PL.min^{-1} scores are considered ($p < 0.05$). Moderate to high correlations between both trials were found across all tasks.

Table 6. 15-30 minutes mSAFT90 results and reliability analysis

	PL (Mean ± SD)				$PL.min^{-1}$ (Mean ± SD)			
Task	Trial 1	Trial 2	*p*	r	Trial 1	Trial 2	*p*	r
Jogging	130.4 ± 23.1	124.5 ± 18.0	0.118	0.863	27.0 ± 4.5	25.6 ± 4.7	0.043	0.903
Side cut	28.6 ± 5.1	27.7± 4.2	0.260	0.892	30.9 ± 5.4	30.5 ± 5.4	0.601	0.921
Stride	6.6 ± 1.8	6.5 ± 1.6	0.929	0.831	29.4 ± 8.4	29.2 ± 6.2	0.901	0.806
Sprint	14.4 ± 2.8	13.9 ± 3.2	0.102	0.949	51.3 ± 1005.8	49.5 ± 10.9	0.352	0.865

Bland-Altman LOA distribution of scores showed an overall good absolute reliability for the PL and $PL.min^{-1}$ variables (Figure 5). The magnitude of the limits around the systematic bias were acceptable considering the average scores in each task, ranging from 17% to 41% relative to the average accelerometry scores.

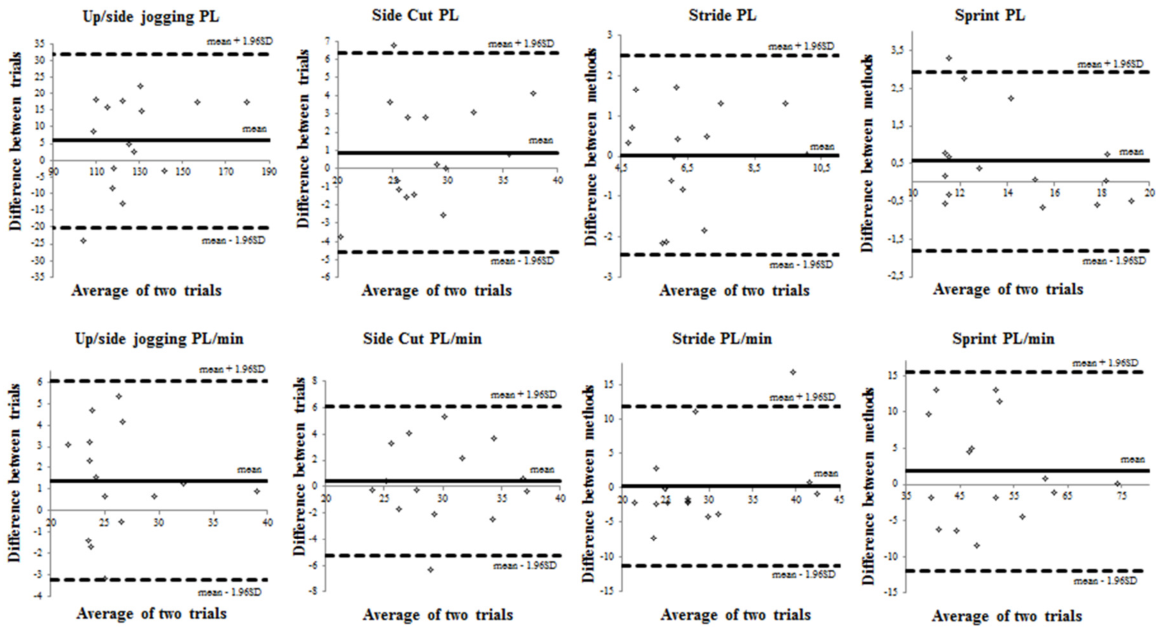

Figure 5. Bland-Altman plots for PL (upper row) and $PL.min^{-1}$ (lower row) for up/side jogging tasks, side cut, stride and sprint (left to right), showing systematic bias (full horizontal line) and lower/upper limits of agreement (dashed lines).

There were also variations according to the nature of the task being performed, with a trend towards higher differences in the stride task with a variation of 37.7% and

39.7% for PL and PL.min^{-1} scores, respectively, compared to the other tasks (see table 7).

Table 7. Variation of LOA for PL and PL.min^{-1}

	Variation of LOA (relative to average difference between trials)	
	PL	PL.min^{-1}
Up/side Jogging	26.0 (20.4%)	4.6 (17.6%)
Side cut	5.5 (19.4%)	5.7 (18.5%)
Stride	2.5 (37.7%)	11.6 (39.7%)
Sprint	2.4 (16.8%)	13.8 (27.3%)

4.4.2 Convergent validity analysis

Between-participant CV across each task showed more considerable variation, with the highest value registered in the stride task (24.5%) and the lowest corresponding to jogging (14.5%). No significant association was found between body mass and BMI on the one hand and PL or PL.min^{-1} scores on the other hand. Height explained between-participant variation for the stride task presenting a significant moderate negative association for PL (r^2= -0.611, p = 0.008) and PL.min^{-1} (r^2= - 0.482, p = 0.034) results.

Results for each participant showed different variations between tasks on trial 2 depending on whether the total accumulated PL or its intensity expression (PL.min^{-1}) was considered (Figure 6). Spearman´s correlation measures showed a significant moderate correlation between ranking of participants´ scores between tasks for PL (0.593-0.764) and PL.min^{-1} (0.282-0.736), except between the stride and the sprint tasks for expressions of PL intensity where no association was found.

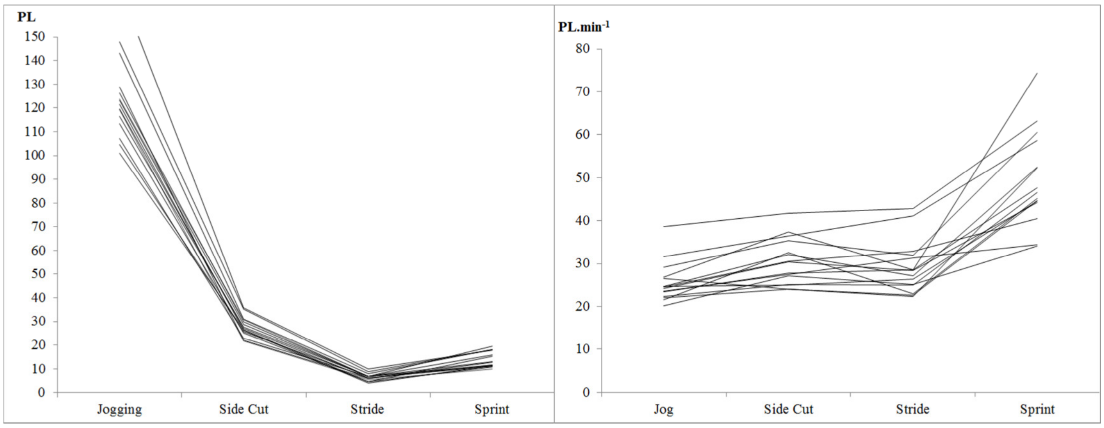

Figure 6. Within-participant variations of PL (left) and PL.min^{-1} (right) between tasks. Each line represents one participant.

Comparisons between tasks (see table 8) using ANOVA for repeated samples showed significant differences for PL and PL.min^{-1} results. Paired sample student t-tests showed significant differences between all tasks, except between side cut and stride PL.min^{-1} ($p= 0.239$).

Table 8. Trial 2 between subject and between task comparisons

	PL (Mean ± SD)					PL.min^{-1} (Mean ± SD)				
Task	Jogging	Side cut	Stride	Sprint	*p*	Jogging	Side cut	Stride	Sprint	*p*
Trial 2	124.5 ± 18.0	27.7 ± 4.2	6.5 ± 1.6	13.9 ± 3.2	0.000*	25.6 ± 4.7	30.5 ± 5.4	29.2 ± 6.2	49.5 ± 10.9	0.000
CV	14.5%	15.2%	24.5%	23.4%		18.2%	17.8%	21.2%	22.1%	
Association- Height	-0.416	-0.317	-0.611**	-0.392		-0.411	-0.406	-0.482**	-0.302	
Association- Weight	-0.277	-0.239	-0.367	-0.338		-0.312	-0.283	-0.239	-0.340	
Association- BMI	0.033	-0.180	0.128	-0.065		-0.032	0.034	0.189	-0.190	

*Sphericity criterion not met, Greenhouse-Geisser correction used.

** Statistical significance (p<0.05)

4.5 Discussion

PL and PL.min^{-1} relative to multidirectional football tasks, performed at different intensity levels, from regular jogging to maximal sprinting, present moderate to high reliability. The convergent validity analysis identified variations in PL and PL.min^{-1} between participants, with a small to moderate negative association between height and both PL and PL.min^{-1} in the stride task. The analysis of accelerometry scores between the four actions performed in this study identified significant differences for PL scores between all the tasks, which were only noticed between jogging and sprinting and the remaining tasks in the case of PL.min^{-1}, showing that when considering intensity, the speed of the task may play a relevant role in accelerometry scores.

Despite differences in protocol with previous studies, our test-retest reliability analysis were in agreement, showing a moderate to high relative reliability, with ICC scores ranging from 0.806 to 0.949 (Barrett, Midgley, & Lovell, 2014; Barret, Widgley, Towlson, Garret, Portas, & Lovell, 2016), and a good absolute reliability with acceptable LOA. This generally agrees with the existing PL reliability research using distinct protocols such as the SAFT^{90} (Barret, Widgley, Towlson, Garret, Portas, & Lovell, 2016), treadmill running (Barrett, Midgley, & Lovell, 2014), and mechanical or outfield setups (Boyd, Ball, & Aughey, 2011) A small systematic bias was found ($p = 0.043$) in the PL.min^{-1} for the jogging task. This could be attributed to a familiarization effect between trials related to protocol execution in the jogging task. Whilst the 29 repetitions of the jogging task were standardized to be performed at the same pace and duration for both trials, careful analysis of our data showed that the jogging tasks were completed 2% faster in the first trial compared to the second trial, basically suggesting that participants systematically arrived a little earlier at the marker and waited a little longer before being instructed to do the following task. This appears to have resulted in a decrease in PL.min^{-1} in the second trial, even if the jogging tasks seemed to have been consistently performed within the pre-allocated time frame. Regarding the use of simulation protocols such as the SAFT^{90}, a low CV for within-subject comparisons was found for the accelerometry data collected during the 90 minutes of the protocol in a recent study (Barret, Widgley, Towlson, Garret, Portas, & Lovell, 2016).

Regarding convergent validity, our findings indicate that from the participants' demographics only height presented a negative association with accelerometry in the stride task. The effect found (p = 0.046) only marginally exceeded the level of significance adopted (alpha = 0.05), and the absence of any other significant finding relating height with the remaining accelerometry scores may attribute it to a type I error. However, the fact that taller subjects presented lower PL and PL.min^{-1} scores may result from the less vertical displacements that the trunk mounted accelerometer would be subject to if the strategy to reach the target speed in the straight line stride task from the taller subjects consisted of greater stride length. Consequently this increase in stride length would be followed by an overall reduction in the shock wave from the foot contacts (Mercer, Devita, Derrick, & Bates, 2003). The association between body height and accelerations was not noticed in the sprint task where an increase in stride frequency is expected instead of stride length, the common strategy to raise velocity at higher speeds, as it was shown in the study of Schache et al. (2014) in which the authors notice that above the threshold of 25.2 km.h^{-1} this strategy was implemented. Regarding the side cut task, with a speed similar to the stride task (15 km.h^{-1}), the fact that a direction change was established within a short distance after the start of the task this may have led the subject to adopt a shorter stride length again in order to prepare the side cut on its designated location, hence changing the acceleration patterns accordingly. However, this line of reasoning is highly hypothetical and we believe that to explain our results further detailed biomechanical analysis of stride characteristics would need to reveal if there is an actual alteration during striding in taller athletes which induces an observable change in trunk accelerations.

Subjects´ body mass did not influence PL or PL.min^{-1}, which may be a surprise. However, in order for the subjects to achieve target speeds due to the pre-established time and space of execution for each task, low variation between participants in the acceleration and deceleration efforts was expected. The aim of trunk mounted accelerometry is to provide an estimation of the ground reaction forces acting on the subject´s body (Wundersitz, Netto, Aisbett, & Gastin, 2013). Hence in order to maintain a similar accelerometry pattern between them, subjects with higher body mass have to apply more force than less heavy ones. Therefore, despite heavier individuals not having greater PL or PL.min^{-1}, the consequent mechanical loads on their musculoskeletal structures are expected to be higher. In summary, effects of anthropometrics on the acceleration and deceleration scores were negligible, despite the significant variation found between subjects for each task, confirmed by the high CV scores. Therefore this variation seems to be dependent on the individual´s biomechanical strategy for propelling their body depending on the action under performance. Factors such as increased stride lengths, increased hip, knee and ankle flexion ranges of motion, and longer stance times have been associated with increases in ground reaction forces during running (Silder, Besier, & Delp, 2015; Mercer, Bezodis, Russell, Purdy, & DeLion, 2005; Mercer, Devita, Derrick, & Bates, 2003; Derrick, Hamill, & Caldwell, 1998), and we assume that our observed inter-individual variations are the consequence of such factors, rather than the differences in demographics.

Differences between accelerometry scores for four different tasks were analysed, either as a cumulative variable (PL) or an expression of intensity ($PL.min^{-1}$). The analysis of intensity showed differences between jogging and sprinting with the remaining tasks, whilst side cut and striding revealed no differences between them. This may be justified by the same target speed adopted (15 $km.h^{-1}$) during the protocol in the latter two efforts. It is interesting to notice that despite side cut and striding actions being constituted by efforts with different types of gestures in this protocol, such as up stride and side stride preliminary to the side cut action itself and a straight line effort for the stride task, this did not show to have an effect on PL intensity. Thus, the target speed to reach whilst performing the efforts seems to have been the key factor contributing to it. In the present study, data collection of continuous speed development was not performed and for that reason association measures with the accelerometry scores developed throughout the course of the $mSAFT^{90}$ that could justify our hypothesis cannot be statistically addressed. We suggest that further research can complement the present findings by addressing this matter.

Our analysis showed that for PL there is a moderate positive association between all efforts, meaning that the participants modify their performance in a similar proportion, which was expected considering that PL is a representation of the sum of accelerations and decelerations. However, when expressions of intensity were considered the variation was not similarly proportional between the stride and sprint tasks. This observation is likely related to the fact that three participants could not increase their speed between these efforts, as seen in Figure 4 from the three lines that do not increase between stride and sprint. As this is contrary to the remaining participants, this appears to have created the variation of ranking, and therefore the use of PL.min^{-1} may allow an alternative differentiation among participants that should be addressed in further research in terms of meaningfulness for injury risk or load monitoring. So altogether, we would conclude that with increasing speed the increase in PL and PL.min^{-1} is similar between participants but further research would need to confirm this.

Our study comes with limitations. First, the methodology adopted in this study regarding accelerometer placement may affect the mechanical load output expressed by PL. As suggested in the previous study from Barrett et al. (2014) PL may present variations when measured with a trunk and hip mounted accelerometer during running. Accelerometer positioning near the centre of mass at a hip level have shown higher PL scores than scapular level, and if PL is used as an expression of mechanical load this variation may make its validity unjustified. However, and despite this limitation regarding the use of trunk mounted accelerometers as indicators of mechanical load, a recent study where different accelerometer locations were tested together with ground reaction forces using a force platform during football actions has also shown that the trunk mounted placement provides the better estimation of mechanical load (Nedergaard et al., 2016).

In an attempt to reproduce the demands of a football period whilst ensuring that fatigue would not be a confounding variable affecting the results, the observed time period of 15-30 minutes included a small number of stride (2) and sprint (3) repetitions. This is considered low for a within-subject reliability analysis. Further work will need to be done to confirm our findings on these tasks, as well as to possibly include other football related tasks in the analysis.

The match simulation protocol adopted excluded actions involving ball contact. Actions involving the ball typically only represent a small proportion of actions done during training or games (Carling, 2010; Rampini, Impellizzeri, Castagnac, Coutts, & Wisloff, 2009), and will likely only have a small impact on PL. Also, the mSAFT[90] match simulation was performed on a surface not specific for football practice, and this may have had a different impact on the acceleration and deceleration behaviour of the participants compared to turf surfaces in football practice. Similarly, differences in ground stiffness and damping behaviour exist between natural and artificial turf (Zanetti, Bignardi, Francheschini, & Audenino, 2013). It is still to be seen how surface characteristics affect trunk accelerometry, something that is hard to predict as the players will likely alter their biomechanical running strategy to compensate for higher impact forces on harder surfaces. However, although the stiffness of the laboratorial floor surface may have affected the PL accumulated score, we believe that the proportion between the scores would be kept the same.

4.6 Conclusion

The use of PL for monitoring accelerations and decelerations in football multidirectional actions using data from the accelerometer inbuilt in trunk mounted GPS devices presents moderate to high reliability across tasks performed at different speeds, ranging from moderate intensity efforts such as jogging to maximal efforts such as sprinting, and therefore can be used to monitor these types of efforts in football. There is significant variation between participants which was not associated with the participants´ anthropometrics and most likely relies on the individual's locomotive skills. Whilst PL measures the cumulative load, $PL.min^{-1}$ measures the intensity of a task. Different football related running actions showed different $PL.min^{-1}$ values, which to a certain extent was related to the running velocity that needed to be achieved in a small space.

Following this study which analysed PL in order to improve its application in professional football, one could progress exploring the application of this variable with regards to its use as a daily training monitoring tool and its potential to inform about hamstring injury risk. This way PL application and its relation with mechanical load could be tested in an applied context such as professional football, and its use challenged regarding hamstring injuries in EPL.

Chapter 5

The value of mechanical load monitoring in the prediction of hamstring injuries in football

5.1 Abstract

Hamstring injury risk assessment represents an increased priority in football considering increased injury rates over the past decades. Acceleration/deceleration efforts performed in football will impose stress on the players´ musculoskeletal system, with potential repercussions for the hamstrings muscles. One way to estimate these loads is through the measurement of mechanical load from trunk-mounted tri-axial accelerometry. The aim of this study was to comprehensively observe the predictive value of mechanical loads from trunk-mounted accelerometry observed during training three weeks prior to hamstring injury occurrence**.**

Data from 40 players from seven EPL clubs were obtained to compose a HIG (n= 20; 26.9 ± 3.8 years) and a matched control group (n= 20; 26.0 ± 4.1 years). Pairwise comparisons of mechanical loads expressed using PL and PL.min^{-1} were performed for every training session in the 21 days leading up to the injury event, and in the four days prior to any games within that time period. Results showed no significant differences between groups for PL expressions relative to the 21 days previous to the injury day. Mechanical load regarding four days previous to game days also did not expose significant differences, and thresholding data to only retain high change in acceleration data did not enhance differentiation between groups in pre-game loads.

Whilst mechanical load as measured through PL was not predictive of hamstring injuries in EPL players, we believe that the novel comprehensive approach of this exploratory study constitutes a promising approach in load monitoring assessments and the prediction of (hamstring) muscle injuries in professional football.

Keywords: Hamstrings, mechanical load, acceleration, PlayerLoad^{TM}

5.2 Introduction

Hamstring strain injuries are arguably the most challenging injury for medical staff, sports scientists, and coaches in professional football. This is due to its high incidence of 16.8 to 25.7% of total injuries, together with a worrying 12-16% rate of re-injury episodes (Ekstrand, Walden, & Hagglund, 2016). On average a football team will present five hamstring injuries throughout the season at a rate of 0.43-0.51 injuries/1000 training hours and 3.70-4.77 injuries/1000 hours of game (Ekstrand & Gillquist, 1983; Orchard & Seward, 2002; Ekstrand, Hagglund, & Walden, 2011; Woods, Hawkins, Maltby, Hulse, Thomas, & Hodson, 2004; Ekstrand, Walden, & Hagglund, 2016). This gets even worse in teams with increased fixture congestion and less recovery days between games during the competitive season (Bengtsson, Ekstrand, & Hagglund, 2013). Hamstring injuries cause prolonged time away from fully participating in training and games, with serious economic and performance consequences for the individual as well as for the club (Woods, Hawkins, Hulse, & Hodson, 2002; Junge, Lamprecht, Stamm, Hasler, Bizzini, Tschopp et al., 2011).

In dynamic team sports such as football, the diverse running activities require the constant involvement of the hamstring muscles. These muscles are particularly stressed when running at high speeds, which is why most hamstring injuries occur during sprint related activities (Gabbe, Finch, Bennell, & Wajswelner, 2005). The stress on the hamstring muscles will lead to positive or negative adaptations, depending on volume and fluctuations of these mechanical loads, and as such it works as a protection or adversely as a risk factor for injury. This raises the question whether persistently high levels of acceleration loads from training and match-play may have detrimental effects on a player's hamstring muscles, or as recently hypothesized, whether sudden dramatic changes in acceleration loads increase the risk of injury (Ehrmann, Duncan, Sindhuase, Franzen, & Greene, 2016; Colby, Dawson, Heasman, Rogalski, & Gabbett, 2014). Ehrmann et al. (2016) identified an accelerometer-related variable as predictable of soft tissue injury in football. Despite not specifically addressing the hamstrings, it suggests the existence of an optimal mechanical loading to be imposed on the players that may work as protective factor against injury. Likewise, players holding back in their activities during training sessions when they notice some kind of restriction in hamstring function may incur a hamstring injury when the training or particularly a game context forces them to repeatedly accelerate maximally. That is, not only may an increased injury risk be associated with a long term effect from weeks/months of accumulated load, or from acute fluctuation in those loads in general, it may also be associated to load periodization in the days leading up to games. Understanding the associations between mechanical stimulus and hamstring injury risk may open new insights in the way these loads are considered for training and game load management purposes.

The association between load variables from accelerometry and the occurrence of a hamstring injury has to our knowledge not yet been addressed. Therefore, the aim of this study was to comprehensively observe in professional football players the predictive value of mechanical loads from trunk-mounted accelerometry observed retrospectively regarding three training weeks prior to hamstring injury occurrence, or as part of a microcycle of four days previous to any game within those three weeks.

5.3 Methods

5.3.1 Subjects

A retrospective analysis was performed of training load data for 21 days preceding the day of a hamstring injury occurrence. Requests for medical and training load data associated with players with a history of a primary unilateral hamstring injury and paired controls were made to fourteen EPL and five Football League Championship clubs. Seven clubs responded positively, of which accelerometry data provided by four EPL clubs could be included in this study, with the remaining ones being excluded due to insufficient training data or pairwise matching issues. The data ranged from the football seasons 2012-2013 until 2015-2016.

Inclusion criterion for the HIG was the occurrence of unilateral hamstring injury, sustained during training or competition, which prevented participation in normal training and/or competition for more than 48 hours, not including the day of injury (Varley & Aughey, 2013). Exclusion criteria were the presence of lower limb or lumbar spine pathology at the time of study; chronic lumbar spine pathology; hamstring muscle surgery; or lumbar spine surgery (Silder, Thelen, & Heiderscheit, 2010; Sole, Milosavljevic, Nicholson, & Sullivan, 2012). Paired selection of CG players was based on similar positional or tactical demands and exposure to training and playing time, selected from the same team as the injured player. This resulted in data from 20 injured professional football players and 20 healthy matched controls (see tables 9 and 10).

The study met the requirements of the Liverpool John Moores University ethics committee and approval was obtained prior to the commencement of the study. Informed consent was obtained from the clubs involved.

Table 9. Sample characterization details

	Age (mean ± SD)	Height (mean ± SD)	Weight (mean ± SD)	Match minutes played (mean ± SD)	Training sessions (mean ± SD)	Position		
						Defender	Midfielder	Striker
HIG	26.9 ± 3.8	1.79 ± 6.9	76.3 ± 5.4	214.2 ± 142.2	10.3 ±1.6	4	12	4
CG	26.0 ± 4.1	1.81 ± 7.4	75.9 ± 5.5	223.8 ± 140.7	10.2 ± 1.8	6	13	1

Table 10. HIG injury-related details

	Grade[1]			Injury event		Injury mechanism			Absence days
	1a 1b 1c	2a 2b 2c	3a 3b 3c	Game	Training	Sprint	Stretching	Insidious	(mean ± SD)
HIG	5 6 0	3 4 1	0 0 1	17	3	8	8	4	22.3 ± 17.6

[1]Injury grading according to Pollock et al. (2014).

5.3.2 Data analysis

Training load data was provided as raw acceleration data from 100Hz tri-axial accelerometers inbuilt in Global Positioning System trunk-mounted units (Viper, Statsports Technologies, USA). These units were systematically worn throughout training sessions. The use of accelerometers is expected to be representative of the mechanical load associated with acceleration or deceleration efforts (Boyd, Ball, & Aughey, 2011; Colby, Dawson, Heasman, Rogalski, & Gabbett, 2014).

PL, a cumulative measure of the total mechanical load, was calculated from the raw accelerometry data and expressed in arbitrary units (AU) as previously described Boyd et al (2011). Similarly PL per minute activity (PL.min^{-1}), a measure of average mechanical load intensity, was calculated from the raw accelerometer data. The test-retest, intra-device and between-device reliability of PL has been assessed with good overall results (Barrett, Midgley, & Lovell, 2014; Barret, Widgley, Towlson, Garret, Portas, & Lovell, 2016; Boyd, Ball, & Aughey, 2011) .

PL and PL.min^{-1} were calculated for every training session within the 21 days prior to injury day, and the pairwise differences between HIG and CG were calculated. The fluctuation and significance of this difference in mechanical load throughout the 21 days was analysed. In this analysis days involving match participation were included, however due to FIFA regulations data from games could not be collected in the form of a trunk-mounted monitoring system. Therefore, in order to take into account mechanical loads induced due to participation in the games, a representative value of PL for game play was obtained from Barrett et al. (2015). An average of 1015.0 AU for PL was adopted for a 90 minutes game, resulting in 11.3 AU PL.min^{-1}. The latter value was multiplied by the amount of minutes played to best represent the amount of accumulated load to which players were exposed on game days.

Considering that most hamstring injuries occur in match play (Ekstrand, Walden, & Hagglund, 2016), training load data for each of the four days preceding any match days within the 21 day period prior to injury was also analysed, in order to determine the role of pre-match day load variations on hamstring injury occurrence. Finally, considering that higher accelerations could be expressing a higher demand imposed on the hamstring muscles and could therefore be more meaningful in terms of injury prediction (Morin, Gimenez, Edouard, & Arnal, 2015), pre-match day load variations of PL and PL.min^{-1} were also calculated after applying different thresholds (above 0.1, 0.5, 1, 2.5 and 5 AU) to these variables.

5.3.3 Statistical analysis

Statistical procedures were conducted using SPSS (v.22.0, SPSS Inc., Chicago, IL, USA). Day-values of PL and PL.min^{-1} were compared between CG and HIG using paired-sample Student's t-tests for each of the 21 days previous to the injury moment, and for each of the four days preceding game days. To allow better interpretation of the effect of thresholding PL in the four days before matches, the magnitudes of paired differences were presented as *t-values*. The level of significance for all tests was set as alpha = 0.05 and the critical threshold was presented graphically. Based on the premise that this is an exploratory study, no correction was applied for multiple testing, avoiding an overly conservative interpretation of our findings.

5.4 Results

Analysis of the effect size of the difference between CG and HIG mechanical load during the 21 days previous to the injury day, expressed by the *t-values* (figure 1, row 2) show that none of the differences between HIG and CG exceeded the critical threshold indicated by the dashed lines (see figure 7).

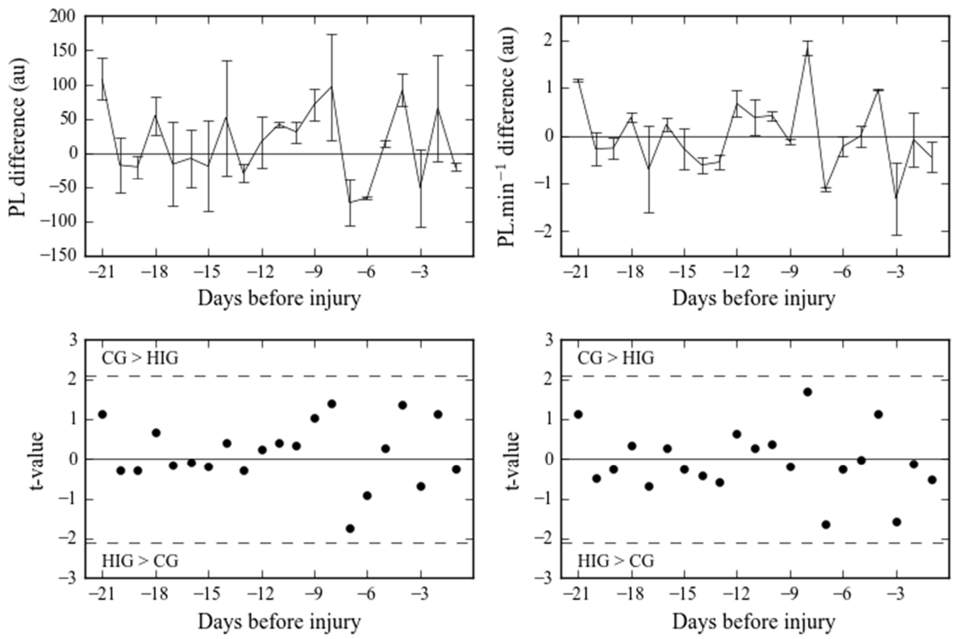

Figure 7. PL (left) and PL.min^{-1} (right) difference between CG and HIG scores throughout the 21 days pre-injury. Bottom panels present the effect size relative to a threshold for alpha < 0.05.

Differences between CG and HIG before match day also showed no significant differences for any of the four days analysed. No statistical significance of the effect size expressed by the t-values for PL and PL.min^{-1} was observed (see Figure 8). Incrementally removing data with low change in accelerations did not reveal systematically greater differentiation between HIG and CG for any of the pre-match days, as displayed in the lower panels of Figure 8 where the t-values do not gradually shift towards a positive or negative value.

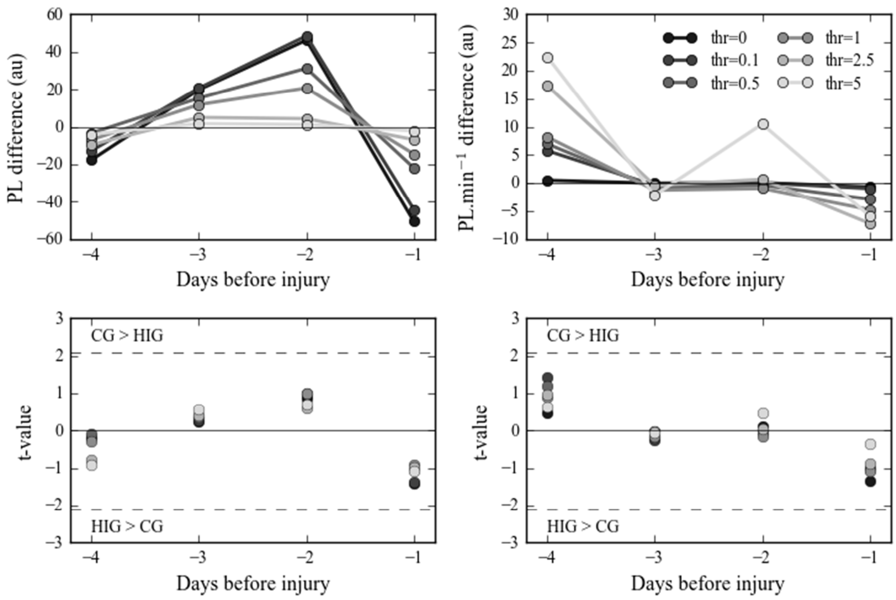

Figure 8. PL (left) and PL.min^{-1} (right) difference between CG and HIG scores four days previous to match day (MD). Besides unthresholded data (thr=0), five incremental levels of thresholds were applied. Bottom panels present the effect size relative to a threshold for alpha < 0.05.

5.5 Discussion

The present study was the first to evaluate mechanical PL in the three weeks leading up to a hamstring injury. Despite the unequivocal contribution of hamstring muscles to running activities (Morin, Gimenez, Edouard, & Arnal, 2015; Schache, Dorn, Blanch, & Brown, 2012), injured players did not present systematically higher or lower mechanical day-loads during the three weeks leading up to the injury, or as part of a microcycle of four days prior to game events in those three weeks. In the latter, the systematic variation of mechanical load thresholds did not expose any improved differentiation between injured and non-injured players.

This exploratory study presented a novel approach towards external training load analysis and hamstring injury. The use of accelerometry derived loads to verify injury risk has been mentioned before in studies around team sports, including football (Colby, Dawson, Heasman, Rogalski, & Gabbett, 2014; Ehrman, Duncan, Sindhuase, Franzen, Greene, 2016). Another variable (New Body Load) that could potentially represent mechanical load has been referred to in the only study so far performed in football (Ehrmann, Duncan, Sindhuase, Franzen, & Greene, 2016). Decreases in the latter variable relative to season averages were found during periods preceding injury. Also Colby et al. (2014) compared injured and non-injured elite Australian Football players regarding pre-season and in-season accumulated weekly loads based on an accelerometer-related variable (Force Load) and identified that 3-weekly accumulated load was associated with 2.5 times likelihood of injury occurrence. A key difference between these studies and our study is that they had a broader definition of injury, covering almost any musculoskeletal injury that would keep the player from participating in training/matches. Our approach targeted hamstring injuries specifically because of the aforementioned mechanical reasons, and our findings suggest that the occurrence of a singular type of injury is less predictable than the occurrence of an injury in general.

Intensity expressions of PL did not expose differences between HIG and CG relative to cumulative scores of mechanical load. PL.min^{-1} helps to identify the role that work density per time could have in the occurrence of hamstrings injuries. A study by Akenhead et al. (2016) showed how variations in total load and load intensity do not follow a similar pattern in EPL players. Intensity of loads was found to be similar between the four days previous to match days, whereas total load showed meaningful variations going from the highest cumulative loads four days before the match and the lowest in the last day before the match. Consequently, higher or lower peaks of mechanical load during the four days regarding its total scores or intensity were expected to result in significant differences that could relate with hamstring injuries, even in the case that these differences were not simultaneously significant for the two expressions of the same variable (PL).

The analysis of mechanical load considering different levels of thresholding did not improve the sensitivity of this data towards predicting hamstring injuries, showing that cut-offs isolating higher acceleration levels regarding the two mechanical load expressions did not result in significant differences between groups. This was somehow unexpected as retaining the higher accelerations only was expected to be associated with the most stressful moments to the hamstring muscles. Additionally, thresholding data at different mechanical load levels presents potential significant higher acceleration data from being dissipated in overall PL scores, decreasing the probabilities of differences being exposed. Despite the absence of differences in our study, future research should still consider thresholding mechanical load data to target injuries obtained during high acceleration tasks.

Our study has a number of limitations. The inability to measure loads during matches could have contributed to our inability to expose meaningful load differences between groups. Match exposure has been shown to increase the likelihood to sustain an injury (Carling, McCall, Le Gall, & Dupont, 2016) and hence it is likely that match data contain meaningful information for injury prediction, considering the magnitude of acceleration and deceleration efforts present in a football match. For example, Terje et al. (2016) recently have shown that accelerations and decelerations will constitute 7-10% and 5-7% of total match load, respectively as measured by a tri-axial body worn accelerometer, placed at lumbar spine level. In fact, hamstring injuries tend to occur more frequently during matches, as was observed in Ekstrand et al. (2016) where hamstring injuries were reported at the rate of 4.77 injuries/1000 hours of game, which is nine times the rate of injuries during training.

Additionally, high levels of match congestion in our sample might also have been responsible for a reduced load during training sessions, with training strategies during weeks involving more than one game tending to involve lower training loads (Anderson, Orme, Di Michele, Close, Morgans, Drust, et al. 2016; Akenhead, Harley, & Tweddle, 2016). The size of our sample is a further limitation of the present study. Gaining access to large samples in an elite football environment can be particularly challenging, and despite a sample of 20 hamstring injuries, there were considerable variations in injury grade, injury event, and injury mechanism, each of which could easily indicate different causalities of the injury too. Similarly, with data from four clubs only, the full spectrum of training methods existent in EPL was likely not covered. These factors, together with the multi-factorial aetiology of injuries in general and hamstring injuries specifically, justify the need for greater sample sizes in future research to account for co-variates that cannot be controlled.

Future research with the purpose of evaluating systematic variations in PL during a period of time preceding a hamstring injury should carefully consider that both increases and decreases in mechanical load can lead to increased injury risk, and that the combination of both may go unnoticed with a study design as employed in our study. Recent work has demonstrated how increased as well as decreased loads relative to average load are predictive of injury (Blanch & Gabbett, 2015). Future studies will therefore need to consider observing positive as well as negative variations in load against average mechanical loads in the prediction of injury.

5.6 Conclusion

Mechanical load analysis during training in the 21 days prior to a hamstring injury, and four days prior to games within that time period, could not reveal predictive value regarding hamstrings injuries in EPL players. Also the application of different levels of thresholds to isolate activities involving higher accelerations did not systematically improve the differentiation between injured and matched controls. The novel approach of this exploratory study has helped gain a better understanding about the role of mechanical load to explain the occurrence of hamstring injuries in professional football.

Chapter 6

General Discussion and Conclusion

The role of acceleration analysis in hamstring injuries

6.1 Introduction

This thesis' overall aim was to observe the relation between acceleration related variables and hamstring injuries in professional football. A secondary aim was to provide additional insights to the approach that regularly clinical professionals such as physiotherapists adopt for the assessment, monitoring or rehabilitation of these injuries. Current practice is often based on clinical range of motion or manual resistive tests combined with subjective reporting by the player. Additionally, often variables like eccentric strength, motor control and power have been associated to the clinical practice in order to improve the sensitivity of the assessment battery of tests regarding hamstring injuries. However, this orthopaedic and isolated testing approach has been revealing insufficiencies as a monitoring tool and for prediction of these injuries. Therefore this research was centred on analysing a fundamental component of hamstring performance during running actions, which refers to their role in accelerating the players´ body. In order to do so the specific objectives of this research were: (a) to assess horizontal force deficits during maximum sprint running on a non-motorized treadmill in football players with previous history of hamstring strains as a pre-season risk-assessment in a club setting and (b) to observe the association and predictive value of mechanical loads observed during training on hamstring injury occurrence in professional football players. A secondary aim in support of (b) was (c) to examine reliability and construct convergent validity of Player Load ™ from trunk mounted accelerometry, expressed as a cumulative measure (PL) and as an intensity measure ($PL.min^{-1}$).

A combination of indoor (NMT) and outfield data regarding acceleration efforts in professional footballers were analysed, whilst a technical study was performed to analyse the reliability and convergent validity of trunk-mounted accelerometer data.

This combined approach provided a unique insight into the translation of research evidence into the professional sporting environment, with key results from our different studies including: (a) chapter 3: the absence of post hamstring injury horizontal force asymmetries assessed on a NMT; (b) chapter 4: high reliability of PL as a mechanical load expression across different football tasks, independent of players´ demographics; and (c) chapter 5: the absence of predictive value of systematic mechanical load variations in the three weeks prior to a hamstrings injury. Therefore, the purpose of this final chapter is to integrate findings from the different experimental studies, and form an overall conclusion of the research conducted. Generalised recommendations for future research directions will also be explored.

6.2 Acceleration related force measurements and mechanical load monitoring. Reliability and validity research.

With the overall focus of this research on the estimation of acceleration related forces and associated mechanical loads in professional football players, it was important to consider reliability and validity of the measurement methods currently in use. This was addressed in the pilot test as described in chapter 3, by assessing reliability of recording forces during accelerating on NMT, and in chapter 4 by assessing validity and reliability of PL in overground locomotion.

Whilst our reliability results from both Chapter 3 and chapter 4 studies show an overall good reliability of our acceleration related variables, this issue should be a matter of permanent focus from researchers whilst assessing acceleration related variables. In the case of the NMT, although reliability was described in several research studies (Highton, Lamb, Twist, & Nicholas, 2012; Lim, & Chia, 2007; Oliver, Armstrong, & Williams, 2007; Tong, Bell, Ball, & Winter, 2001; Gonzalez, Wells, Hoffman, Stout, Fragala, Mangine, et al. 2013; Cronin & Rumpf, 2014; Stevens, Hacene, Wellham, Sculley, Callister, Taylor, & Dascombe, 2015), analysis of horizontal and vertical forces had not been addressed so far. The fact that an original NMT testing protocol during pre-season period was implemented, together with the modifications from previous studies, such as the duration of the sprint or the non-tethered model adopted, informs sport scientists and medical staff that these measurements are feasible in an elite club setup, without excluding the necessity of continuously assessing the reliability of their own measurements. The application of the protocols in a team environment will have to consider factors such as time of the season and fixtures, other frequent testing protocols adopted in professional football, and the familiarization of the sports scientist or health professional conducting the protocol. Despite this, our findings improved the previous information in this field, through a protocol that better represents a typical sprint effort from football, due to the fact of being shorter in duration and of maximal intensity (Lim, & Chia, 2007; Hughes, Doherty, Tong, Reilly, & Cable, 2006; Oliver, Armstrong, & Williams, 2007; Highton, Lamb, Twist, & Nicholas, 2012). However, moving forward in this field might mean changing the protocol to further reductions in maximal sprint times in NMTs and the introduction of repeated bouts for example, for which robustness of these methods again needs to be challenged, making reliability a continuous effort.

The second variable of which reliability was addressed in this research was PL, which aims to assess mechanical load in overground running from an accelerometry-derived signal. The practical applications of our findings regarding accelerometry relate to the daily training monitoring routines widespread in professional football, and particularly in EPL. Often decision making processes are influenced by data monitoring information, and this extends to not only performance related issues but also load management. With our findings we have shown that in specific football related actions data collected from the tri-axial accelerometer and expressed through PL is overall reliable. This way a team's coaching and medical staff handling the data on a regular basis may rely on accelerometry scores of multidirectional movements such as a side cut, or maximal accelerations present in sprint efforts, as these were reliably represented by PL. Previous research on reliability considered the accumulation of all types of different actions during football or other sports (Barrett, Midgley, & Lovell, 2014; Barrett, Widgley, Towlson, Garrett, Portas, & Lovell, 2016; Boyd, Ball, & Aughey, 2011). However, and similarly to what was described in the previous paragraph, reliability in this field is yet to be fully determined. First, in our protocol presented in chapter 4, despite the familiarization sessions provided to the participants, there was still a minor systematic bias for expressions of $PL.min^{-1}$ in the jogging task. Second, our protocol was developed in a laboratory under controlled conditions and specifically isolating four actions only. Despite the value of the $mSAFT^{90}$ protocol in reproducing football efforts, we believe that outfield training conditions like other players' presence, weather, emotional factors, or coaching staff changes and consequently changes in training routines, might be able to influence the consistency of the measurements, which is a reason why reliability is a matter to continue to be explored when working with trunk mounted systems to assess mechanical load from accelerometry.

Advancing our knowledge on the construct validity of PL was also important for practical applications and future research in this field. It was unknown if, for example, taller subjects would have locomotive strategies that would implicate systematically different trunk movement than smaller subjects, or if heavier subjects would have propelling strategies different from lighter ones. Our results showed that variations of PL are independent of the participants' key anthropometric features and exclusively related with the nature of the task being performed, which negates a necessity to individualize PL based on anthropometry in an applied setting. For example, from a physiotherapist perspective, the relevance of these findings could be largely applied in a rehabilitation scenario, where often players tend to change their body mass, especially after prolonged absence from training, despite the efforts to counter that tendency. This way, either by delivering indoor football specific drills or starting an outfield rehabilitation, the rehabilitation professional will be aware that the mechanical load absorbed by the player´s body will be highly dependent on its locomotion skills and the demands of the exercises performed, in which speed targets seem to play a determinant role according to our finding from chapter 5, and not body mass. Rehabilitation and performance are both based on creating adaptations to progressive loading by the players musculoskeletal system, whilst allowing the affected structure to heal or improve its functional and morphological features following injury. The knowledge of the highest number of variables that affect that process are a fundamental factor to improving these strategies, aiming at a safer and quicker return to team training and competition.

Validity is also a permanent matter of research, with findings contradicting previous research concerning the validity of trunk acceleration data, mostly as some have recently attempted to validate these signals as an expression of the ground reaction forces acting on the subject. For example, a good correlation was found between resultant accelerations from trunk-mounted accelerometry and ground reaction forces as measured on a force platform during landing and jumping tasks (Simons & Bradshaw, 2016), and that it is moderately valid in expressing impact forces in tasks involving changes of direction (Wundersitz, Netto, Aisbett, & Gastin, 2013).

However, these measures of validity have recently been challenged by investigators in our research group (Nedergaard, Robinson, Eusterwiemann, Drust, Lisboa, & Vanrenterghem, 2016) in a study involving running and side cut actions at different speeds, demonstrating weak correlations and questioning the validity of trunk-mounted accelerometry as an indicator of whole-body mechanical load. Further work is underway to assess whether other approaches could be used to better relate trunk accelerometry to whole body mechanical load.

6.3 Hamstring injuries and acceleration-related variables in Football. Where do we stand and where could we be heading.

It seems unequivocal that hamstring muscles during high speed running actions are tested to the limit when eccentrically decelerating the shank during the last part of the swing phase, particularly the biceps femoris muscle part (Higashihara, Ono, Kubota, Okuwaki, & Fukubayashi, 2010; Chumanov, Heiderscheit, & Thelen, 2011; Chumanov, Schache, Heiderscheit, & Thelen, 2011; Schache, Dorn, Wrigley, Brown, & Pandy, 2013). However, these muscles also have an important contribution in the early to middle stance phase, propelling the body forward by generating horizontal forces (Morin, Gimenez, Edouard, & Arnal, 2015; Hamner, Seth, & Delp, 2010) which in turn are instrumental for rapidly increasing speed in sprint efforts (Morin, Edouard, & Samozino, 2011; Buchheit, Samozino, Alexander, Glynn, Michael, Haddad, Mendez-Villanueva, & Morin, 2014). This knowledge about hamstrings actions during running should be essential to medical staff in the analysis and the design of assessment and rehabilitation strategies around these injuries. However, in elite environments such as the EPL, self-proclaimed cutting edge resources are more and more present to allow the implementation of such strategies to prevent hamstring injury occurrence or better understand the consequences of previous injury. The existence of these resources should allow professionals from different fields such as clinicians, with limited knowledge about technical or biomechanical aspects of such resources, to use them in an applied context to add value to their clinical practice. However, as it will be further highlighted throughout this discussion and it was already mentioned in chapters 3 and 5, often the biomechanical value of these assessments is limited. Nevertheless, to explore the relationship between accelerations and hamstring injuries we chose to adopt strategies involving laboratory and outfield assessments, which ultimately differed not only in the environment where data were collected (laboratorial versus outfield) but also in the variables under analysis.

Results from our NMT force analysis and outfield training load analysis did not show an association between acceleration related variables and hamstrings injuries in professional football players. This has important consequences for interpreting hamstrings performance indicators in relation to its acceleration capabilities and derived loads. This way not only an alternative approach regarding hamstring injuries was explored through our research, which we believe should enforce medical staff to include this type of knowledge in their consideration for the management and prediction of these injuries, but we also verified the feasibility of these methods in professional EPL players, translating research methods to an applied field setting.

6.3.1 Force application during acceleration efforts

Our laboratorial study (chapter 3) contradicted the existing research in this field which had shown promising results relative to the physical management of these injuries upon return to train and play (Brughelli et al., 2010). Returning to train and play following a hamstring injury is a challenging moment for the medical staff, and although normally an outfield based progression is carried out to test and provide the hamstrings a critical adaptation level to these efforts before return to train, there are some isolated clinical and functional markers regarding the muscle's physical qualities that are included in this process. Despite there not being any differences between the groups of this study, the ideological principle associated to this method, in what is the individual analysis of the capability of each limb producing force at high speed during the most stressing moment for these muscles, and subsequently maintaining that action during a steady state moment, could better inform rehabilitation strategies. It was already mentioned that during rehabilitation following a hamstring injury the player will undergo a progressive outfield program, however the fact that he is able to reach the same level of load as prior to the injury does not expose any compensatory mechanisms from one hamstring to the other during running actions. Among these, eccentric strength peak torque is usually considered as an important marker to return to train, as it normally correlates with the muscle's capability to sustain outfield running related stresses. However, considering the behaviour of these muscles during outfield running actions, one could assume that because testing speeds and positions fail to match running mechanics, there is still an ecologically valid test missing in these assessments to allow the medical and sport science staff to monitor readiness for play. This underpins a necessity of addressing the behaviour performance of the muscles separately during acceleration actions during sprint efforts. Developments in research after our study are still showing how acceleration deficits are associated with hamstrings in a post-injury situation (Mendiguchia, Samozino, Martinez-Ruiz, Brughelli, Schmikli, Morin, et al.

2014). Mendiguchia et al. (2014) showed how horizontal force developments in players with recent hamstring injuries were reduced compared to a control group during the performance of 50 meter sprints. In our study, these types of findings were questioned. Consequently, the publication of our paper (Barreira, Drust, Robinson, & Vanrenterghem, 2015) served an important purpose as it led to the initiation of a critical debate through a letter to the editor from the Brughelli group which we rebutted. These communications can be found in appendix 1 (Barreira, Robinson, Drust, & Vanrenterghem, 2015a). In summary, the criticisms related to the differences in methods that we had reported on, and challenged the fact that our findings had negated theirs. Nonetheless, the importance of our paper was to point out that in a field setting one would often be forced to adopt minor variations to published methodologies as part of re-injury risk screening. Our results exposed how the applicability of novel laboratorial-based protocols can present limitations when implemented in a professional club environment.

The fact that previous injury is still nowadays the main risk factor for hamstring injuries should be sufficient to assume that simply gathering clinical tests where the player normally lays flat on a bed, together with strength assessments and outfield progression is not being sufficient to predict the behaviour of the previously injured hamstring throughout time and with repetitive loading from training and games. Focusing too much exclusively to isolated variables post injury such as eccentric strain may have led to a failure of reducing the number of re-injuries in modern-day football. A hamstring injury leads to altered morphology caused by scar tissue (Silder, Heiderscheit, Thelen, Enright, & Tuite 2008), which influences the muscle load absorption properties (Silder, Reeder, & Thelen, 2010) and the post-injury neuromuscular inhibition phenomenon (Fyfe, Opar, Williams, & Shield, 2013).

These effects are difficult to assess through a single variable like strength (Opar, Williams, Timmins, Hickey, Duhig, & Shield, 2015; Timmins, Bourne, Shield, Williams, Lorenzen, & Opar, 2015), flexibility (Witvrouw, Danneels, & Asselman, 2003; Gabbe, Bennell, & Finch, 2006; Dadebo, White, & George, 2004), power (Henderson, Barnes, & Portas, 2010) or neuromuscular control (Fousekis, Tsepis, Poulmedis, Athanasopoulos, & Vagenas, 2011). We believe that addressing horizontal forces and the bilaterally observed capacity and behaviour of hamstrings muscles during the most common mechanism of injury such as sprint actions can provide additional information to support decisions concerning a safe return to training. That is, the changes in running mechanics following injury (Silder, Thelen, & Heiderscheit, 2010) or the way repeated sprinting detriments biceps femoris activity over time (Timmins, Opar, Williams, Schache, Dear, & Shield, 2014), may justify the assessment of force generating capacity during accelerations in sprint tasks. This way a broader spectrum of performance qualities of these muscles are addressed, able to influence outfield performance and adaptation to training and game loading. Whilst this method proposes to improve the assessment of the functional behaviour of the hamstring during running actions, it is still limited to a laboratorial environment, in an instrument such as the NMT that limits performance as compared to overground sprint running, and normally it is a single moment assessment, not exposing therefore the effects of repetitive loading caused by continuous training and playing. Maintaining an analysis purely based on indoor assessments will fail to see the broader picture regarding the occurrence of these injuries and its recurrences, as outfield load represents a fundamental stimulus to these muscles. This reason has made us to progress our work using data from outfield training that could better express mechanical body load, yet in a limited way, reflect at least partially how hamstring muscles may be exposed to over or underload and verify the association with injury risk, to complete our analysis regarding acceleration related variables and hamstring muscles injury.

6.3.2 Outfield acceleration training loads and hamstring injury in EPL

The study in chapter 5 aimed to analyse how periodically and systematic training related mechanical loads could consequently lead to positive adaptations or failure of structures such as the hamstrings muscles, ultimately leading to injury in this last case. The analysis of PL differences between professional players between injured and non-injured players with similar positional demands and exposed to similar competition times did not reveal systematic differences. However, the planning and delivering of the loading content and its periodization in football still presents high relevance for coaching staff, and consequently should be an information particularly relevant for physiotherapists whilst monitoring hamstring muscle behaviour during the week. That is, although in this study clinical assessments or variables such as eccentric strength are not reported for the correspondent period of PL analysis, the combination of these assessments improves the understanding of physiotherapists regarding the hamstring muscle behaviour and its clinical signs. For example, if a player does reveal a particular performance noted by PL analysis after a set of trainings this should be correlated with their subjective clinical state regarding fatigue, tightness, neural tension tests, etc, and inclusively an objective marker of eccentric strength could be a useful addition to observe an hypothetical deficit in the hamstrings strength performance. Additionally, it also could be relevant to observe if a particular player is able to maintain the same level of tolerance to mechanical loads as expressed by PL, despite reporting symptoms during the training week to his medical staff, regarding his hamstring muscles. This particular fact would challenge practitioners to reflect on the validity of those monitoring strategies.

Load monitoring associations with injury risk are currently applied to a large spectrum of injuries in professional football and other team field sports (Ehrmann, Duncan, Sindhuase, Franze, & Greene, 2016; Colby, Dawson, Heasman, Rogalski, & Gabbett, 2014; Gabbett & Ullah, 2012), and not solely to the hamstrings muscles as discussed in this thesis. In the particular case of the hamstrings muscles, as already mentioned, there is the necessity of improving injury risk assessments to obtain a broader picture. In order to do so, one cannot ignore the role of loading resulting from outfield training and competition. If there were to be established risk assessments guidelines for hamstring injuries, we believe this will have to gather the muscles physical qualities together with the outfield load monitoring. This is due to the fact that ultimately either of these variables will provide insufficient information without being complemented with the other. Hypothetically, this might be one of the reasons why there is an increasing training related hamstring injury incidence in professional football. Due to the importance of physical loads on hamstring injury risk, just recently Duhig et al. (2016) found an association between the volume of high speed running and hamstring injuries in Australian Rules Football. However, and despite the importance that GPS derived variables such as speed zones may have on injury risk assessment, external mechanical load is believed to give a more representative assessment of the role of the hamstrings during acceleration efforts, advocating for the added value of analysing loads related to acceleration efforts to determine hamstring injury risk. This is for different reasons. Firstly, because it is imperative to complement extensive research efforts around hamstrings injuries risk factors performed over the years (Kujala, Orava, & Järvinen, 1997; van Beijsterveldt, van de Port, Vereijken, & Backx, 2013). Previous research has been proven insufficient to reduce injury rates, as training related hamstring injuries have actually increased (Ekstrand, Walden, & Hagglund, 2016). Secondly, and as previously mentioned, the assessment for hamstring injury risk and prediction should result from a combination of multiple variables if the isolated value of a variable may be insufficient to prevail over the remaining ones, such as eccentric strength which is commonly more explored in research (Brukner, 2015; Opar, Williams, Timmins, Hickey, Duhig, & Shield, 2015). It is questionable if the best level of eccentric strength will be sufficient to attenuate the impact caused by training strategies when these fail to create correct adaptations in the player's musculoskeletal system. This fact justifies the importance that external load may have with the risk of sustaining an injury.

The analysis of training loads in association with hamstring injuries might be challenging at an elite level, like the EPL clubs with highly congested schedules that were involved in our study. In our study detailed in chapter 5, comparisons throughout 21 days and specifically in the four day period before games call to our attention the insufficiency of training related loads to predict injury. First, there is the fact that game mechanical loads may be important for exposing significant differences between players. As most of hamstring injuries from our sample occurred during matches, in agreement with epidemiological reports (Ekstrand, Walden, & Hagglund, 2016), and match exposition increases injury rates (Bengtsson, Ekstrand, & Hagglund, 2013), hypothetically the development of forces during competition should be considered. Second, although in our study comparisons involving the four days previous to games were included, several players had more than one game per week. This not only made data regarding MD-4 and MD-3 less abundant, it may also have contributed to an insufficient volume of mechanical load which would allow to reveal differences between players. Previous research has confirmed that the fixture schedule affects the load performed during training by football players, with MD-4 corresponding to the day with highest load as opposed to MD-1 (Carling, McCall, Le Gall, & Dupont, 2016). That means that if players with a heavy fixture schedule did not have a four day pre-match period, this may have prevented them to see the kind of training loads that may distinguish injured from controls.

Although our exploratory study could not show the value of addressing mechanical load, previous research has shown that mechanical load can provide different information than GPS based data regarding for example running distance, speed zones, or metabolic power. For example, the study of Barrett et al. (2015) showed increases of PL to total distance ratios during the latter stages of game halves observed due to decreases in total distance performed by the players. If in this case a risk assessment analysis was performed based solely on running distances obtained using GPS, perhaps the decrease of total distance would not represent the variations in physical stress noted with the increased PL.

Overall, with time it is believed that studies focusing on the role of acceleration related loads will be able to contribute to our understanding of how functional assessments can help identify hamstring (re-)injury risk.

6.4 Future research

Research on the monitoring of player load, the prediction of injuries, and the prevention of injuries has in the past decade known a considerable growth, and is expected to continue evolving rapidly in the coming years. However, experienced medical and sport science staff are confronted daily with the limitations that risk assessment strategies have for hamstring injury prevention purposes.

For this reason future research should aim not only to improve laboratory assessments to make them as informative as possible regarding hamstrings physical qualities, but also to consider the crucial role of outfield loading as a stimulus to provide the correct level of adaptation to football performance, and therefore the potential that excessive or insufficient mechanical load might have on hamstring injury risk. Future research on hamstring prevention should gather both types of information to establish an overall risk profile during the course of a season, which should be a continuous and not an isolated action in time.

In what specifically concerns the assessment of force asymmetries on NMT (chapter 3), future research protocols could evaluate the capacity of players to maintain these (horizontal) forces over time during repeated sprints. Such protocol may improve the sensitivity of this type of testing, considering that hamstring muscles often sustain injuries during the latter stages of the game (Woods, Hawkins, Hulse, Hodson, 2002; Hawkins, Hulse, Wilkinson, Hodson, & Gibson, 2001), with this period being associated with changes in force production capacity during running (Greig & Siegler, 2009; Small, McNaughtona, Greig, & Lovell, 2013). Assessing the capability of the hamstring muscles to maintain their performance over time, together with verifying side-to-side asymmetries, may improve the value of this assessment.

Considering the potential of mechanical load analysis strategies and hamstring injury prediction (chapter 5), future research in this field will need to overcome some of the key limitations as experienced with our study. Games represent the moment where hamstring injuries happen more frequently (Ekstrand, Walden, & Hagglund, 2016) and therefore the monitoring of loads during games might reveal information that from regular training load monitoring is unavailable. At the time of our study, trunk mounted devices or accelerometers were not allowed to be used in EPL games. This has recently changed which creates exciting new opportunities for future research.

6.4 General conclusions

In this research a significant and novel development was undertaken in the way hamstring injury risk is assessed, and with potential to be further developed and improved in future studies. In professional football clinicians in particular are confronted with monitoring strategies based on clinical tests and subjective reporting from the players which is insufficient to allow a decision making process in order to prevent injury. For this reason this research thesis was the first research project to investigate how variables resulting from acceleration efforts in a laboratorial and outfield context may associate with injury in a professional football club setting, performed under a physiotherapist working in professional football.

As hamstring injuries continue to be a major concern in professional football we believe that the future of risk assessment should consider that their aetiology is multifactorial, and that analysing individual parameters in isolation may not allow a clear observation of a broader scenario regarding these injuries. In the present research we have looked into hamstring (re-)injury risk, addressing both laboratory and outfield related variables regarding the player’s ability to accelerate/decelerate the body. This will hopefully become part of future research paradigms addressing hamstring injury risk management in professional football.

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Appendix 1

Letter to the Editor entitled "Questionable data, accuracy needed" and answer.

Following the publication of this article (Barreira, P., Drust, B., Robinson, M.A., & Vanrenterghem, J., 2015) a letter to the Editor from the authors Matt Brughelli, Jean-Benoit Morin and Jordan Mendiguchia has been addressed questioning data accuracy (Brughelli, M., Morin, J.B., & Mendiguchia, J., 2015). Our published answer regarding the authors comments is presented below and it was also published (Barreira, P., Robinson, M., Drust, B., Vanrenterghem, J., 2015a).

Thank you for the opportunity to respond to the letter by Brughelli et al. regarding our recent paper "Asymmetry after hamstring injury in English Premier League: Issue resolved, or perhaps not?". Brughelli et al. were the first to highlight the issue of asymmetry after hamstring injury, and we wish to thank them for continuing debate in this area. In their letter, Brughelli et al. reiterated the importance of hamstring injuries as a major concern in all codes of football and the need to rigorously investigate this with careful scrutiny of data and thorough review processes. We fully agree. They however (1) question whether this had been the case in our recent paper, and (2) stated that "the data presented are invalid, leading to untrustworthy results". We beg to disagree with the latter. We will first offer further explanation of specific technical issues that were raised based on the data presented in Figure 2 of our paper, addressing each of the numbered remarks from Brughelli et al. We notice first that the references cited by Brughelli et al. are not based on the some model adopted in our study, which may lead to inaccurate comparisons between data collection methods.

1. *Forces do not return to zero*

The sprint assessment instrument adopted in our study was a non-motorized Woodway® curved treadmill, which differs from the methods adopted in the studies used by Brughelli et al. (2010) to reference the present criticism to our work. This fact likely justifies why the vertical force profiles highlighted by the example graph do not return to zero. The nature of this treadmill with its curved anterior and posterior aspects, promotes an earlier contact phase as well a later take off. This, combined with the high speed of movement that was requested of the participants during the sprint protocol leads to dramatically shortened flight phases between contacts, if indeed there is flight at all. Furthermore, because the treadmill belt is mounted on the force transducers, the deceleration of the treadmill belt during flight will lead to a sagittal plane torque on the force transducers, again preventing the force immediately dropping to zero in between steps. After all though, it was the distinct peak vertical forces that were used to identify steps with the synchronously recorded video, and whilst we agree with Brughelli et al. that there are limitations to the frame mounted force transducers this was not of immediate concern for our data analysis.

2. *Horizontal forces do not demonstrate distinct braking and propulsion phase*

The curvature of the treadmill ranges from 0-25% incline (both at front and back), and to accelerate the treadmill one has to mimic uphill running. As shown in the study by Gottschall and Kram (2005), running uphill will progressively modify the horizontal ground reaction force profile; increasing the magnitude of the propulsive peak whilst significantly decreasing the braking peak. They reported that an uphill inclines of 3º resulted in 19% less braking force, 6º resulted in 38% less braking force, and a 9º incline resulted in 54% less braking force. For the same inclinations (3º, 6º and 9º), propulsive forces increased by 28%, 50% and 75% respectively. Hence, the curved shape of the treadmill justifies a different horizontal force pattern.

3. *Peak horizontal forces at maximum velocity were considerably lower than in previous studies.*

Taking into consideration the altered biomechanics due to the curved nature of the treadmill, as described above, we disagree that horizontal forces are different than what has been previously reported. Our results for horizontal force development are in agreement with existing literature where a similar treadmill model was used (e.g. (Mangine, G.T., Fukuda, D.H., Towsend, J.R., Wells, A.J., Gonzalez, A.M., Jajtner, A.R., Bohner, J.D., Lamonica, M., Hoffman, J.R., Fragala, M.S., & Stout, J.R., 2014; Mangine G.T., Hoffman, J.R., Gonzalez, A.M., Wells, A.J., Towsend, J.R., Jattner, A.R., McCormack, W.P., Robinson, E.H., Fragala, M.S., Fukuda, D.H.,& Stout, J.R., 2014a)). In Mangine et al. (2014a) participants performed two trials of a 30 seconds maximum sprint on a non-motorized treadmill similar to the model used in our study. Results from this study (Mangine et al., 2014a) for peak horizontal force ranged between 183 to 352 N for the first trial and 220 to 358 N for the second trial. Our findings are in these ranges (196 to 211 N). The observed force profile further appropriately represented the forces needed to accelerate and decelerate the treadmill throughout the trial, with maximum forces during the first part of the acceleration phase, gradually reducing forces as the treadmill speed reaches its maximum, slightly positive forces to overcome the frictional resistance of the treadmill during the steady state phase, and negative forces to help decelerate the treadmill after that.

4. *Number of observed peaks in horizontal compared to vertical forces*

We agree that the force profile of individual steps for horizontal forces is considerably less clear than for the vertical forces. The short flight phase together with the fact that the treadmill frame was not fixed to the floor are two reasons that can help explain this. As both force components were recorded simultaneously, we manually verified the vertical peak forces through synchronous video recording, and then used the horizontal force values at the time of those peaks.

We hope that with these responses to the listed technical issues we have been able to demonstrate the necessary rigour with which the data was processed, analysed, and interpreted. Data analysis was done manually in MS Excel from raw exported data rather than through an automated process. We do not see why programming this process into software, as Brughelli et al. suggest, would improve the rigour of this kind of work. In fact, we would argue that the automation process should be done by an engineer who is duly trained to write software and implement accuracy checks, rather than stimulate sport scientists.

Finally, we would like to reinforce the fact that the technical issues 1, 3 and 4 were actually raised by the reviewers. Importantly though, the reviewers recognised that the aim of our study was not to validate this particular method but to explore whether its application in a club setting can reveal previously reported asymmetries. As we stated in the discussion section, there is a 'need to rigorously test whether modifications to an assessment protocol eliminate its capacity to actually reveal deficiencies'. As such, we believe that the limitations of the work were duly considered during a thorough review process as is common practise for the IJSM.

The phrasing of key messages that form the basis of the translational nature of our work was re-worded based on reviewers' suggestions, such that at no time it implied that previous findings are rejected. In fact, with our paper we aimed to stimulate care in data collection and data interpretation in an applied setting, and from that perspective we seem to fully agree with Brughelli et al.

Appendix 2

Authorization from publisher to include chapter 3 study of the present thesis in the e-thesis version "Asymmetry after hamstring injury in English Premier League: issue resolved, or perhaps not".

Dear Dr. Barreira,

From the publisher's side I can confirm that you are entitled to use your article in the electronic version of your thesis.

Best regards

Volker Niem

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Appendix 3

Authorization from publisher to include chapter 4 study of the present thesis in the e-thesis version "Mechanical PlayerLoad^{TM} using trunk mounted accelerometry in Football: Is it a reliable, task- and player-specific observation?"

Mr. Paulo Barreira

That's fine,

Best wishes,

Eric Wallace

-----Original Message-----
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RJSP-2016-0021.R1 - Mechanical PlayerLoadTM using trunk mounted accelerometry in Football: Is it a reliable, task- and player-specific observation?"

Dear Prof. Eric Wallace:

I am the author of the above mentioned article.

I wish to include this work within the electronic version of my thesis, which I am required to deposit in Liverpool John Moores University's E-Theses Collection (http://digitool.jmu.ac.uk:8881/R). The Collection is non-commercial and openly available to all.
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Thank you

Sincerely,
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Journal of Sports Sciences